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EU harmonised testing procedure: Determination of water electrolyser energy performance

Specific energy consumption and energy efficiency

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Contents

Abstract

The objective of this pre-normative research (PNR) document is to present a testing procedure for establishing the energy performance of water (steam) electrolyser systems (WE systems), whether grid-connected or off-grid and individual water electrolysers (WEs)/high-temperature electrolysers (HTEs) for the generation of hydrogen by water/steam electrolysis. The WE systems use electricity mostly from variable renewable energy sources. HTE may additionally utilise (waste) heat from energy conversion and other industrial processes.

By applying this procedure, the determination of the specific energy consumption per unit of hydrogen output under standard ambient temperature and pressure (SATP) conditions allows for an adequate comparison of different WE systems. Also, the energy performance potential of WEs or WE systems employing low-temperature water electrolysis (LTWE) technologies compared to HTE employing high-temperature steam electrolysis (HTSEL) technologies may be established under actual hydrogen output conditions by applying this procedure.

The test method is to evaluate the specific energy consumption during steady-state operation at specified conditions including rated input power, pressure and temperature of hydrogen recommended by the manufacturer of the WE or WE system. The energy efficiency and the electrical efficiency based on higher and lower heating value of hydrogen can be derived from respectively the specific energy consumption and the specific electric energy consumption as additional energy performance indicators (EPIs). In a plant setting, the specific energy consumption of an individual water electrolyser including HTE under hydrogen output conditions may also be determined using this testing procedure.

This procedure is intended to be used as a general characterisation method for evaluating the energy performance of WEs including HTEs and systems by the research community and industry alike.

Foreword

This report was carried out under the framework contract between the Directorate-General (DG) JRC of the European Commission (EC) and the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU) (1). The JRC contractual activities are summarised in the strategic research and innovation agenda 2021-2027 of the Clean Hydrogen Partnership for Europe (SRIA) (2). This report constitutes the deliverable B.2 of the Rolling Plan 2022, contained in the Clean H_2 JU Work Programme 2022 (3). It is the result of a collaborative effort between European partners from research and technology organisations in industry and academia participating to European Union (EU) funded research, development and innovation (R&D&I) projects (4) in power-to-hydrogen (P2H2) and hydrogen-to-industry (H2I) applications involving WE for demonstration and eventually, industrial deployment.

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(1) According to Article 3(1)(c) of Council Regulation (EU) No 2021/2085 of 19/11/2021 (EU OJ L 427, 30.11.2021, p. 17), the Clean Hydrogen Joint Undertaking (Clean H_2 JU) is the universal successor to FCH2JU as of 30 November 2021.

(2) See online at https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en, page 103

(3) See online at https://www.clean-hydrogen.europa.eu/about-us/key-documents/annual-work-programmes_en, page 208

(4) For a list of projects, see at https://www.clean-hydrogen.europa.eu/projects-repository_en. More comprehensive information can be searched at https://cordis.europa.eu.

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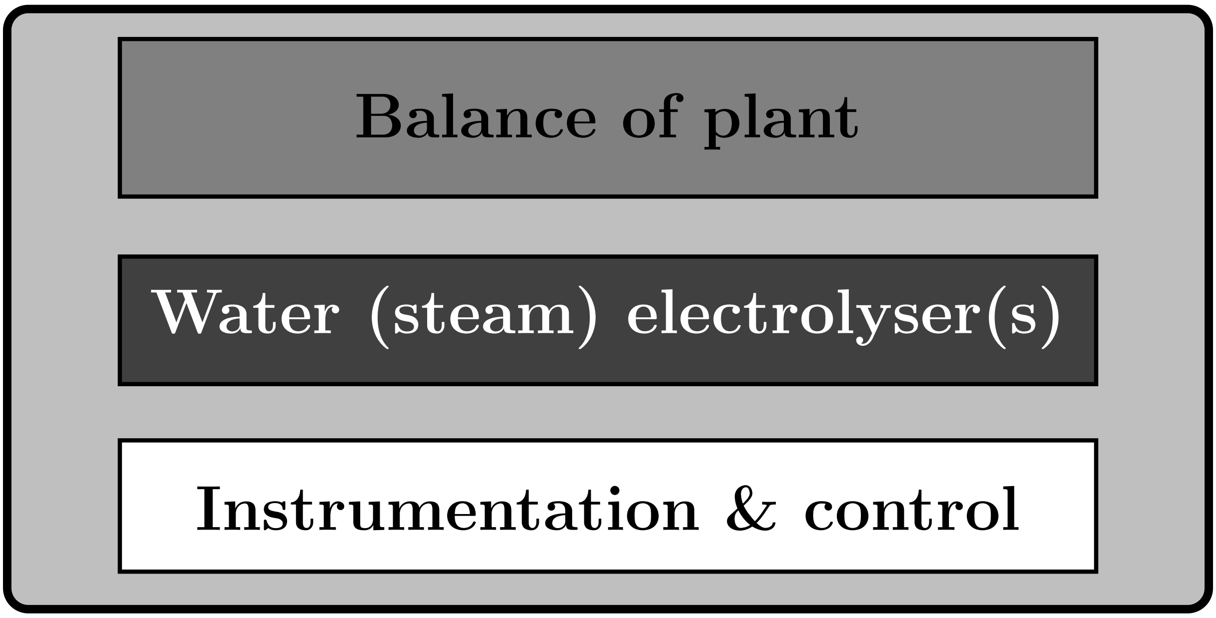
1 Introduction

For an adequate comparison of one water (steam) electrolyser system (WE system) to another system (Figure 1.1) in respect of the specific energy consumption (ε_{e}) per unit output (mole, $\varepsilon_{\mathrm{e,n}}$, volume, $\varepsilon_{\mathrm{e,V}}$ and mass, $\varepsilon_{\mathrm{e,m}}$) of hydrogen ($\mathrm{H_2}$) generated under standard ambient temperature and pressure (SATP) conditions, section 3.2.1 provides for these energy performance indicators (EPIs). For the same three units of hydrogen output, the specific energy consumption is complemented by two additional EPIs namely the specific electric energy consumption ($\varepsilon_{\mathrm{el}}$) in section 3.2.2 and the specific thermal energy consumption ($\varepsilon_{\mathrm{th}}$) in section 3.2.3.

In section 3.2.4, two more EPIs namely the energy efficiency (η_{e}) based on higher heating value (HHV), $\eta^{0}_{\mathrm{HHV,e,sys}}$ and lower heating value (LHV) of hydrogen, $\eta^{0}_{\mathrm{LHV,e,sys}}$, generated by the water (steam) electrolyser system (WE system) are derived from the specific energy consumption while in section 3.2.5, the electrical efficiency (η_{el}) based on these two heating values, $\eta^{0}_{\mathrm{HHV,el,sys}}$ and $\eta^{0}_{\mathrm{LHV,el,sys}}$, are derived from the specific electric energy consumption.

Note, under SATP conditions namely T^0 = 298,15 K and p^0 = 100 kPa (IUPAC, 2019), the HHV and LHV of hydrogen are respectively $\mathrm{HHV_{H_2}}$ = 79,4 kWh/mol and $\mathrm{LHV_{H_2}}$ = 67,2 kWh/mol (Tsotridis and Pilenga, 2018).

Figure 1.1: Schematic of a water (steam) electrolyser system comprising one or more water electrolysers including high-temperature electrolyser, common balance of plant, instrumentation & control devices including safety sensors and operation software.



Source: JRC, 2022.

Based on the application particularly the intended use of the generated hydrogen (including purity) (5) whether as fuel for mobility (road, rail, maritime), combined heat and power (CHP) generation, energy-storage (ES) or directly in hydrogen-to-industry (H2I) processes (*i. e.* direct reduction of iron (DRI), methanation, synthetic fuels, methanol, ammonia and fertiliser production, etc) (Chatenet et al., 2022, Shih et al., 2022), the manufacturer is to define which balance of plant (BoP) components form part of the system. This applies to alkaline water electrolyser (AWE), anion exchange polymer membrane water electrolyser (AEMWE), bipolar polymer membrane water electrolyser (BPMWE), proton exchange polymer membrane water electrolyser (PEMWE), solid oxide electrolyser (SOE) and proton conducting ceramic electrolyser (PCE) alike.

Besides common hardware (piping, valves, actuators, sensors, wiring/cabling, etc), BoP usually consists of (Tsotridis and Pilenga, 2021)

- **power supply** such as an alternating current-to-direct current (AC/DC) converter (rectifier) when grid-connected or direct current-to-direct current (DC/DC) converter(s) when directly coupled to one or more renewable energy sources (RESs), for example, photovoltaic (PV) arrays, wind turbine (off-grid), etc ,

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(5) Note, the strategic research and innovation agenda 2021-2027 of the Clean Hydrogen Partnership for Europe (SRIA) key performance indicator (KPI) targets state a hydrogen purity of 5 (99,999 vol-% of hydrogen in the product gas) irrespective of the four mentioned water/steam electrolysis technologies namely alkaline water electrolysis (AEL), proton exchange polymer membrane water electrolysis (PEMEL), anion exchange polymer membrane water electrolysis (AEMEL) and solid oxide steam electrolysis (SOEL), see the notes at https://www.clean-hydrogen.europa.eu/knowledge-management/sria-key-performance-indicators-kpis_en.

- **water conditioning** including pumps, ion exchanger, heat exchanger for feeding de-ionised water to an AWE, an AEMWE, a BPMWE or a PEMWE,
- **steam generator** for feeding steam (water vapour) to SOE/PCE or **conditioning unit** for externally supplied steam and
- **gas purification** including liquid/gas separators, demisters, coolers, dryers, steam-trap and de-oxidiser.

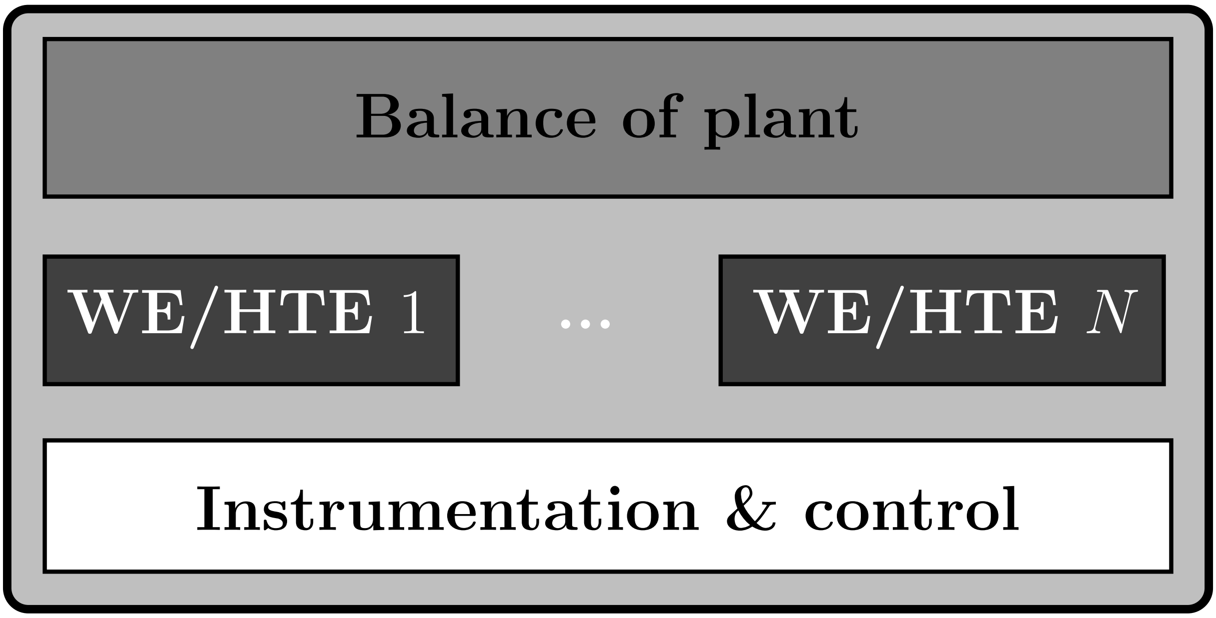
Depending on the immediate use of the generated hydrogen especially in power-to-gas (P2G) applications as well as in industrial processes requiring high pressure hydrogen, BoP usually includes compression equipment. In ES applications with hydrogen stored as compressed hydrogen (CH_2) in vessels or large (seasonal) underground storage facilities, compression equipment may or may not be part of BoP of a particular WE system.

Similarly, in power-to-mobility (P2M) applications with hydrogen stored as liquefied hydrogen (LH_2) in vessels, liquefaction equipment including proton exchange polymer membrane (PEM) based electrochemical hydrogen compressors (EHCs) may or may not be part of BoP of a particular WE system.

Under given conditions, the comparison of WE systems by their specific energy consumption per unit of hydrogen output and the energy efficiency may irrespective of the employed water/steam electrolysis technology serve to

- evaluate research and development (R&D) progress made in power-to-hydrogen (P2H2) applications such as P2G, P2M and power-to-X (P2X) including power-to-chemical (P2C), power-to-liquid (P2L) and power-to-fuel (P2F).
- set research and innovation (R&I) priorities, development milestones and technological benchmarks for improved specific energy consumption and assess impact on cost.
- make informed decisions regarding technology selection and energy demand of a system or plant (Figure 1.2).

Figure 1.2: Schematic of an electrolysis plant comprising N water electrolysers including high-temperature electrolysers, shared balance of plant, instrumentation & control devices including safety sensors and operation software.



Source: JRC, 2022.

For a comparison, the hydrogen generated by the WE system should be put out under SATP conditions (see section 3.2). Additionally, other reference conditions namely the pressure and temperature at which hydrogen is eventually put out by the system may be agreed upon (6).

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(6) For example, the SRIA KPI targets state for AEL and PEMEL technologies a hydrogen pressure of 30 bar while for AEMEL and SOEL technologies, an atmospheric pressure of hydrogen is stated, see the respective notes at https://www.clean-hydrogen.europa.eu/knowledge-management/sria-key-performance-indicators-kpis_en.

The specific energy consumption per mole, $\varepsilon_{\text{e, n, sys}}^{\text{p, T}}$, unit volume, $\varepsilon_{\text{e, V, sys}}^{\text{p, T}}$ and unit mass, $\varepsilon_{\text{e, m, sys}}^{\text{p, T}}$, of generated hydrogen by a WE system put out at its actual pressure and temperature (hydrogen output conditions), is the subject-matter of section 3.3.1.

In addition, for the same output units of generated hydrogen, section 3.3.2 and section 3.3.3 provide respectively for the specific electric energy consumption, $\varepsilon_{\text{el, n, sys}}^{\text{p, T}}$, $\varepsilon_{\text{el, V, sys}}^{\text{p, T}}$ and $\varepsilon_{\text{el, m, sys}}^{\text{p, T}}$ and specific thermal energy consumption (ε_{th}), $\varepsilon_{\text{th, n, sys}}^{\text{p, T}}$, $\varepsilon_{\text{th, V, sys}}^{\text{p, T}}$ and $\varepsilon_{\text{th, m, sys}}^{\text{p, T}}$, of a WE system under actual hydrogen output conditions. These EPIs of a WE system may serve to

a) verify meeting specifications through acceptance testing whether in a factory or on-site.

b) exchange data in commercial transactions between manufacturer and customer.

c) assess technological developments in target applications.

Where systems share common BoP or jointly use points of connection (PoCs) for electricity and/or fluid supplies as well as for conveying exiting hydrogen, the delineation (system boundary) between system interior and exterior should be well defined by the manufacturer preferably in agreement with the system operator (user).

The sharing of all or several BoP components by two or more water electrolysers/high-temperature electrolysers is of particular relevance for an electrolysis plant (Figure 1.2) with several individual water electrolysers/high-temperature electrolysers, whether or not all operate simultaneously or operate at a fraction or a multiple of their rated input power, $P_{\text{WE, in}}$.

In a plant setting (Figure 1.2), the specific energy consumption per output unit of hydrogen generated by a water electrolyser (WE)/high-temperature electrolyser (HTE), $\varepsilon_{\text{e, n, WE}}^{\text{p, T}}$, $\varepsilon_{\text{e, V, WE}}^{\text{p, T}}$ and $\varepsilon_{\text{e, m, WE}}^{\text{p, T}}$, is the subject-matter of section 3.4.1.

Under actual hydrogen output conditions and for the same output units, section 3.4.2 and section 3.4.3 provide respectively for the specific electric energy consumption, $\varepsilon_{\text{el, n, WE}}^{\text{p, T}}$, $\varepsilon_{\text{el, V, WE}}^{\text{p, T}}$ and $\varepsilon_{\text{el, m, WE}}^{\text{p, T}}$ and specific thermal energy consumption, $\varepsilon_{\text{th, n, WE}}^{\text{p, T}}$, $\varepsilon_{\text{th, V, WE}}^{\text{p, T}}$ and $\varepsilon_{\text{th, m, WE}}^{\text{p, T}}$, of a WE/HTE.

Notably, the application of this procedure does not require specification of the type and characteristic of an WE/HTE or WE system. Particularly, the size and the application-specific BoP may affect the comparison of one to another WE/HTE.

2 Objective and scope

The objective of this pre-normative research (PNR) document is to present a testing procedure for establishing the energy performance of WE systems and of individual WE/HTE in an electrolysis plant setting. By generating bulk amounts of hydrogen in the electrolysis of water (steam), the WE/HTE use electricity mostly from sources of variable renewable energy (VRE) (solar, tidal, wave, wind, etc) which is not readily dispatchable. In addition, waste heat may be utilised by HTE whether SOE including reversible solid oxide electrolyser (rSOE) or PCE including reversible proton conducting ceramic electrolyser (rPCE).

By applying this procedure, the determination of the specific energy consumption per unit of hydrogen output (mole, volume and mass), ε_{e}, $\varepsilon_{\mathrm{e,V}}$ and $\varepsilon_{\mathrm{e,m}}$, allows for a fair and adequate comparison of different WE systems. It also allows comparing the energy performance potential of the various technologies of

- Low-temperature water electrolysis (LTWE) such as
  - AEL,
  - AEMEL,
  - PEMEL and
  - bipolar polymer membrane water electrolysis (BPMEL) that is, water electro-dissociation under reverse bias.
- High-temperature steam electrolysis (HTSEL) namely
  - SOEL,
  - proton conducting ceramic steam electrolysis (PCCEL) and
  - hybrid-solid oxide cell (SOC) electrolysis.

The test method is to determine the specific energy consumption, ε_{e}, the specific electric energy consumption, $\varepsilon_{\mathrm{el}}$ and the specific thermal energy consumption, $\varepsilon_{\mathrm{th}}$, of WE systems during steady-state operation at specified operating conditions recommended by the manufacturer, *i. e.* the input power to the WE system, $P_{\mathrm{sys,in}}$. These EPIs are calculated as average (mean) values from the results of repetitive measurements of test input parameters (TIPs) particularly the said input power and the input electric power, $P_{\mathrm{el,in}}$ as well as test output parameters (TOPs) particularly pressure, $p_{\mathrm{sys,H_2}}$, temperature, $T_{\mathrm{sys,H_2}}$ and molar flow rate of hydrogen, $q_{\mathrm{n,sys,out,H_2}}$, generated by the WE system.

For the comparison of WE system, the hydrogen is to be put out under SATP conditions. The energy efficiency based on HHV, $\eta^0_{\mathrm{HHV,e,sys}}$ and LHV of hydrogen, $\eta^0_{\mathrm{LHV,e,sys}}$ both derived from the specific energy consumption as well as the electrical efficiency based on HHV, $\eta^0_{\mathrm{HHV,el,sys}}$ and LHV of hydrogen, $\eta^0_{\mathrm{LHV,el,sys}}$ both derived from the specific electric energy consumption are additional EPIs.

In an electrolysis plant setting, the specific energy consumption, specific electric energy consumption, and specific thermal energy consumption per unit of output of hydrogen generated by one or more water electrolysers/high-temperature electrolysers may also be determined using this procedure.

As a general characterisation method for determining the energy performance of water electrolysers/high-temperature electrolysers and systems whether grid-connected or directly coupled to one or another RES (off-grid), this procedure is intended to be used by the research community and industry alike. It may serve to evaluate the energy performance of water electrolysers/high-temperature electrolysers and systems for research, development and innovation (R&D&I) purposes including technology monitoring and assessment (TMA) as well as for measuring their accomplishments in technology development.

The method applies to different types of water electrolyser including high-temperature electrolyser in various P2H2 applications whether for ES, hydrogen-to-power (HtP), hydrogen-to-mobility (HtM) and H2I processes. The hydrogen generated by water (steam) electrolysis is used as an energy carrier (fuel or commodity) among others in applications such as P2M, P2G and P2X including P2C, P2L and P2F.

The scope of this procedure includes LTWE technologies such as AWE, AEMWE, BPMWE and PEMWE including reversible proton exchange polymer membrane water electrolyser (rPEMWE) as well as HTSEL technologies namely HTE whether oxygen ion conducting solid oxide electrolyser (O-SOE) or proton conducting solid oxide electrolyser (P-SOE) also known as PCE.

As EPIs, the specific energy consumption, specific electric energy consumption and specific thermal energy consumption allow to readily evaluate the energy-related production cost of hydrogen generated by water (steam) electrolysis knowing the unit price of the kind of energy used.

Note, electrolysers employing seawater or waste water directly are not in the scope of this procedure. The same holds for redox flow batteries (RFBs) performing water electrolysis.

3 Energy performance indicators

3.1 General

In this document, EPIs are

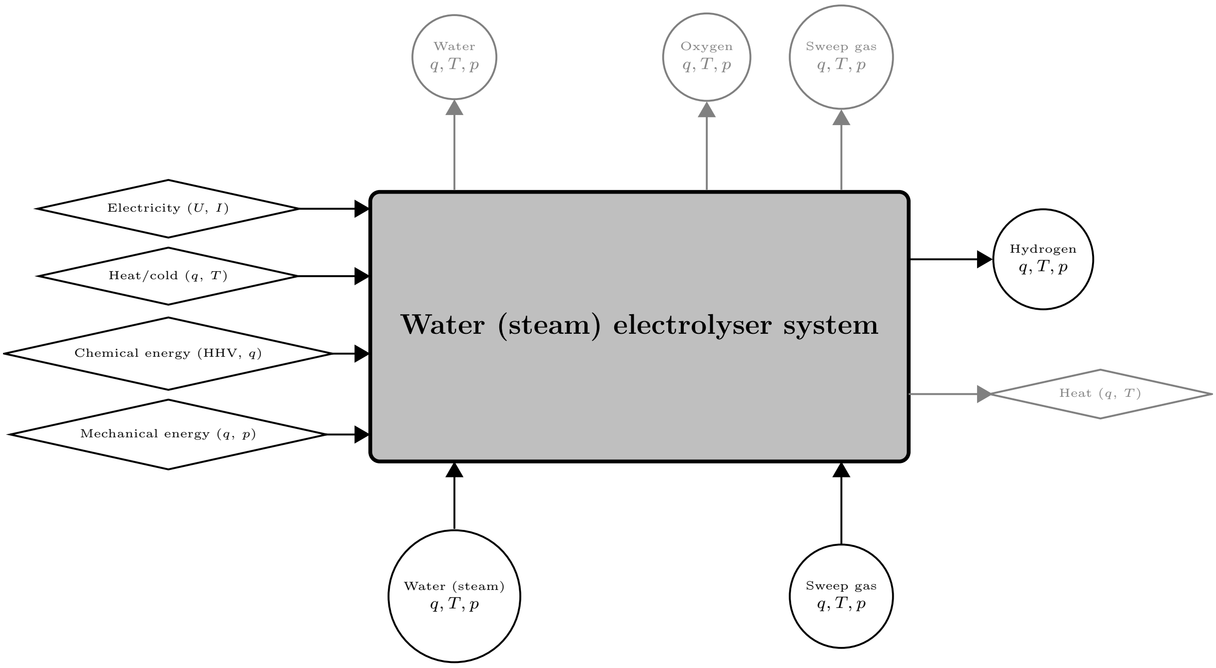
for a WE system (Figure 3.1)

- under SATP conditions of hydrogen output (see section 3.2),
  - the specific energy consumption (mole, volume and mass), see equation (3.2.1),
  - the specific electric energy consumption (mole, volume and mass), see equation (3.2.9),
  - the specific thermal energy consumption (mole, volume and mass), see equation (3.2.10),
  - the energy efficiency based on HHV and LHV of hydrogen, see equation (3.2.11) and
  - the electrical efficiency based on HHV and LHV of hydrogen, see equation (3.2.12).
- under actual conditions of hydrogen output (see section 3.3),
  - the specific energy consumption (mole, volume and mass), see equation (3.3.1),
  - the specific electric energy consumption (mole, volume and mass), see equation (3.3.2) and
  - the specific thermal energy consumption (mole, volume and mass), see equation (3.3.3).

for a WE/HTE (Figure 3.2) under actual conditions of hydrogen generation (see section 3.4),

- the specific energy consumption (mole, volume and mass), see equation (3.4.1),
- the specific electric energy consumption (mole, volume and mass), see equation (3.4.4) and
- the specific thermal energy consumption (mole, volume and mass), see equation (3.4.5).

Figure 3.1: Schematic of the input and output streams (directional arrows) of energy forms (diamond shape) and substances (circular shape) for a water (steam) electrolyser system (rectangular shape). The thick line around the grey shaded box represents the system boundary.



Source: JRC, 2022.

At the PoCs, the input energy streams to a WE system are

- **Electricity** in the form of electric energy (E_{el}),

$$E_{\text{el}}\ (\text{kW}) \ = \ P_{\text{el, sys}}\ (\text{kW}) \cdot t\ (\text{h}) \ \ \text{where} \qquad (3.1.1)$$

  $P_{\text{el, sys}}$ is the electric power of the WE system given by equation (3.2.3a) and t is the time of the applied electric power; U is the voltage of the WE system and I is the input current to the WE system.

- **Heat/cold**, if any, in the form of thermal energy (E_{th}),

  $$E_{\text{th}}\ (\text{kW}) = \big(P_{\text{th, sys, in}}\ (\text{kW}) - \text{HHV}^{\text{f}}\ (\text{kWh/mol}) \cdot q_{\text{n}}^{\text{f}}\ (\text{mol/h})\big) \cdot t\ (\text{h}) \ \text{ where} \tag{3.1.2}$$

  $P_{\text{th, sys, in}}$ is the input thermal power to the WE system given by the second term on the right hand side (RHS) of equation (3.2.4), HHV^{f} is the input fuel's HHV, q_{n}^{f} is the molar flow rate of fuel and t is the time of the heat/cold supply. The heat/cold is carried by fluids (air, water/steam, etc) being at temperature, T and having flow rate, q; for example, heat may be used to heat-up water or to generate steam while cold may be used to cool down the generated hydrogen and oxygen.
  Note, heat rejected by the WE system may be utilised, for example, in district heating or seawater desalination. The oxygen rejected by the WE system may be utilised, for example, in downstream processes of steel and fertiliser plants or used in aquaculture.

- **Chemical energy** (E_{chem}), if any,

  $$E_{\text{chem}}\ (\text{kW}) = \text{HHV}^{\text{f}}\ (\text{kWh/mol}) \cdot q_{\text{n}}^{\text{f}}\ (\text{mol/h}) \cdot t\ (\text{h}) \ \text{ where} \tag{3.1.3}$$

  t is the time of the fuel supply; for example, natural gas (NG) may be used to generate steam from water. Such fuel may also be used for heat-up especially during start-up of the WE system and for maintaining the temperature of the enclosure containing HTE stack(s) during transient operation as needed.

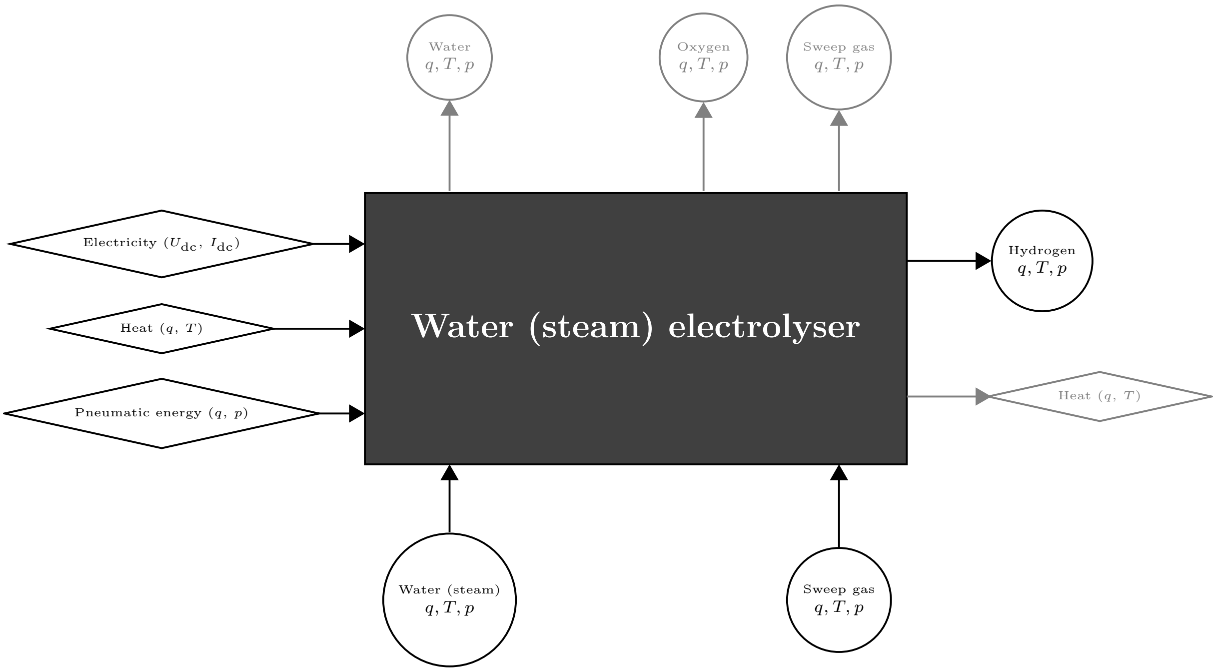
- **Mechanical energy**, if any, in the form of compression energy (E_{compr}),

  $$E_{\text{compr}}\ (\text{kW}) = P_{\text{compr, sys, in}}\ (\text{kW}) \cdot t\ (\text{h}) \ \text{ where} \tag{3.1.4}$$

  $P_{\text{compr, sys, in}}$ is the input power of compression into the WE system given by equation (3.2.5) and t is the time of compression. The compression is conveyed by a hydraulic fluid (*i. e.* oil) or pneumatic fluids (compressed air and pressurised steam), or both; for example, stack compression may require a hydraulic fluid, control devices may be actuated by compressed air and substances (steam, hydrogen, oxygen) may be compressed by such fluids having flow rate, q and pressure, p.

In accordance with clause 4.1.2 of ISO 22734:2019 (ISO, 2019), the manufacturer of the WE system should specify the feed water (steam) quality.

Figure 3.2: Schematic of the input and output streams (directional arrows) of energy forms (diamond shape) and substances (circular shape) of a water electrolyser/high-temperature electrolyser (rectangular shape). The thick line around the rectangular box shaded in dark grey represents the boundary of the electrolyser.



Source: JRC, 2022.

At the PoCs, the input energy streams to a WE/HTE are

- **Electricity** in the form of electric energy (E_{el}), see equation (3.1.1), using exclusively DC electric power ($P_{\text{el, dc}}$); U_{dc} is the stack voltage and I_{dc} is the input stack current.
- **Heat**, if any, in the form of thermal energy (E_{th}), see equation (3.1.2), carried by fluids such as
  - water as feed to BPMWEs and PEMWEs,
  - air as sweep gas to SOEs and
  - steam as feed to SOEs and as feed and sweep gas to PCEs.
- **Pneumatic energy**, if any, in the form of compression energy (E_{compr}), see equation (3.1.4), conveyed by fluids such as
  - pressurised water to AEMWEs, BPMWEs and PEMWEs,
  - pressurised steam to SOEs and PCEs, and
  - compressed air to SOEs.

3.2 WE system under SATP conditions

3.2.1 Specific energy consumption

In order to determine the specific energy consumption under SATP conditions, a by-pass may be required when an electrolyser operates normally at a pressure higher than ambient pressure unless system control allows electrolyser operation at atmospheric pressure. Also, it is assumed that the hydrogen generated by the electrolyser is cooled down to near ambient temperature, for example, to knock-off any remaining water vapour in the product gas (7).

The specific energy consumption per mole ($\varepsilon^0_{\text{e, n, sys}}$), unit volume ($\varepsilon^0_{\text{e, V, sys}}$) and unit mass ($\varepsilon^0_{\text{e, m, sys}}$) of hydrogen generated and put out by a WE system under SATP conditions are respectively given by

$$\varepsilon^0_{\text{e, n, sys}}\ (\text{kWh/mol}) \ = \ \frac{P_{\text{sys, in}}\ (\text{kW})}{q_{\text{n, sys, out, H}_2}\ (\text{mol/h})}, \tag{3.2.1a}$$

$$\varepsilon^0_{\text{e, V, sys}}\ (\text{kWh/m}^3) \ = \ \frac{\varepsilon^0_{\text{e, n, sys}}\ (\text{kWh/mol})}{V_{\text{m, H}_2}\ (\text{m}^3/\text{mol})} \ \approx \ 40,34\ (\text{mol/m}^3) \cdot \varepsilon^0_{\text{e, n, sys}}\ (\text{kWh/mol}) \ \text{ and} \tag{3.2.1b}$$

$$\varepsilon^0_{\text{e, m, sys}}\ (\text{kWh/kg}) \ = \ \frac{\varepsilon^0_{\text{e, n, sys}}\ (\text{kWh/mol})}{m_{\text{H}_2}\ (\text{kg/mol})} \ \approx \ 495,05\ (\text{mol/kg}) \cdot \varepsilon^0_{\text{e, n, sys}}\ (\text{kWh/mol}); \tag{3.2.1c}$$

$P_{\text{sys, in}}$ is given by equation (3.2.2), $q_{\text{n, sys, out, H}_2}$ is given by equation (3.2.6), $V_{\text{m, H}_2} \approx 24,79 \cdot 10^{-3}$ m^3/mol is the molar volume of hydrogen at SATP and $m_{\text{H}_2} \approx 2,02 \cdot 10^{-3}$ kg/mol is the molar mass of hydrogen not considering the isotopes of deuterium and tritium.

$$P_{\text{sys, in}}\ (\text{kW}) \ = \ P_{\text{el, sys}}\ (\text{kW}) + P_{\text{th, sys, in}}\ (\text{kW}) + P_{\text{compr, sys, in}}\ (\text{kW}) \tag{3.2.2}$$

is the input power of the system; $P_{\text{el, sys}}$ is given by equation (3.2.3a), $P_{\text{th, sys, in}}$ is given by equation (3.2.4) and $P_{\text{compr, sys, in}}$ is given by equation (3.2.5).

$$P_{\text{el, sys}}\ (\text{kW}) \ = \ P_{\text{el, ac, sys}}\ (\text{kW}) + P_{\text{el, dc, sys}}\ (\text{kW}) \tag{3.2.3a}$$

is the electric power of the system ($P_{\text{el, sys}}$) at its PoCs with AC electric power ($P_{\text{el, ac, sys}}$) which may be symmetrical three-phase AC electric power ($P_{\text{el, 3p, ac, sys}}$) given by

$$P_{\text{el, 3p, ac, sys}}\ (\text{kW}) \ = \ \sqrt{3} \cdot U_{\text{ac, sys}}\ (\text{kV}) \cdot I_{\text{ac, sys}}\ (\text{A}) \cdot \cos\varphi \tag{3.2.3b}$$

or single-phase AC electric power ($P_{\text{el, 1p, ac, sys}}$) given by

$$P_{\text{el, 1p, ac, sys}}\ (\text{kW}) \ = \ U_{\text{ac, sys}}\ (\text{kV}) \cdot I_{\text{ac, sys}}\ (\text{A}) \cdot \cos\varphi; \tag{3.2.3c}$$

$U_{\text{ac, sys}}$ and $I_{\text{ac, sys}}$ are the root mean square (rms) of respectively the AC voltage and the alternating current (AC) and $\cos\varphi$ is the power factor (IEEE, 2010). Note, for simplicity and ease of use, harmonics (IEEE, 2010) are omitted. The DC electric power ($P_{\text{el, dc, sys}}$) is given by

$$P_{\text{el, dc, sys}}\ (\text{kW}) \ = \ U_{\text{dc, sys}}\ (\text{kV}) \cdot I_{\text{dc, sys}}\ (\text{A}); \tag{3.2.3d}$$

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(7) For the purpose of this document, we only consider hydrogen containing gas as product gas of a WE/HTE and WE system.

$U_{\text{dc, sys}}$ and $I_{\text{dc, sys}}$ are respectively DC voltage and direct current (DC). Remark, the electric power may also be used for operating system auxiliaries such as control devices and other instrumentation.

$$P_{\text{th, sys, in}}\ (\text{kW}) \;=\; \text{HHV}^{\text{f}}\ (\text{kWh/mol}) \cdot q_{\text{n}}^{\text{f}}\ (\text{mol/h}) + \sum_{\text{i}} q_{\text{m}}^{\text{i}}\ (\text{kg/s}) \cdot c_{\text{p}}^{\text{i}}\ (\text{kJ/(kg K)}) \cdot \big(T^{\text{i}}\ (\text{K}) - T^{0}\ (\text{K})\big) \qquad (3.2.4)$$

is the input thermal power of the system at its PoCs by fluid i having mass flow rate, q_{m}^{i} and by fuel with higher heating value, HHV^{f} and molar flow rate, q_{n}^{f}; c_{p}^{i} is the fluid's specific heat capacity at constant pressure, p^{i} and temperature, T^{i}.

Remark, a non-zero temperature difference can be positive or negative. A WE system may not directly be involved in the electrolysis process. Note, the first term on the RHS of equation (3.2.4) is relevant when fuel is put into and used by the WE system. The second term on the RHS of equation (3.2.4) is relevant when heat/cold is transferred to the system.

$$P_{\text{compr, sys, in}}\ (\text{kW}) \;=\; \sum_{\text{j}} \big(p^{\text{j}}\ (\text{kPa}) - p^{0}\ (\text{kPa})\big) \cdot \frac{V_{\text{m}}^{\text{j}}\ (\text{m}^3/\text{mol})}{3600\ (\text{s/h})} \cdot q_{\text{n}}^{\text{j}}\ (\text{mol/h}) \qquad (3.2.5\text{a})$$

is the input power of compression provided to the WE system at its PoCs by incompressible fluid j of pressure, p^{j}, molar volume, V_{m}^{j} and molar flow rate, q_{n}^{j}.

$$P_{\text{compr, sys, in}}\ (\text{kW}) \;=\; \sum_{\text{j}} \left(\frac{\gamma^{\text{j}}}{\gamma^{\text{j}}-1}\right) \frac{\bar{Z}^{\text{j}} \cdot R_{\text{g}}\ (\text{kJ/(mol K)}) \cdot T^{0}\ (\text{K}) \cdot q_{\text{n}}^{\text{j}}\ (\text{mol/h})}{3600\ (\text{s/h})} \left(\left(\frac{p^{\text{j}}\ (\text{kPa})}{p^{0}\ (\text{kPa})}\right)^{\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}} - 1\right) \qquad (3.2.5\text{b})$$

is the input power of compression provided to the WE system at its PoCs by compressible fluid j where $\bar{Z}^{\text{j}}$ is the average average compressibility factor of this fluid and R_{g} is the universal gas constant. The isentropic expansion factor of this fluid is given by

$$\gamma^{\text{j}} \;=\; \frac{c_{\text{p}}^{\text{j}}\ (\text{kJ/(kg K)})}{c_{\text{V}}^{\text{j}}\ (\text{kJ/(kg K)})}; \qquad (3.2.5\text{c})$$

c_{V} is the specific heat capacity at constant volume. Note, the summations (3.2.5a) and (3.2.5b) are only relevant when fluids are put into the WE system. When both, incompressible and compressible fluids are put into the WE system, the summations (3.2.5a) and (3.2.5b) must be added together.

$$q_{\text{n, sys, out, H}_2}\ (\text{mol/h}) \;=\; x_{\text{n, sys, H}_2}\ (\text{mol/mol}) \cdot q_{\text{n, sys, out}}\ (\text{mol/h}) \qquad (3.2.6)$$

is the output molar flow rate of hydrogen generated by the system with $x_{\text{n, sys, H}_2}$, the molar concentration of hydrogen in the product gas to be determined by gas analysis (8) and $q_{\text{n, sys, out}}$ is the molar flow rate of the product gas exiting the system.

Remark, incompressible gases are assumed to behave according to the ideal gas law given by

$$p\ (\text{kPa}) \cdot V\ (\text{m}^3) \;=\; n\ (\text{mol}) \cdot R_{\text{g}}\ (\text{kJ/(mol K)}) \cdot T\ (\text{K}); \qquad (3.2.7)$$

p, V, n and T are respectively the pressure, volume, number of moles and temperature of the gas concerned (9). For compressible gases, this law reads

$$p\ (\text{kPa}) \cdot V\ (\text{m}^3) \;=\; n\ (\text{mol}) \cdot \bar{Z} \cdot R_{\text{g}}\ (\text{kJ/(mol K)}) \cdot T\ (\text{K}). \qquad (3.2.8)$$

Note, the pressure and temperature of the product gas are taken as those of hydrogen.

3.2.2 Specific electric energy consumption

The specific electric energy consumption per mole ($\varepsilon_{\text{el, n, sys}}^{0}$), unit volume ($\varepsilon_{\text{el, V, sys}}^{0}$) and unit mass ($\varepsilon_{\text{el, m, sys}}^{0}$) of hydrogen generated and put out by a WE system under SATP conditions are respectively given by

$$\varepsilon_{\text{el, n, sys}}^{0}\ (\text{kWh/mol}) \;=\; \frac{P_{\text{el, sys}}\ (\text{kW})}{q_{\text{n, sys, out, H}_2}\ (\text{mol/h})}, \qquad (3.2.9\text{a})$$

$$\varepsilon_{\text{el, V, sys}}^{0}\ (\text{kWh/m}^3) \;=\; \frac{\varepsilon_{\text{el, n, sys}}^{0}\ (\text{kWh/mol})}{V_{\text{m, H}_2}\ (\text{m}^3/\text{mol})} \;\approx\; 40{,}34\ (\text{mol/m}^3) \cdot \varepsilon_{\text{el, n, sys}}^{0}\ (\text{kWh/mol}) \ \text{ and} \qquad (3.2.9\text{b})$$

$$\varepsilon_{\text{el, m, sys}}^{0}\ (\text{kWh/kg}) \;=\; \frac{\varepsilon_{\text{el, n, sys}}^{0}\ (\text{kWh/mol})}{m_{\text{H}_2}\ (\text{kg/mol})} \;\approx\; 495{,}05\ (\text{mol/kg}) \cdot \varepsilon_{\text{el, n, sys}}^{0}\ (\text{kWh/mol}); \qquad (3.2.9\text{c})$$

$P_{\text{el, sys}}$ is given by equation (3.2.3a) and $q_{\text{n, sys, out, H}_2}$ is given by equation (3.2.6).

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(8) See note (8) of Table 6.1.

(9) Note, the pressure and temperature of hydrogen are taken identical to those of the product gas of a WE system or WE/HTE.

3.2.3 Specific thermal energy consumption

The specific thermal energy consumption per mole ($\varepsilon^{0}_{\text{th, n, sys}}$), unit volume ($\varepsilon^{0}_{\text{th, V, sys}}$) and unit mass ($\varepsilon_{\text{th, m, sys}}$) of hydrogen generated and put out by a WE system under SATP conditions are respectively given by

$$\varepsilon^{0}_{\text{th, n, sys}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{th, sys, in}}\ \text{(kW)}}{q_{\text{n, sys, out, H}_2}\ \text{(mol/h)}}, \tag{3.2.10a}$$

$$\varepsilon^{0}_{\text{th, V, sys}}\ (\text{kWh/m}^3) \ = \ \frac{\varepsilon^{0}_{\text{th, n, sys}}\ \text{(kWh/mol)}}{V_{\text{m, H}_2}\ (\text{m}^3\text{/mol})} \ \approx \ 40,34\ (\text{mol/m}^3) \cdot \varepsilon^{0}_{\text{th, n, sys}}\ \text{(kWh/mol)} \ \text{ and} \tag{3.2.10b}$$

$$\varepsilon_{\text{th, m, sys}}\ \text{(kWh/kg)} \ = \ \frac{\varepsilon^{0}_{\text{th, n, sys}}\ \text{(kWh/mol)}}{m_{\text{H}_2}\ \text{(kg/mol)}} \ \approx \ 495,05\ \text{(mol/kg)} \cdot \varepsilon^{0}_{\text{th, n, sys}}\ \text{(kWh/mol)}; \tag{3.2.10c}$$

$P_{\text{th, sys, in}}$ is given by equation (3.2.4) and $q_{\text{n, sys, out, H}_2}$ is given by equation (3.2.6).

3.2.4 Energy efficiency

Using the estimated specific energy consumption ($\varepsilon^{0}_{\text{e, n, sys}}$) given by equation (3.2.1a), the energy efficiency based on HHV ($\eta^{0}_{\text{HHV, e, sys}}$) and LHV of hydrogen ($\eta^{0}_{\text{LHV, e, sys}}$) generated by the WE system under SATP conditions are respectively given by

$$\eta^{0}_{\text{HHV, e, sys}}\ (\%) \ = \ \frac{\text{HHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\varepsilon^{0}_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \% \ \text{ and} \tag{3.2.11a}$$

$$\eta^{0}_{\text{LHV, e, sys}}\ (\%) \ = \ \frac{\text{LHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\varepsilon^{0}_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%. \tag{3.2.11b}$$

Note, one has $\eta^{0}_{\text{HHV, e, sys}}\ (\%) \ \approx \ 1,18 \cdot \eta^{0}_{\text{LHV, e, sys}}\ (\%)$ and $\eta^{0}_{\text{LHV, e, sys}}\ (\%) \ \approx \ 0,85 \cdot \eta^{0}_{\text{HHV, e, sys}}\ (\%)$.

3.2.5 Electrical efficiency

Using the estimated specific electric energy consumption ($\varepsilon^{0}_{\text{el, n, sys}}$) given by equation (3.2.9a), the electrical efficiency based on HHV ($\eta^{0}_{\text{HHV, el, sys}}$) and LHV of hydrogen ($\eta^{0}_{\text{LHV, el, sys}}$) generated by the WE system under SATP conditions are respectively given by

$$\eta^{0}_{\text{HHV, el, sys}}\ (\%) \ = \ \frac{\text{HHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\varepsilon^{0}_{\text{el, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \% \ \approx \ 1,18 \cdot \eta^{0}_{\text{LHV, el, sys}}\ (\%) \ \text{ and} \tag{3.2.12a}$$

$$\eta^{0}_{\text{LHV, el, sys}}\ (\%) \ = \ \frac{\text{LHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\varepsilon^{0}_{\text{el, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \% \ \approx \ 0,85 \cdot \eta^{0}_{\text{HHV, el, sys}}\ (\%). \tag{3.2.12b}$$

3.3 WE system under hydrogen output conditions

3.3.1 Specific energy consumption

The specific energy consumption per mole ($\varepsilon^{\text{p, T}}_{\text{e, n, sys}}$), unit volume ($\varepsilon^{\text{p, T}}_{\text{e, V, sys}}$) and unit mass ($\varepsilon^{\text{p, T}}_{\text{e, m, sys}}$) of hydrogen generated and put out by a WE system under hydrogen output conditions are respectively given by

$$\varepsilon^{\text{p, T}}_{\text{e, n, sys}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{sys, in}}\ \text{(kW)}}{q_{\text{n, sys, out, H}_2}\ \text{(mol/h)}}, \tag{3.3.1a}$$

$$\varepsilon^{\text{p, T}}_{\text{e, V, sys}}\ (\text{kWh/m}^3) \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{e, n, sys}}\ \text{(kWh/mol)}}{V_{\text{m, H}_2}\ (\text{m}^3\text{/mol})} \ \text{ and} \tag{3.3.1b}$$

$$\varepsilon^{\text{p, T}}_{\text{e, m, sys}}\ \text{(kWh/kg)} \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{e, n, sys}}\ \text{(kWh/mol)}}{m_{\text{H}_2}\ \text{(kg/mol)}}; \tag{3.3.1c}$$

$P_{\text{sys, in}}$ is given by equation (3.2.2) ([10]) and $q_{\text{n, sys, out, H}_2}$ is given by equation (3.2.6).

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[10] Note, for input parameters, no distinction is made between SATP conditions and hydrogen output conditions throughout this report. The measured values of these parameters may nevertheless differ under these conditions.

3.3.2 Specific electric energy consumption

The specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$) and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$) of hydrogen generated and put out by a WE system under hydrogen output conditions are respectively given by

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{P_{\mathrm{el,sys}}\ (\mathrm{kW})}{q_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}, \tag{3.3.2a}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \quad \text{and} \tag{3.3.2b}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}\ (\mathrm{kWh/kg}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{3.3.2c}$$

$P_{\mathrm{el,sys}}$ is given by equation (3.2.3a) and $q_{\mathrm{n,sys,out,H_2}}$ is given by equation (3.2.6).

3.3.3 Specific thermal energy consumption

The specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$), unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$) and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$) of hydrogen generated and put out by a WE system under hydrogen output conditions are respectively given by

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{P_{\mathrm{th,sys,in}}\ (\mathrm{kW})}{q_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}, \tag{3.3.3a}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \quad \text{and} \tag{3.3.3b}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}\ (\mathrm{kWh/kg}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{3.3.3c}$$

$P_{\mathrm{th,sys,in}}$ is given by equation (3.2.4) and $q_{\mathrm{n,sys,out,H_2}}$ is given by equation (3.2.6).

3.4 WE/HTE under hydrogen output conditions

3.4.1 Specific energy consumption

The specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$), unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$) and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$) of hydrogen generated by a WE/HTE under hydrogen output conditions namely the pressure ($p_{\mathrm{WE,H_2}}$) and temperature of hydrogen ($T_{\mathrm{WE,H_2}}$), are respectively given by

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol}) \;=\; \frac{P_{\mathrm{WE,in}}\ (\mathrm{kW})}{q^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}, \tag{3.4.1a}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \quad \text{and} \tag{3.4.1b}$$

$$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}\ (\mathrm{kWh/kg}) \;=\; \frac{\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{3.4.1c}$$

$P_{\mathrm{WE,in}}$ is given by equation (3.4.2a) and $q^{\mathrm{WE}}_{\mathrm{n,H_2}}$ is given by equation (3.4.3).

$$P_{\mathrm{WE,in}}\ (\mathrm{kW}) \;=\; P_{\mathrm{el,dc,WE}}\ (\mathrm{kW}) + P_{\mathrm{th,WE,in}}\ (\mathrm{kW}) + P_{\mathrm{compr,WE,in}}\ (\mathrm{kW}) \tag{3.4.2a}$$

is the input power to the WE/HTE with the DC electric power given by

$$P_{\mathrm{el,dc,WE}}\ (\mathrm{kW}) \;=\; U_{\mathrm{dc,WE}}\ (\mathrm{kV}) \cdot I_{\mathrm{dc,WE}}\ (\mathrm{A}); \tag{3.4.2b}$$

$U_{\text{dc, WE}}$ and $I_{\text{dc, WE}}$ are respectively the DC voltage and direct current of the WE/HTE. The input thermal power to the WE/HTE is given by

$$P_{\text{th, WE, in}}\ \text{(kW)} \ = \ \sum_{\text{i}} q^{\text{i}}_{\text{m, WE}}\ \text{(kg/s)} \cdot c^{\text{i}}_{\text{p}}\ \text{(kJ/(kg K))} \cdot \left(T^{\text{i}}_{\text{WE}}\ \text{(K)} - T^0\ \text{(K)}\right); \tag{3.4.2c}$$

$q^{\text{i}}_{\text{m, WE}}$ and T^{i}_{WE} are respectively the input mass flow rate and temperature of fluid i to the WE/HTE. For incompressible fluids j, the input power of compression to the WE/HTE is given by

$$P_{\text{compr, WE, in}}\ \text{(kW)} \ = \ \sum_{\text{j}} \left(p^{\text{j}}_{\text{WE}}\ \text{(kPa)} - p^0\ \text{(kPa)}\right) \cdot \frac{V^{\text{j}}_{\text{m}}\ \text{(m}^3\text{/mol)}}{3600\ \text{(s/h)}} \cdot q^{\text{j}}_{\text{n, WE}}\ \text{(mol/h)}; \tag{3.4.2d}$$

p^{j}_{WE} and $q^{\text{j}}_{\text{n, WE}}$ are respectively the input pressure and molar flow rate of fluid j to the WE/HTE. For compressible fluids j, the input power of compression to the WE/HTE is given by

$$P_{\text{compr, WE, in}}\ \text{(kW)} \ = \ \sum_{\text{j}} \left(\frac{\gamma^{\text{j}}}{\gamma^{\text{j}} - 1}\right) \frac{\bar{Z}^{\text{j}} \cdot R_{\text{g}}\ \text{(kJ/(mol K))} \cdot T^0\ \text{(K)} \cdot q^{\text{j}}_{\text{n, WE}}\ \text{(mol/h)}}{3600\ \text{(s/h)}} \left(\left(\frac{p^{\text{j}}_{\text{WE}}\ \text{(kPa)}}{p^0\ \text{(kPa)}}\right)^{\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}} - 1\right). \tag{3.4.2e}$$

Remark, equation (3.4.2d) and equation (3.4.2e) are relevant when one or more fluids enter the WE/HTE. When both, incompressible and compressible fluids enter the WE/HTE, equation (3.4.2d) and equation (3.4.2e) must be added together.

The molar flow rate of hydrogen generated by the WE/HTE is given by

$$q^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/h)} \ = \ x^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/mol)} \cdot q^{\text{WE}}_{\text{n, out}}\ \text{(mol/h)}; \tag{3.4.3}$$

$x^{\text{WE}}_{\text{n, H}_2}$ is the molar concentration of hydrogen in the product gas exiting the WE/HTE with molar flow rate $q^{\text{WE}}_{\text{n, out}}$.

3.4.2 Specific electric energy consumption

The specific electric energy consumption per mole ($\varepsilon^{\text{p, T}}_{\text{e, n, WE}}$), unit volume ($\varepsilon^{\text{p, T}}_{\text{e, V, WE}}$) and unit mass ($\varepsilon^{\text{p, T}}_{\text{e, m, WE}}$) of hydrogen generated by a WE/HTE under hydrogen output are respectively given by

$$\varepsilon^{\text{p, T}}_{\text{el, n, WE}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{el, dc, WE}}\ \text{(kW)}}{q^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/h)}}, \tag{3.4.4a}$$

$$\varepsilon^{\text{p, T}}_{\text{el, V, WE}}\ \text{(kWh/m}^3\text{)} \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{el, n, WE}}\ \text{(kWh/mol)}}{V_{\text{m, H}_2}\ \text{(m}^3\text{/mol)}} \quad \text{and} \tag{3.4.4b}$$

$$\varepsilon^{\text{p, T}}_{\text{el, m, WE}}\ \text{(kWh/kg)} \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{el, n, WE}}\ \text{(kWh/mol)}}{m_{\text{H}_2}\ \text{(kg/mol)}}; \tag{3.4.4c}$$

$P_{\text{el, dc, WE}}$ is given by equation (3.4.2b) and $q^{\text{WE}}_{\text{n, H}_2}$ is given by equation (3.4.3).

3.4.3 Specific thermal energy consumption

The specific thermal energy consumption per mole ($\varepsilon^{\text{p, T}}_{\text{e, n, WE}}$), unit volume ($\varepsilon^{\text{p, T}}_{\text{e, V, WE}}$) and unit mass ($\varepsilon^{\text{p, T}}_{\text{e, m, WE}}$) of hydrogen generated by a WE/HTE are respectively given by

$$\varepsilon^{\text{p, T}}_{\text{th, n, WE}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{th, WE, in}}\ \text{(kW)}}{q^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/h)}}, \tag{3.4.5a}$$

$$\varepsilon^{\text{p, T}}_{\text{th, V, WE}}\ \text{(kWh/m}^3\text{)} \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{th, n, WE}}\ \text{(kWh/mol)}}{V_{\text{m, H}_2}\ \text{(m}^3\text{/mol)}} \quad \text{and} \tag{3.4.5b}$$

$$\varepsilon^{\text{p, T}}_{\text{th, m, WE}}\ \text{(kWh/kg)} \ = \ \frac{\varepsilon^{\text{p, T}}_{\text{th, n, WE}}\ \text{(kWh/mol)}}{m_{\text{H}_2}\ \text{(kg/mol)}}; \tag{3.4.5c}$$

$P_{\text{th, WE, in}}$ is given by equation (3.4.2c) and $q^{\text{WE}}_{\text{n, H}_2}$ is given by equation (3.4.3).

4 Terminology

4.1 General

Terms and definitions used in this document are given below as well as in two Joint Research Centre (JRC) reports (Tsotridis and Pilenga, 2018, Malkow et al., 2021). In addition, the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) maintain terminological databases at the following websites:

- ISO Online browsing platform available at https://www.iso.org/obp.
- IEC Electropedia available at http://www.electropedia.org.

Remark, the following verbal forms are principally used as follows:

- "shall" indicates a requirement,
- "should" indicates a recommendation,
- "may" indicates a permission and
- "can" indicates a possibility or a capability.

Note, reference herein to Système International d'Unités (SI) coherent (derived) units include, as appropriate, metric prefixes of the concerned unit. Decimal fractions are denoted by comma. Alongside SI units, non-SI units may be used when customary. For example, we use kWh instead of kJ as unit of energy.

4.2 Terms and definitions

4.2.1 conditioning phase
test duration of specified length for determining the specific energy consumption of a WE/HTE or WE system under steady-state operation (**4.2.13**) meeting the stability criterion (**4.2.9**) which precedes the data acquisition (DAQ) phase (**4.2.2**)

4.2.2 data acquisition (DAQ) phase
test duration of specified length for determining the specific energy consumption of a WE/HTE or WE system under steady-state operation (**4.2.13**) during which the stability criterion (**4.2.9**) is met throughout and relevant TIPs (**4.2.11**) and TOPs (**4.2.12**) are continuously monitored, synchronously sampled and fail-safe recorded at specified rates

4.2.3 digital twin
digital replica of physical assets (physical twin), processes and systems that can be used for various purposes or a fit-for-purpose digital representation of something outside its own context with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronization

`[Source: ISO 23704-1:2022, 3.1.14]`

4.2.4 hydrogen output conditions
specified conditions of pressure and temperature of hydrogen put out by a WE/HTE or WE system

4.2.5 specific electric energy consumption ($\varepsilon_{\mathrm{el}}$)
ratio of input electric power to flow rate of hydrogen generated

4.2.6 specific energy consumption (ε_{e})
ratio of input power to flow rate of hydrogen generated

4.2.7 specific thermal energy consumption ($\varepsilon_{\mathrm{th}}$)
ratio of input thermal power to flow rate of hydrogen generated

4.2.8 machine learning (ML)
process using algorithms rather than procedural coding that enables learning from existing data in order to predict future outcomes

`[Source: ISO/IEC 38505-1:2017, 3.7]`

4.2.9 stability criterion
condition of a test output parameter (TOP) (**4.2.12**) to be met within a specified margin for a given time interval

4.2.10 standard ambient temperature and pressure (SATP) conditions
conditions of standard ambient pressure (p^0=100 kPa) and standard ambient temperature (T^0=298,15 K)

4.2.11 test input parameter (TIP)
physical quantity whether static or variable, which sets a condition for the test

4.2.12 test output parameter (TOP)
physical quantity whether measured or calculated, which results from carrying out the test

4.2.13 steady-state operation
operation of a WE/HTE or WE system meeting the stability criterion (**4.2.9**) during either the conditioning phase (**4.2.1**) or the DAQ phase (**4.2.2**)

4.3 Abbreviations and Acronyms used

A list of abbreviations and acronyms used in this report are appended, see page 38.

4.4 Symbols used

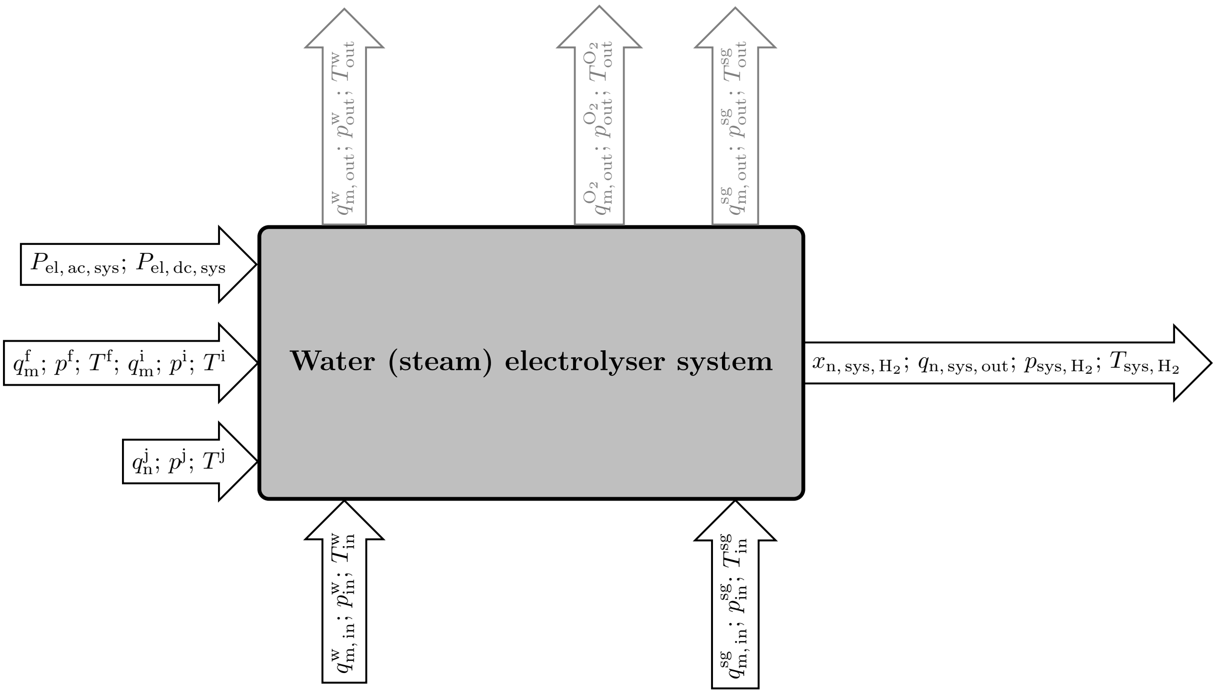
A list of symbols used in this report are appended, see page 41.

5 Test parameters

5.1 WE system

Schematically displayed in Figure 5.1, the TIPs and TOPs listed respectively in Table 5.1 and Table 5.2 are used to determine the EPIs of a WE system.

Figure 5.1: Schematic of test input parameters and test output parameters for a water (steam) electrolyser system.



Source: JRC, 2022.

Note, $P_{\mathrm{el,ac,sys}}$ and $P_{\mathrm{el,dc,sys}}$ are respectively the input AC electric power and DC electric power, see equation (3.2.3a); p^{i}, p^{j}, p^{f}, $p^{\mathrm{w}}_{\mathrm{in}}$ and $p^{\mathrm{sg}}_{\mathrm{in}}$ are respectively the input pressure of fluid i, fluid j, fuel, water (steam) and sweep gas; T^{i}, T^{j}, T^{f}, $T^{\mathrm{w}}_{\mathrm{in}}$ and $T^{\mathrm{sg}}_{\mathrm{in}}$ are respectively the input temperature of fluid i, fluid j, fuel, water (steam) and sweep gas; $q^{\mathrm{i}}_{\mathrm{m}}$, $q^{\mathrm{f}}_{\mathrm{m}}$, $q^{\mathrm{w}}_{\mathrm{m,in}}$ and $q^{\mathrm{sg}}_{\mathrm{m,in}}$ are respectively the input mass flow rate of fluid i, fuel, water (steam) and sweep gas; $q^{\mathrm{j}}_{\mathrm{n}}$ is the molar flow rate of fluid j; $p^{\mathrm{w}}_{\mathrm{out}}$, $p^{\mathrm{O_2}}_{\mathrm{out}}$, $p^{\mathrm{sg}}_{\mathrm{out}}$ and $p_{\mathrm{sys,H_2}}$ are respectively the output pressure of water (steam), oxygen, sweep gas and product gas (hydrogen) (11); $T^{\mathrm{w}}_{\mathrm{out}}$, $T^{\mathrm{O_2}}_{\mathrm{out}}$, $T^{\mathrm{sg}}_{\mathrm{out}}$ and $T_{\mathrm{sys,H_2}}$ are respectively the output temperature of water (steam), oxygen, sweep gas and product gas (hydrogen) (12); $q^{\mathrm{w}}_{\mathrm{m,out}}$, $q^{\mathrm{O_2}}_{\mathrm{m,out}}$ and $q^{\mathrm{sg}}_{\mathrm{m,out}}$ are respectively the output mass flow rate of water (steam), oxygen and sweep gas; $q_{\mathrm{n,sys,out}}$ is the product gas molar flow rate and $x_{\mathrm{n,sys,H_2}}$ is the molar concentration of hydrogen.

Table 5.1: Test input parameters for a water (steam) electrolyser system.

Symbol (unit)	**Description**	**Control accuracy (unit)**
$P_{\mathrm{el,ac}}$ (kW)	AC electric power	1 %
$P_{\mathrm{el,dc}}$ (kW)	DC electric power	0,3 %
$q^{\mathrm{w}}_{\mathrm{m,in}}$ (kg/s)	mass flow rate of water (steam)	2 %
$p^{\mathrm{w}}_{\mathrm{in}}$ (kPa)	pressure of water (steam)	2 %
$T^{\mathrm{w}}_{\mathrm{in}}$ (K)	temperature of water (steam)	2 K
$q^{\mathrm{i}}_{\mathrm{m}}$ (kg/s)	mass flow rate of fluid i (1)	2 %
p^{i} (kPa)	pressure of fluid i (2)	2 %
T^{i} (K)	temperature of fluid i (2)	2 K

Continue to next page

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(11) See footnote 9.

(12) See footnote 9.

Table 5.1 – continued from previous page

$q_{\mathrm{n}}^{\mathrm{f}}$ (mol/h)	molar flow rate of fuel (3)	2 %
p^{f} (kPa)	pressure of fuel (4)	2 %
T^{f} (K)	temperature of fuel (4)	2 K
$q_{\mathrm{n}}^{\mathrm{j}}$ (mol/h)	molar flow rate of fluid j (5)	2 %
p^{j} (kPa)	pressure of fluid j (6)	2 %
T^{j} (K)	temperature of fluid j (6)	2 K

Note: Primarily, the input of liquid water is with reference to AWE, AEMWE and PEMWE systems while steam is solely with reference to HTE systems whether SOE or PCE.

(1) Except for water (steam) as fluid, i may stand for oil, air, fuel and/or sweep gas.

(2) Required to look up $c_{\mathrm{p}}^{\mathrm{i}}$, the specific heat at constant pressure of fluid i.

(3) Fuel j can be a fluid such as NG.

(4) Required to look up $\mathrm{HHV}^{\mathrm{f}}$, the HHV of fuel.

(5) Except for steam as a fluid, j may stand for oil and/or air.

(6) Required to look up $V_{\mathrm{m}}^{\mathrm{j}}$, the molar volume of fluid j.

Source: JRC, 2022.

Table 5.2: Test output parameters for a water (steam) electrolyser system.

Symbol (unit)	**Description**	**Measurement accuracy (unit)**
$x_{\mathrm{n,sys,H_2}}$ (mol/mol)	molar concentration of hydrogen	0.01 (mol/mol)
$q_{\mathrm{n,sys,out}}$ (mol/h)	product gas molar flow rate	2 %
$q_{\mathrm{n,sys,H_2}}$ (mol/h)	molar flow rate of hydrogen (1)	-
$p_{\mathrm{sys,H_2}}$ (kPa)	pressure of hydrogen (2)	2 %
$T_{\mathrm{sys,H_2}}$ (K)	temperature of hydrogen (2)	2 K
	EPI related to SATP conditions of hydrogen	
$\varepsilon_{\mathrm{e,n,sys}}^{0}$ (kWh/mol)	specific energy consumption per mole (3)	-
$\varepsilon_{\mathrm{e,V,sys}}^{0}$ (kWh/m^3)	specific energy consumption per unit volume (4)	-
$\varepsilon_{\mathrm{e,m,sys}}^{0}$ (kWh/kg)	specific energy consumption per unit mass (5)	-
$\varepsilon_{\mathrm{el,n,sys}}^{0}$ (kWh/mol)	specific electric energy consumption per mole (6)	-
$\varepsilon_{\mathrm{el,V,sys}}^{0}$ (kWh/m^3)	specific electric energy consumption per unit volume (7)	-
$\varepsilon_{\mathrm{el,m,sys}}^{0}$ (kWh/kg)	specific electric energy consumption per unit mass (8)	-
$\varepsilon_{\mathrm{th,n,sys}}^{0}$ (kWh/mol)	specific thermal energy consumption per mole (6)	-
$\varepsilon_{\mathrm{th,V,sys}}^{0}$ (kWh/m^3)	specific thermal energy consumption per unit volume (7)	-
$\varepsilon_{\mathrm{th,m,sys}}$ (kWh/kg)	specific thermal energy consumption per unit mass (8)	-
$\eta_{\mathrm{HHV,e,sys}}^{0}$ (%)	energy efficiency based on HHV (9)	-
$\eta_{\mathrm{LHV,e,sys}}^{0}$ (%)	energy efficiency based on LHV (10)	-
$\eta_{\mathrm{HHV,el,sys}}^{0}$ (%)	electrical efficiency based on HHV (11)	-
$\eta_{\mathrm{LHV,el,sys}}^{0}$ (%)	electrical efficiency based on LHV (12)	-
	EPI related to hydrogen output conditions	
$\varepsilon_{\mathrm{e,n,sys}}^{\mathrm{p,T}}$ (kWh/mol)	specific energy consumption per mole (13)	-
$\varepsilon_{\mathrm{e,V,sys}}^{\mathrm{p,T}}$ (kWh/m^3)	specific energy consumption per unit volume (14)	-
$\varepsilon_{\mathrm{e,m,sys}}^{\mathrm{p,T}}$ (kWh/kg)	specific energy consumption per unit mass (15)	-
$\varepsilon_{\mathrm{el,n,sys}}^{\mathrm{p,T}}$ (kWh/mol)	specific electric energy consumption per mole (16)	-
$\varepsilon_{\mathrm{el,V,sys}}^{\mathrm{p,T}}$ (kWh/m^3)	specific electric energy consumption per unit volume (17)	-
$\varepsilon_{\mathrm{el,m,sys}}^{\mathrm{p,T}}$ (kWh/kg)	specific electric energy consumption per unit mass (18)	-
$\varepsilon_{\mathrm{th,n,sys}}^{\mathrm{p,T}}$ (kWh/mol)	specific thermal energy consumption per mole (19)	-
$\varepsilon_{\mathrm{th,V,sys}}^{\mathrm{p,T}}$ (kWh/m^3)	specific thermal energy consumption per unit volume (20)	-
$\varepsilon_{\mathrm{th,m,sys}}^{\mathrm{p,T}}$ (kWh/kg)	specific thermal energy consumption per unit mass (21)	-

Note: The symbols of TOPs stand synonymously for both, their respective instantaneous values (see section A.2.2 and section A.2.3) and average values (see section 8.2.1, section 8.2.2, section A.3.2 and section A.3.3).

(1) Calculated by equation (3.2.6).

(2) See footnote 9.

(3) Calculated by equation (3.2.1a).

(4) Calculated by equation (3.2.1b).

(5) Calculated by equation (3.2.1c).

(6) Calculated by equation (3.2.9a).

(7) Calculated by equation (3.2.9b).

(8) Calculated by equation (3.2.9c).
(9) Calculated by equation (3.2.11a).
(10) Calculated by equation (3.2.11b).
(11) Calculated by equation (3.2.12a).
(12) Calculated by equation (3.2.12b).
(13) Calculated by equation (3.3.1a).
(14) Calculated by equation (3.3.1b).
(15) Calculated by equation (3.3.1c).
(16) Calculated by equation (3.3.2a).
(17) Calculated by equation (3.3.2b).
(18) Calculated by equation (3.3.2c).
(19) Calculated by equation (3.3.3a).
(20) Calculated by equation (3.3.3b).
(21) Calculated by equation (3.3.3c).
Source: JRC, 2022.

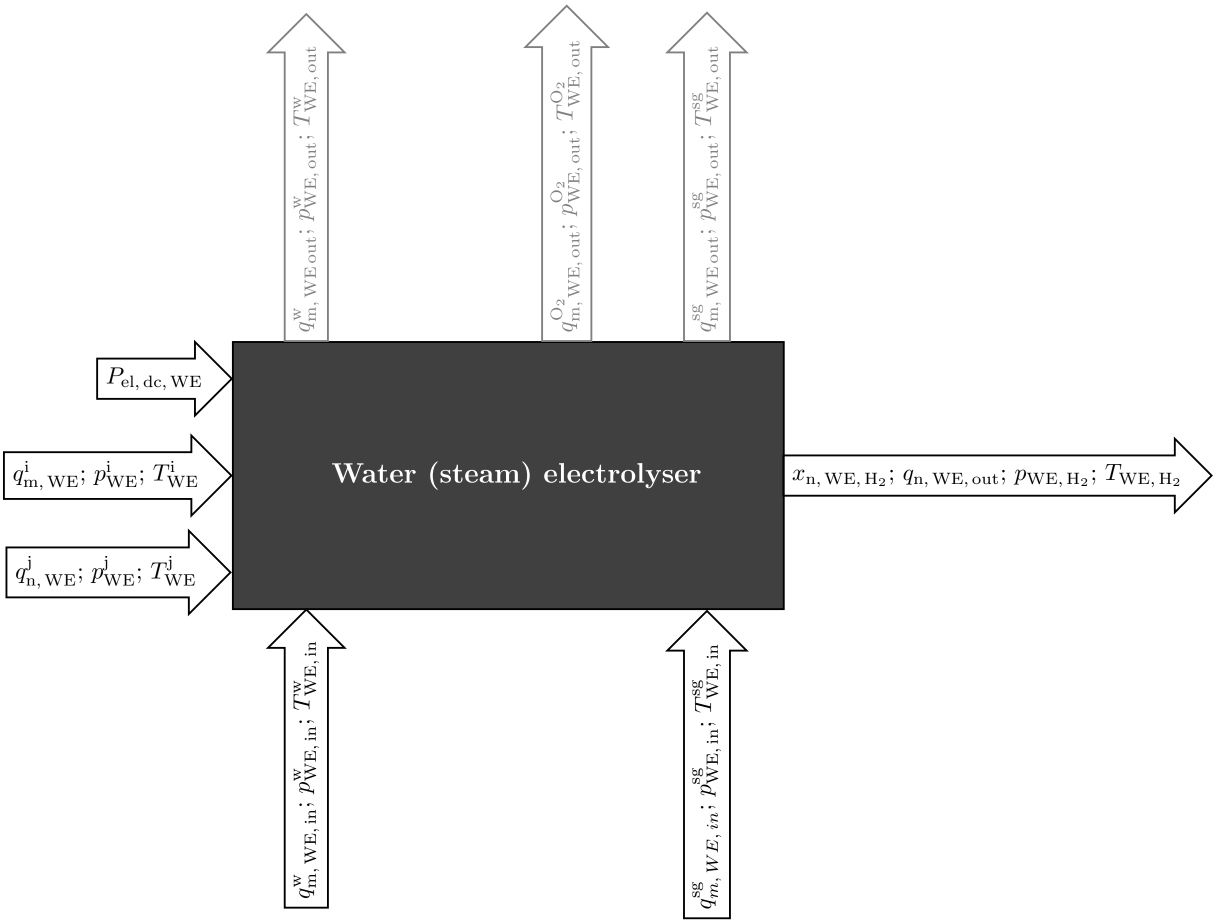
It is recommended to sample test parameters at a minimum sampling rate of **1 Hz**. When this is not possible, the minimum sampling rate common to all test parameters except the molar concentration of hydrogen in the product gas should be the sampling rate of the test parameter exhibiting the lowest sampling rate.

Depending on the time required between two successive intervals for gas sampling and analysis, the test parameter exhibiting the lowest sampling rate can be the molar concentration of hydrogen in the product gas, $x_{\mathrm{n,sys,H_2}}$, see also note (8) of Table 6.1.

5.2 WE/HTE

Schematically displayed in Figure 5.2, the TIPs and TOPs listed respectively in Table 5.3 and Table 5.4 are used to determine the EPIs of a WE/HTE.

Figure 5.2: Schematic of test input parameters and test output parameters for a water electrolyser/high-temperature electrolyser.



Source: JRC, 2022.

Note, $P_{\mathrm{el,\,dc,\,WE}}$ is the input DC electric power, see equation (3.4.2b); $p^{\mathrm{i}}_{\mathrm{WE}}$, $p^{\mathrm{j}}_{\mathrm{WE}}$, $p^{\mathrm{w}}_{\mathrm{WE,\,in}}$ and $p^{\mathrm{sg}}_{\mathrm{WE,\,in}}$ are respectively the input pressure of fluid i, fluid j, water (steam) and sweep gas; $T^{\mathrm{i}}_{\mathrm{WE}}$, $T^{\mathrm{j}}_{\mathrm{WE}}$, $T^{\mathrm{w}}_{\mathrm{WE,in}}$ and $T^{\mathrm{sg}}_{\mathrm{WE,in}}$ are respectively the input temperature of fluid i, fluid j, water (steam) and sweep gas; $q^{\mathrm{i}}_{\mathrm{m,WE}}$, $q^{\mathrm{w}}_{\mathrm{m,WE,in}}$ and $q^{\mathrm{sg}}_{\mathrm{m,WE,in}}$ are respectively the input mass flow rate of fluid i, water (steam) and sweep gas; $p^{\mathrm{w}}_{\mathrm{WE,out}}$, $p^{\mathrm{O_2}}_{\mathrm{WE,out}}$, $p^{\mathrm{sg}}_{\mathrm{WE,out}}$ and $p_{\mathrm{WE,H_2}}$ are respectively the output pressure of water (steam), oxygen, sweep gas and product gas (hydrogen) (13); $T^{\mathrm{w}}_{\mathrm{WE,out}}$, $T^{\mathrm{O_2}}_{\mathrm{WE,out}}$, $T^{\mathrm{sg}}_{\mathrm{WE,out}}$ and $T_{\mathrm{WE,H_2}}$ are respectively the output temperature of water (steam), oxygen, sweep gas and product gas (hydrogen) (14); $q^{\mathrm{w}}_{\mathrm{m,WE,out}}$, $q^{\mathrm{O_2}}_{\mathrm{m,WE,out}}$ and $q^{\mathrm{sg}}_{\mathrm{m,WE,in}}$ are respectively the output mass flow rate of water (steam), oxygen and sweep gas; $q^{\mathrm{WE}}_{\mathrm{n,out}}$ is the product gas molar flow rate and $x^{\mathrm{WE}}_{\mathrm{n,H_2}}$ is the molar concentration of hydrogen.

Table 5.3: Test input parameters for a water electrolyser/high-temperature electrolyser.

Symbol (unit)	**Description**	**Control accuracy (unit)**
$P_{\mathrm{el,dc,WE}}$ (kW)	DC electric power	0,3 %
$q^{\mathrm{w}}_{\mathrm{m,WE,in}}$ (kg/s)	input mass flow rate of water (steam)	2 %
$p^{\mathrm{w}}_{\mathrm{WE,in}}$ (kPa)	input pressure of water (steam)	2 %
$T^{\mathrm{w}}_{\mathrm{WE,in}}$ (K)	input temperature of water (steam)	2 K
$q^{\mathrm{i}}_{\mathrm{m,WE}}$ (kg/s)	mass flow rate of fluid i (1)	2 %
$p^{\mathrm{i}}_{\mathrm{WE}}$ (kPa)	pressure of fluid i (2)	2 %
$T^{\mathrm{i}}_{\mathrm{WE}}$ (K)	temperature of fluid i (2)	2 K
$q^{\mathrm{j}}_{\mathrm{n,WE}}$ (mol/h)	molar flow rate of fluid j (3)	2 %
$p^{\mathrm{j}}_{\mathrm{WE}}$ (kPa)	pressure of fluid j (3)	2 %
$T^{\mathrm{j}}_{\mathrm{WE}}$ (K)	temperature of fluid j (4)	2 K

Note: Primarily, the input of liquid water is with reference to AWE, AEMWE, BPMWE and PEMWE while steam is solely with reference to HTE whether SOE or PCE.

(1) Except for water (steam) as fluid, i may stand for air, fuel or sweep gas.

(2) Required to look up $c^{\mathrm{i}}_{\mathrm{p}}$, the specific heat at constant pressure of fluid i.

(3) Except for steam as a fluid, j may stand for air.

(4) Required to look up $V^{\mathrm{j}}_{\mathrm{m}}$, the molar volume of fluid j.

Source: JRC, 2022.

Table 5.4: Test output parameters for a water electrolyser/high-temperature electrolyser.

Symbol (unit)	**Description**	**Measurement accuracy (unit)**
$x^{\mathrm{WE}}_{\mathrm{n,H_2}}$ (mol/mol)	molar concentration of hydrogen	0.01 (mol/mol)
$q^{\mathrm{WE}}_{\mathrm{n,out}}$ (mol/h)	product gas molar flow rate	2 %
$q^{\mathrm{WE}}_{\mathrm{n,H_2}}$ (mol/h)	molar flow rate of hydrogen (1)	-
$p_{\mathrm{WE,H_2}}$ (kPa)	pressure of hydrogen (2)	2 %
$T_{\mathrm{WE,H_2}}$ (K)	temperature of hydrogen (2)	2 K
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$	specific energy consumption per mole of hydrogen (3)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$	specific energy consumption per unit volume of hydrogen (4)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$	specific energy consumption per unit mass of hydrogen (5)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$	specific electric energy consumption per mole of hydrogen (6)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$	specific electric energy consumption per unit volume of hydrogen (7)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$	specific electric energy consumption per unit mass of hydrogen (8)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$	specific thermal energy consumption per mole of hydrogen (9)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$	specific thermal energy consumption per unit volume of hydrogen (10)	-
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$	specific thermal energy consumption per unit mass of hydrogen (11)	-

Note: The symbols of TOPs stand synonymously for both, their respective instantaneous values (see section A.2.4) and average values (see section 8.2.3 and section A.3.4).

(1) Calculated by equation (3.4.3).

(2) See footnote 9.

(3) Calculated by equation (3.4.1a).

(4) Calculated by equation (3.4.1b).

(5) Calculated by equation (3.4.1c).

(6) Calculated by equation (3.4.4a).

(7) Calculated by equation (3.4.4b).

(8) Calculated by equation (3.4.4c).

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(13) See footnote 9.

(14) See footnote 9.

(9) Calculated by equation (3.4.5a).
(10) Calculated by equation (3.4.5b).
(11) Calculated by equation (3.4.5c).
Source: JRC, 2022.

6 Measurement set-up

6.1 General

Note, in the near future, the likely use of artificial intelligence (AI) based work flows of electrolysis processes to regularly monitor and periodically optimise the energy performance of a WE/HTE or WE system will entail a greater amount of instrumentation to be built-in ex-ante.

This will necessitate employing many more sensors and other measuring devices as compared to current practices especially when deploying ML algorithms (ISO and IEC, 2017) and a digital twin (ISO, 2022) of a WE/HTE or WE system to reliably perform on-demand grid services or be integrated into a continual industrial process requiring hydrogen. Then, most of the needed measurement instrumentation (devices and sensors) may already be included in the WE/HTE or WE system ex-factory.

6.2 WE system

Besides system internal control and measurement devices, the measurement instrumentation recommended to measure the TIPs and TOPs of a WE system is given in Table 6.1.

Table 6.1: Recommended measurement instrumentation for testing a WE system.

Instrumentation	Parameter measured	Symbol (unit)	Quantity (minimum)
power meter	AC electric power (1)	$P_{\mathrm{el,ac}}$ (kW)	1 (2)
	DC electric power (1)	$P_{\mathrm{el,dc}}$ (kW)	1 (2)
Flow meter	mass flow rate of water (steam)	$q_{\mathrm{m,in}}^{\mathrm{w}}$ (kg/s)	1 (3)
	mass flow rate of fluid i	$q_{\mathrm{m}}^{\mathrm{i}}$ (kg/s)	1 (4)
	mass flow rate of fuel	$q_{\mathrm{m}}^{\mathrm{f}}$ (kg/s)	1 (5)
	molar flow rate of fluid j	$q_{\mathrm{n}}^{\mathrm{j}}$ (mol/h)	1 (6)
	product gas molar flow rate	$q_{\mathrm{n,sys,out}}$ (mol/h)	1
pressure sensor	pressure of water (steam)	$p_{\mathrm{in}}^{\mathrm{w}}$ (kPa)	1 (3)
	pressure of fluid i	p^{i} (kPa)	1 (4)
	pressure of fuel	p^{f} (kPa)	1 (5)
	pressure of fluid j	p^{j} (kPa)	1 (6)
	product gas pressure (9)	$p_{\mathrm{sys,H_2}}$ (kPa)	1
temperature sensor	temperature of water (steam)	$T_{\mathrm{in}}^{\mathrm{w}}$ (K)	1 (3)
	temperature of fluid i	p^{i} (K)	1 (4)
	temperature of fuel	T^{f} (K)	1 (5)
	temperature of fluid j	T^{j} (K)	1 (6)
	product gas temperature (7)	$T_{\mathrm{sys,H_2}}$ (K)	1
Gas analyser (8)	molar concentration of hydrogen	$x_{\mathrm{n,sys,H_2}}$ (mol/mol)	1

Note: Especially temperature sensors such as thermocouples can be subject to faults. It is advised to account for their redundancy.

(1) An AC (DC) power meter may besides the value of $P_{\mathrm{el,ac,sys}}$ ($P_{\mathrm{el,dc,sys}}$) provide simultaneously for values of $U_{\mathrm{ac,sys}}$ ($U_{\mathrm{dc,sys}}$), $I_{\mathrm{ac,sys}}$ ($I_{\mathrm{dc,sys}}$) and $\cos\varphi$.

(2) In case a WE system has more than one PoC, the number of power meters shall match the number PoCs unless a single power meter can provide for the measurement at more than one PoC simultaneously.

(3) In case a WE system has more than one PoC, the number of flow meters shall match the number of PoCs. The same applies to the number of sensors required for measuring pressure and temperature. For example, a WE system have one PoC for the input of liquid water and another PoC for steam input. In such case two different flow meters, two pressure sensors and two temperature sensors are required.

(4) Depending whether or not other fluid(s) than water (steam) transfer heat/cold to the WE system (*i. e.* sweep gas).

(5) Depending whether or not fuel is supplied to the WE system.

(6) Depending whether or not fluid(s) enter the WE system (*e. g.* compressed air, pressurised steam, etc).

(7) See footnote 9.

(8) Conditional on the intended use of the generated hydrogen in upstream processes or customer requirements, product gas sampling and analysis may be employed merely as a quality control (QC) measure, for example, to check on oxygen content using a oxygen meter and residual humidity using a dew point meter. More strictly implemented, product gas analysis may be employed as a regular means of quality assurance (QA).

Source: JRC, 2022.

The various devices and sensors used in the measurements shall be synchronised in time and sampling frequency so that the values of the TIPs and TOPs are acquired in the same instant during a sampling interval.

Remark, accurate temperature measurements of a fluid require appropriate insulation of its containment against unintended thermal losses including the point of measurement where the temperature sensor is located.

Accurate measurements of fluid pressure and flow require leak-tight piping of the fluid concerned including at the point of measurement where the pressure sensor and the flow meter are respectively located.

Preferably, the location for measuring fluid temperature, pressure and flow is the same. It should be near the fluid's PoC to the WE system. The sampling of the product gas to analyse the molar concentration of hydrogen should ideally occur at the PoC where the product gas exits the WE system.

The input electric power of the WE system should ideally be measured at its PoC or PoCs to the WE system.

6.3 WE/HTE

The measurement instrumentation recommended to measure the TIPs and TOPs of a WE/HTE is given in Table 6.2.

Table 6.2: Recommended measurement instrumentation for testing a water electrolyser/high-temperature electrolyser.

Instrumentation	Parameter measured	Symbol (unit)	Quantity (minimum)
power meter	DC electric power (1)	$P_{\mathrm{el,dc,WE}}$ (kW)	1 (2)
	stack current (1)	$I_{\mathrm{dc,WE}}$ (A)	- (2)
	stack voltage (1)	$U_{\mathrm{dc,WE}}$ (V)	- (2)
Flow meter	mass flow rate of water (steam)	$q^{\mathrm{w}}_{\mathrm{m,WE,in}}$ (kg/s)	1
	mass flow rate of fluid i	$q^{\mathrm{i}}_{\mathrm{m,WE}}$ (kg/s)	1 (3)
	molar flow rate of fluid j	$q^{\mathrm{j}}_{\mathrm{n,WE}}$ (mol/h)	1 (4)
	product gas molar flow rate	$q_{\mathrm{n,out}}$ (mol/h)	1
pressure sensor	pressure of water (steam)	$p^{\mathrm{w}}_{\mathrm{WE,in}}$ (kPa)	1
	pressure of fluid i	$p^{\mathrm{i}}_{\mathrm{WE}}$ (kPa)	1 (3)
	pressure of fluid j	$p^{\mathrm{j}}_{\mathrm{WE}}$ (kPa)	1 (4)
	product gas pressure (e)	$p_{\mathrm{WE,H_2}}$ (kPa)	1
temperature sensor	temperature of water (steam)	$T^{\mathrm{w}}_{\mathrm{WE,in}}$ (K)	1
	temperature of fluid i	$T^{\mathrm{i}}_{\mathrm{WE}}$ (K)	1 (3)
	temperature of fluid j	$T^{\mathrm{j}}_{\mathrm{WE}}$ (K)	1 (4)
	product gas temperature (5)	$T_{\mathrm{WE,H_2}}$ (K)	1
Gas analyser (6)	molar concentration of hydrogen	$x^{\mathrm{WE}}_{\mathrm{n,H_2}}$ (mol/mol)	1

Note: Especially temperature sensors such as thermocouples can be subject to faults. It is advised to account for their redundancy.

(1) A power meter to measure the DC electric power may besides the value of $P_{\mathrm{el,dc,WE}}$ provide simultaneously for values of $U_{\mathrm{dc,WE}}$ as a measure of voltage loss (degradation) and $I_{\mathrm{dc,WE}}$ as a measure for the production rate (yield) of hydrogen.

(2) In case the WE/HTE has more than one stack, the number of power (ampere and volt) meters should be more than one unless a single of such meter can provide for the measurement of more than one stack simultaneously.

(3) Depending whether or not another fluid than water (steam) transfers heat to the WE/HTE (*i. e.* air in SOE).

(4) Depending whether or not another fluid than pressurised steam transfers compression power to the WE/HTE (*i. e.* compressed air in SOE).

(5) See footnote 9.

(6) See note (8) of Table 6.1.

Source: JRC, 2022.

For a WE/HTE, PoCs refer to the input and output connections of electricity and fluids.

7 Test safety

In water electrolysers/high-temperature electrolysers and WE systems, hazards may especially arise from

- hydrogen and oxygen gases,
- alkaline electrolyte, hot water, steam and other fluids (combustible fuel, compressed air, hydraulic oil, etc) as well as
- high temperature, high pressure and high voltage.

During installation, commissioning, operation including quiescence (standby) and maintenance as well as decommissioning, safety requires due care and vigilance by all persons involved. The entity carrying out the testing should comply with the occupational health and safety (OHS) requirements of ISO 45001:2018 (ISO, 2018).

Tests on a WE/HTE or WE system ([15]) shall be conducted in accordance with the applicable legislation as well as granted licenses and issued permits so as to pose no harm and unacceptable risk to humans, property and the environment.

ISO has published guidance regarding basic safety considerations for hydrogen systems (ISO, 2015) ([16]) which shall be observed while performing tests. Additionally, IEC published guidance on the classification of areas where explosive atmospheres can occur (IEC, 2020) which shall also be followed.

In the European Economic Area (EEA) ([17]), the ATEX Directives 2014/34/EU (European Parliament and Council, 2014b) and 94/9/EC (European Parliament and Council, 1994) apply ([18]).

In addition, the WE system should comply with other EU legislation such as the electromagnetic compatibility (EMC) Directive 2014/30/EU (European Parliament and Council, 2014a) ([19]), the Low-Voltage Directive (LVD) 2014/35/EU (European Parliament and Council, 2014c) ([20]), the general product safety Directive 2001/95/EC (European Parliament and Council, 2001) ([21]), the machinery Directive 2006/42/EC (European Parliament and Council, 2006) ([22]) and the Pressure Equipment Directive (PED) 2014/68/EU (European Parliament and Council, 2014d) ([23]).

Generally, an electrolyser or a WE system which does not conform to these EU legislation shall not be used within the EEA.

([15]) Note, working group (WG) 32 of ISO Technical Committee (TC) 197 currently prepares the approved working item (AWI) "ISO 22734-2 Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications - Part 2: Testing guidance for performing electricity grid service".

([16]) Currently, WG 29 of ISO TC 197 reviews this Technical Report (TR).

([17]) At present, this comprises the territories of the European Union (EU), Island, Norway and Liechtenstein. It also applies to Switzerland under a mutual recognition agreement and Türkiye under a customs union agreement with the EU.

([18]) The European Commission (EC) publishes guidance online at https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/equipment-explosive-atmospheres-atex_en.

([19]) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/electromagnetic-compatibility-emc-directive_en.

([20]) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/low-voltage-directive-lvd_en.

([21]) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/general-product-safety_en.

([22]) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/mechanical-engineering/machinery_en.

([23]) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/pressure-equipment-and-gas-appliances/pressure-equipment-sector/pressure-equipment-directive_en.

8 Test method and data reporting

8.1 Test execution and measurement of test parameters

Prior to the measurement of the TIPs and TOPs, the WE/HTE or WE system shall be operated under steady-state at the operating conditions specified by the manufacturer namely, rated input power (P_{in}), pressure and temperature of hydrogen generated and put out by the WE/HTE or WE system (*conditioning phase*). A duration of 30 minutes is recommended for this phase of the test.

Unless otherwise specified by the manufacturer, steady-state operation is considered achieved when

- the temperature of the WE/HTE (as specified by the manufacturer) deviates during a specified duration from its setting by not more than a specified value and successively,

- the product gas molar flow rate exiting the WE/HTE or WE system deviates for the same length of time from its setting by not more than a specified value (*stability criterion*).

A value of $\pm$ **2 K** for LTWE and $\pm$ **5 K** for HTSEL consecutively measured during **30 minutes** is recommended as deviation from the temperature setting of the WE/HTE. A value of $\pm$ **5 %** is recommended as *stability criterion* for the deviation of the product gas molar flow rate.

For the actual test during which TIPs and TOPs shall continuously be measured at their respective sampling rates, the WE/HTE or WE system shall be operated for a specified duration under the same conditions as prevalent during the preceding *conditioning phase* including meeting the *stability criterion* for the entire duration of this *DAQ phase*. A duration of **one hour** is recommended for the *DAQ phase* of the test. This ensures a sufficient number of data points (L) are acquired for all test parameters relevant to determine the sought EPI.

Consequentially, L=**3600** is recommended as the number of data points considering a sampling rate of **1 Hz** for the test parameters and **one hour** duration for the *DAQ phase*. In any case, the choice for the number of data points shall be consistent with the sampling rate of all relevant test parameters and the duration of the *DAQ phase* to allow statistically meaningful EPI estimation, see also Annex A.

In case the specific energy consumption is to be determined also for a fraction or a multiple of the rated input power, a different pressure and/or a different temperature of hydrogen, these operating conditions shall accordingly be adjusted for the *conditioning phase* and the *DAQ phase* of the test preferably without changes to the duration of either test phase.

Remark, neither should an external supply of hydrogen to the WE system nor a storage of hydrogen in the system be used during the DAQ phase of the test. Proper measures should nevertheless be taken to prevent the oxidation of metals in SOC cermet electrodes of HTE stacks using additions of hydrogen gas. In any case, a system internal hydrogen storage should completely be filled prior to the test and the test should not end until such storage is replenished.

8.2 Reporting of energy performance indicators

In a test report (see Annex B), the EPIs estimated as TOPs should be reported as:

- the average (arithmetic mean) values (JCGM, 2008) of TOPs namely
  - the specific energy consumption per mole ($\varepsilon^{0}_{\mathrm{e,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}$, unit volume ($\varepsilon^{0}_{\mathrm{e,V,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,V,sys}}$ and unit mass ($\varepsilon^{0}_{\mathrm{e,m,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,m,sys}}$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.1),
  - the specific electric energy consumption per mole ($\varepsilon^{0}_{\mathrm{el,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{el,n,sys}}$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.3),
  - the specific thermal energy consumption per mole ($\varepsilon^{0}_{\mathrm{th,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{th,n,sys}}$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.5),
  - the energy efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,e,sys}}$), $\bar{\eta}^{0}_{\mathrm{HHV,e,sys}}$ and LHV ($\eta^{0}_{\mathrm{LHV,e,sys}}$), $\bar{\eta}^{0}_{\mathrm{LHV,e,sys}}$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.7),
  - the electrical efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,el,sys}}$), $\bar{\eta}^{0}_{\mathrm{HHV,el,sys}}$ and LHV ($\eta^{0}_{\mathrm{LHV,el,sys}}$), $\bar{\eta}^{0}_{\mathrm{LHV,el,sys}}$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.9),
  - the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.11),
  - the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$, and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.13a),

  - the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$, and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.15a),
  - the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$, and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.17),
  - the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.19) and
  - the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$, and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.21)

- along with their combined standard uncertainties (u_{c}) (JCGM, 2008) defined as positive square root of the combined standard variance (u_{c}^2) of TOPs namely
  - the specific energy consumption per mole ($\varepsilon^{0}_{\mathrm{e,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)$, unit volume ($\varepsilon^{0}_{\mathrm{e,V,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,V,sys}}\right)$ and unit mass ($\varepsilon^{0}_{\mathrm{e,m,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,m,sys}}\right)$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.2),
  - the specific electric energy consumption per mole ($\varepsilon^{0}_{\mathrm{el,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{el,sys}}\right)$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.4),
  - the specific thermal energy consumption per mole ($\varepsilon^{0}_{\mathrm{th,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{th,sys}}\right)$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.6),
  - the energy efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,e,sys}}$), $u_{\mathrm{c}}^2\left(\eta^{0}_{\mathrm{HHV,e,sys}}\right)$ and LHV ($\eta^{0}_{\mathrm{LHV,e,sys}}$), $u_{\mathrm{c}}^2\left(\eta^{0}_{\mathrm{LHV,e,sys}}\right)$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.8),
  - the electrical efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,el,sys}}$), $u_{\mathrm{c}}^2\left(\eta^{0}_{\mathrm{HHV,el,sys}}\right)$ and LHV ($\eta^{0}_{\mathrm{LHV,el,sys}}$), $u_{\mathrm{c}}^2\left(\eta^{0}_{\mathrm{LHV,el,sys}}\right)$, of hydrogen generated and put out by the WE system tested under SATP conditions, see equation (8.2.10),
  - the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}\right)$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.12),
  - the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}\right)$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.14),
  - the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}\right)$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions, see equation (8.2.16),
  - the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}\right)$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.18),
  - the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}\right)$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.20) and
  - the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,WE}}\right)$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$), $u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,WE}}\right)$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions, see equation (8.2.22).

Remark, the multiplier or coverage factor (k) (JCGM, 2008) by which the estimated combined standard uncertainties are to be multiplied and reported should be taken as k=3, see equation (A.4.1). It is to associate test results with an interval of uncertainty at a level of confidence greater than 99 %.

The test conditions whether SATP conditions or actual hydrogen output conditions along with the operating conditions such as input power, pressure and temperature of hydrogen shall also be reported, see section B.3.

8.2.1 WE system tested under SATP conditions

Using equation (3.2.1), the averages of the specific energy consumption per mole ($\varepsilon^{0}_{\mathrm{e,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}$, unit volume ($\varepsilon^{0}_{\mathrm{e,V,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,V,sys}}$ and unit mass ($\varepsilon^{0}_{\mathrm{e,m,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{e,m,sys}}$, of hydrogen generated and put out by a WE system tested under SATP conditions are respectively calculated as

$$\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol}) \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{0}_{\mathrm{e,n,sys,l}}\ (\mathrm{kWh/mol}), \tag{8.2.1a}$$

$$\bar{\varepsilon}^{0}_{\mathrm{e,V,sys}}\ (\mathrm{kWh/m^3}) \ = \ \frac{\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \ \approx \ 40,34\ (\mathrm{mol/m^3})\cdot\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})\ \text{and} \tag{8.2.1b}$$

$$\bar{\varepsilon}^{0}_{\mathrm{e,m,sys}}\ (\mathrm{kWh/kg}) \ = \ \frac{\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})} \ \approx \ 495,05\ (\mathrm{mol/kg})\cdot\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol}); \tag{8.2.1c}$$

$\varepsilon^{0}_{\mathrm{e,n,sys,l}}$ is given by equation (A.2.1a). Correspondingly, the combined standard variances of the specific energy consumption per mole ($\varepsilon^{0}_{\mathrm{e,n,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)$, unit volume ($\varepsilon^{0}_{\mathrm{e,V,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,V,sys}}\right)$ and unit mass of hydrogen ($\varepsilon^{0}_{\mathrm{e,m,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,m,sys}}\right)$, are respectively calculated as

$$\begin{aligned} u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2 \ &= \ \left(\tilde{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{sys,in}}\right) \\ &\quad + \left(\underline{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)\right), \end{aligned} \tag{8.2.2a}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,V,sys}}\right)\ (\mathrm{kWh/m^3})^2 \ = \ \frac{u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \ \approx \ 1,63\cdot 10^3\ (\mathrm{mol/m^3})^2\cdot u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2 \tag{8.2.2b}$$

and

$$u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,m,sys}}\right)\ (\mathrm{kWh/kg})^2 \ = \ \frac{u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2} \ \approx \ 2,45\cdot 10^5\ (\mathrm{mol/kg})^2\cdot u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2; \tag{8.2.2c}$$

$\tilde{\varepsilon}^{0}_{\mathrm{e,n,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{sys,in}}\right)$, $\underline{\varepsilon}^{0}_{\mathrm{e,n,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)$ are respectively given by equation (A.3.2b), equation (A.4.4a), equation (A.3.2a), equation (A.4.4m) and equation (A.4.4n).

Using equation (3.2.9), the average of the specific electric energy consumption per mole ($\varepsilon^{0}_{\mathrm{el,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{el,n,sys}}$, of hydrogen generated and put out by a WE system tested under SATP conditions is calculated as

$$\bar{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol}) \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{0}_{\mathrm{el,n,sys,l}}\ (\mathrm{kWh/mol}), \tag{8.2.3}$$

$\varepsilon^{0}_{\mathrm{el,n,sys,l}}$ is given by equation (A.2.1b). Correspondingly, the combined standard variance of the specific electric energy consumption per mole ($\varepsilon^{0}_{\mathrm{el,n,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{el,sys}}\right)$, of hydrogen is calculated as

$$\begin{aligned} u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{el,sys}}\right)\ (\mathrm{kWh/mol})^2 \ &= \ \left(\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{el,sys}}\right) \\ &\quad + \left(\underline{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)\right), \end{aligned} \tag{8.2.4}$$

$\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{el,sys}}\right)$, $\underline{\varepsilon}^{0}_{\mathrm{el,n,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)$ are respectively given by equation (A.3.3b), equation (A.4.4b), equation (A.3.3a), equation (A.4.4m) and equation (A.4.4n).

Using equation (3.2.10), the average of the specific thermal energy consumption per mole ($\varepsilon^{0}_{\mathrm{th,n,sys}}$), $\bar{\varepsilon}^{0}_{\mathrm{th,n,sys}}$, of hydrogen generated and put out by a WE system tested under SATP conditions is calculated as

$$\bar{\varepsilon}^{0}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{0}_{\mathrm{th,n,sys,l}}\ (\mathrm{kWh/mol}), \tag{8.2.5}$$

$\varepsilon^{0}_{\mathrm{th,\,n,\,sys,\,l}}$ is given by equation (A.2.1c). Correspondingly, the combined standard variance of the specific thermal energy consumption per mole ($\varepsilon^{0}_{\mathrm{th,\,n,\,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{th,\,sys}}\right)$, of hydrogen is calculated as

$$u^2_{\mathrm{c}}\left(\varepsilon^{0}_{\mathrm{th,\,sys}}\right)\ (\mathrm{kWh/mol})^2 \;=\; \left(\tilde{\varepsilon}^{0}_{\mathrm{th,\,n,\,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{th,\,sys,\,in}}\right) + \left(\underline{\varepsilon}^{0}_{\mathrm{th,\,n,\,sys}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)\right), \tag{8.2.6}$$

$\tilde{\varepsilon}^{0}_{\mathrm{th,\,n,\,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{th,\,sys,\,in}}\right)$, $\underline{\varepsilon}^{0}_{\mathrm{th,\,n,\,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)$ are respectively given by equation (A.3.4b), equation (A.4.4c), equation (A.3.4a), equation (A.4.4m) and equation (A.4.4n).

Using equation (3.2.11), the averages of the energy efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,\,e,\,sys}}$), $\bar{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$ and LHV of hydrogen ($\eta^{0}_{\mathrm{LHV,\,e,\,sys}}$), $\bar{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$, are respectively calculated as

$$\bar{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}\ (\%) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L}\eta^{0}_{\mathrm{HHV,\,e,\,sys,\,l}}\ (\%)\ \text{ and} \tag{8.2.7a}$$

$$\bar{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}\ (\%) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L}\eta^{0}_{\mathrm{LHV,\,e,\,sys,\,l}}\ (\%); \tag{8.2.7b}$$

$\eta^{0}_{\mathrm{HHV,\,e,\,sys,\,l}}$ and $\eta^{0}_{\mathrm{LHV,\,e,\,sys,\,l}}$ are respectively given by equation (A.2.2a) and equation (A.2.2b). Correspondingly, the combined standard variances of the energy efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,\,e,\,sys}}$), $u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{HHV,\,e,\,sys}}\right)$ and LHV of hydrogen ($\eta^{0}_{\mathrm{LHV,\,e,\,sys}}$), $u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{LHV,\,e,\,sys}}\right)$, are respectively calculated as

$$u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{HHV,\,e,\,sys}}\right)(\%)^2 \;=\; \left(\underline{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}\ (\%)\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)\right) + \left(\tilde{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}\ (\%)\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{sys,\,in}}\right) \tag{8.2.8a}$$

and

$$u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{LHV,\,e,\,sys}}\right)(\%)^2 \;=\; \left(\underline{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}\ (\%)\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)\right) + \left(\tilde{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}\ (\%)\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{sys,\,in}}\right); \tag{8.2.8b}$$

$\underline{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$, $s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)$, $\tilde{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{sys,\,in}}\right)$, $\underline{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$ and $\tilde{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$ are respectively given by equation (A.3.2c), equation (A.4.4m), equation (A.4.4n), equation (A.3.2d), equation (A.4.4a), equation (A.3.2e) and equation (A.3.2f).

Using equation (3.2.12), the averages of the electrical efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,\,el,\,sys}}$), $\bar{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}$ and LHV of hydrogen ($\eta^{0}_{\mathrm{LHV,\,el,\,sys}}$), $\bar{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$, are respectively calculated as

$$\bar{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}\ (\%) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L}\eta^{0}_{\mathrm{HHV,\,el,\,sys,\,l}}\ (\%) \;\approx\; 1{,}18\cdot\bar{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}\ (\%)\ \text{ and} \tag{8.2.9a}$$

$$\bar{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}\ (\%) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L}\eta^{0}_{\mathrm{LHV,\,el,\,sys,\,l}}\ (\%) \;\approx\; 0{,}85\cdot\bar{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}\ (\%); \tag{8.2.9b}$$

$\eta^{0}_{\mathrm{HHV,\,el,\,sys,\,l}}$ and $\eta^{0}_{\mathrm{LHV,\,el,\,sys,\,l}}$ are respectively given by equation (A.2.3a) and equation (A.2.3b). Correspondingly, the combined standard variances of the electrical efficiency based on HHV ($\eta^{0}_{\mathrm{HHV,\,el,\,sys}}$), $u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{HHV,\,el,\,sys}}\right)$ and LHV of hydrogen ($\eta^{0}_{\mathrm{LHV,\,el,\,sys}}$), $u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{LHV,\,el,\,sys}}\right)$, are respectively calculated as

$$u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{HHV,\,el,\,sys}}\right)(\%)^2 \;=\; \left(\underline{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}\ (\%)\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)\right) + \left(\tilde{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}\ (\%)\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{el,\,sys}}\right) \tag{8.2.10a}$$

and

$$u^2_{\mathrm{c}}\left(\eta^{0}_{\mathrm{LHV,\,el,\,sys}}\right)(\%)^2 \;=\; \left(\underline{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}\ (\%)\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)\right) + \left(\tilde{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}\ (\%)\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{el,\,sys}}\right); \tag{8.2.10b}$$

$\underline{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$, $s^2_{\mathrm{r}}\left(q_{\mathrm{n,\,sys,\,out}}\right)$, $\tilde{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{el,\,sys}}\right)$, $\underline{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$ and $\tilde{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$ are respectively given by equation (A.3.3c), equation (A.4.4m), equation (A.4.4n), equation (A.3.3d), equation (A.4.4b), equation (A.3.3e) and equation (A.3.3f).

8.2.2 WE system tested under hydrogen output conditions

Using equation (3.3.1), the averages of the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$, of hydrogen generated and put out by a WE system tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol}) = \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys,l}}\ (\mathrm{kWh/mol}), \tag{8.2.11a}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\ (\mathrm{kWh/m^3}) = \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})}\ \text{and} \tag{8.2.11b}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,sys}}\ (\mathrm{kWh/kg}) = \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{8.2.11c}$$

$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys,l}}$ is given by equation (A.2.4a). Correspondingly, the combined standard variances of the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\right)$ and unit mass of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}\right)$, are respectively calculated as

$$\begin{aligned} u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,sys}}\right)\ (\mathrm{kWh/mol})^2 &= \left(\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{sys,in}}\right) \\ &\quad + \left(\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)\right), \end{aligned} \tag{8.2.12a}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\right)\ (\mathrm{kWh/m^3})^2 = \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\right)\ (\mathrm{kWh/m^3})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2}\ \text{and} \tag{8.2.12b}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}\right)\ (\mathrm{kWh/kg})^2 = \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}\right)\ (\mathrm{kWh/m^3})^2}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2}; \tag{8.2.12c}$$

$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{sys,in}}\right)$, $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)$ are respectively given by equation (A.3.5b), equation (A.4.4a), equation (A.3.5a), equation (A.4.4m) and equation (A.4.4n).

Using equation (3.3.2), the averages of the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol}) = \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys,l}}\ (\mathrm{kWh/mol}), \tag{8.2.13a}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,sys}}\ (\mathrm{kWh/m^3}) = \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})}\ \text{and} \tag{8.2.13b}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,sys}}\ (\mathrm{kWh/kg}) = \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{8.2.13c}$$

$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys,l}}$ is given by equation (A.2.4b). Correspondingly, the combined standard variances of the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}\right)$ and unit mass of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}\right)$, are respectively calculated as

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys}}\right)\ (\mathrm{kWh/mol})^2 = \left(\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{el,sys}}\right)$$

$$+\left(\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)+s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)\right), \quad (8.2.14\mathrm{a})$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,sys}}\right)\ (\mathrm{kWh/m^3})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \text{ and} \quad (8.2.14\mathrm{b})$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,sys}}\right)\ (\mathrm{kWh/kg})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2}; \quad (8.2.14\mathrm{c})$$

$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{el,sys}}\right)$, $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)$ are respectively given by equation (A.3.5d), equation (A.4.4b), equation (A.3.5c), equation (A.4.4m) and equation (A.4.4n).

Using equation (3.3.3), the averages of the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$, of hydrogen generated and put out by the WE system tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys,l}}\ (\mathrm{kWh/mol}), \quad (8.2.15\mathrm{a})$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,sys}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \text{ and} \quad (8.2.15\mathrm{b})$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,sys}}\ (\mathrm{kWh/kg}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \quad (8.2.15\mathrm{c})$$

$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys,l}}$ is given by equation (A.2.4c). Correspondingly, the combined standard variances of the specific thermal energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,sys}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}\right)$ and unit mass of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}\right)$, are respectively calculated as

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,sys}}\right)\ (\mathrm{kWh/mol})^2 \;=\; \left(\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{th,sys,in}}\right)$$

$$+\left(\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,sys}}\ (\mathrm{kWh/mol})\right)^2\left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)+s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)\right), \quad (8.2.16\mathrm{a})$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}\right)\ (\mathrm{kWh/m^3})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \text{ and} \quad (8.2.16\mathrm{b})$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}\right)\ (\mathrm{kWh/kg})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{th,sys}}\right)\ (\mathrm{kWh/mol})^2}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2}; \quad (8.2.16\mathrm{c})$$

$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{th,sys,in}}\right)$, $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,sys}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,sys,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,sys,out}}\right)$ are respectively given by equation (A.3.5f), equation (A.4.4c), equation (A.3.5e), equation (A.4.4m) and equation (A.4.4n).

8.2.3 WE/HTE tested under hydrogen output conditions

Using equation (3.4.1), the averages of the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol}) \;=\; \frac{1}{L}\sum_{\mathrm{l}=1}^{L}\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE,l}}\ (\mathrm{kWh/mol}), \quad (8.2.17\mathrm{a})$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,WE}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \ \text{ and} \tag{8.2.17b}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,WE}}\ (\mathrm{kWh/kg}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2}; \tag{8.2.17c}$$

$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE,l}}$ is given by equation (A.2.5a). Correspondingly, the combined standard variances of the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}\right)$ and unit mass of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}\right)$, are respectively calculated as

$$\begin{aligned} u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\right)\ (\mathrm{kWh/mol})^2 \;=\;& \left(\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{WE,in}}\right) \\ &+ \left(\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,WE,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,WE,out}}\right)\right), \end{aligned} \tag{8.2.18a}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}\right)\ (\mathrm{kWh/m^3})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\right)\ (\mathrm{kWh/mol})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \ \text{ and} \tag{8.2.18b}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}\right)\ (\mathrm{kWh/kg})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\right)\ (\mathrm{kWh/mol})^2}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^2}; \tag{8.2.18c}$$

$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$, $u^2_{\mathrm{r}}\left(P_{\mathrm{WE,in}}\right)$, $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$, $s^2_{\mathrm{r}}\left(x_{\mathrm{n,WE,H_2}}\right)$ and $s^2_{\mathrm{r}}\left(q_{\mathrm{n,WE,out}}\right)$ are respectively given by equation (A.3.7b), equation (A.4.7a), equation (A.3.7a), equation (A.4.7h) and equation (A.4.7i).

Using equation (3.4.4), the averages of the specific energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$ and unit mass ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$), $\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol}) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L} \varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE,l}}\ (\mathrm{kWh/mol}), \tag{8.2.19a}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,WE}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \ \text{ and} \tag{8.2.19b}$$

$$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,m,WE}}\ (\mathrm{kWh/kg}) \;=\; \frac{\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{8.2.19c}$$

$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE,l}}$ is given by equation (A.2.5b). Correspondingly, the combined standard variances of the specific electric energy consumption per mole ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\right)$, unit volume ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}\right)$ and unit mass of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}$), $u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,m,WE}}\right)$, are respectively calculated as

$$\begin{aligned} u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\right)\ (\mathrm{kWh/mol})^2 \;=\;& \left(\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol})\right)^2 u^2_{\mathrm{r}}\left(P_{\mathrm{el,dc,WE}}\right) \\ &+ \left(\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol})\right)^2 \left(s^2_{\mathrm{r}}\left(x_{\mathrm{n,WE,H_2}}\right) + s^2_{\mathrm{r}}\left(q_{\mathrm{n,WE,out}}\right)\right), \end{aligned} \tag{8.2.20a}$$

$$u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}\right)\ (\mathrm{kWh/m^3})^2 \;=\; \frac{u^2_{\mathrm{c}}\left(\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\right)\ (\mathrm{kWh/mol})^2}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^2} \ \text{ and} \tag{8.2.20b}$$

$$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{el,m,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/kg})^{2} \;=\; \frac{u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{el,n,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/mol})^{2}}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^{2}}; \tag{8.2.20c}$$

$\tilde{\varepsilon}_{\mathrm{el,n,WE}}^{\mathrm{p,T}}$, $u_{\mathrm{r}}^{2}\left(P_{\mathrm{el,dc,WE}}\right)$, $\underline{\varepsilon}_{\mathrm{el,n,WE}}^{\mathrm{p,T}}$, $s_{\mathrm{r}}^{2}\left(x_{\mathrm{n,WE,H_2}}\right)$ and $s_{\mathrm{r}}^{2}\left(q_{\mathrm{n,WE,out}}\right)$ are respectively given by equation (A.3.7d), equation (A.4.7b), equation (A.3.7c), equation (A.4.7h) and equation (A.4.7i).

Using equation (3.4.5), the averages of the specific energy consumption per mole ($\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}$), $\bar{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}$, unit volume ($\varepsilon_{\mathrm{th,V,WE}}^{\mathrm{p,T}}$), $\bar{\varepsilon}_{\mathrm{th,V,WE}}^{\mathrm{p,T}}$ and unit mass ($\varepsilon_{\mathrm{th,m,WE}}^{\mathrm{p,T}}$), $\bar{\varepsilon}_{\mathrm{th,m,WE}}^{\mathrm{p,T}}$, of hydrogen generated by the WE/HTE tested under hydrogen output conditions are respectively calculated as

$$\bar{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol}) \;=\; \frac{1}{L}\sum_{\mathrm{l=1}}^{L}\varepsilon_{\mathrm{th,n,WE,l}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol}), \tag{8.2.21a}$$

$$\bar{\varepsilon}_{\mathrm{th,V,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/m^3}) \;=\; \frac{\bar{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol})}{V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})} \quad \text{and} \tag{8.2.21b}$$

$$\bar{\varepsilon}_{\mathrm{th,m,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/kg}) \;=\; \frac{\bar{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol})}{m_{\mathrm{H_2}}\ (\mathrm{kg/mol})}; \tag{8.2.21c}$$

$\varepsilon_{\mathrm{th,n,WE,l}}^{\mathrm{p,T}}$ is given by equation (A.2.5c). Correspondingly, the combined standard variances of the specific thermal energy consumption per mole ($\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}$), $u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\right)$, unit volume ($\varepsilon_{\mathrm{th,V,WE}}^{\mathrm{p,T}}$), $u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,V,WE}}^{\mathrm{p,T}}\right)$ and unit mass of hydrogen ($\varepsilon_{\mathrm{th,m,WE}}^{\mathrm{p,T}}$), $u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,m,WE}}^{\mathrm{p,T}}\right)$, are respectively calculated as

$$\begin{aligned} u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/mol}) \;&=\; \left(\tilde{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol})\right)^{2} u_{\mathrm{r}}^{2}\left(P_{\mathrm{th,WE,in}}\right) \\ &+ \left(\underline{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\ (\mathrm{kWh/mol})\right)^{2}\left(s_{\mathrm{r}}^{2}\left(x_{\mathrm{n,WE,H_2}}\right)+s_{\mathrm{r}}^{2}\left(q_{\mathrm{n,WE,out}}\right)\right), \end{aligned} \tag{8.2.22a}$$

$$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,V,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/m^3}) \;=\; \frac{u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/mol})}{\left(V_{\mathrm{m,H_2}}\ (\mathrm{m^3/mol})\right)^{2}} \quad \text{and} \tag{8.2.22b}$$

$$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,m,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/kg}) \;=\; \frac{u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\right)\ (\mathrm{kWh/mol})}{\left(m_{\mathrm{H_2}}\ (\mathrm{kg/mol})\right)^{2}}; \tag{8.2.22c}$$

$\tilde{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}$, $u_{\mathrm{r}}^{2}\left(P_{\mathrm{th,WE,in}}\right)$, $\underline{\varepsilon}_{\mathrm{th,n,WE}}^{\mathrm{p,T}}$, $s_{\mathrm{r}}^{2}\left(x_{\mathrm{n,WE,H_2}}\right)$ and $s_{\mathrm{r}}^{2}\left(q_{\mathrm{n,WE,out}}\right)$ are respectively given by equation (A.3.7f), equation (A.4.7c), equation (A.3.7e), equation (A.4.7h) and equation (A.4.7i).

9 Conclusions with final remarks

This report provides for a testing procedure to determine the specific energy consumption and specific electric energy consumption per unit of hydrogen output of WE systems as well as their energy efficiency and electrical efficiency under SATP conditions allowing to compare different systems and technologies of water electrolysers/high-temperature electrolysers.

Under hydrogen output conditions, this testing procedure determines as EPIs the specific energy consumption, specific electric energy consumption and specific thermal energy consumption per unit of hydrogen output of water electrolysers/high-temperature electrolysers and WE systems.

This testing procedure may be used by the research community and industry alike.

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List of Abbreviations and Acronyms

A/S	Aktieselskab
AC	alternating current
AC/DC	alternating current-to-direct current
AEL	alkaline water electrolysis
AEMEL	anion exchange polymer membrane water electrolysis
AEMWE	anion exchange polymer membrane water electrolyser
AG	Aktiengesellschaft
AI	artificial intelligence
AS	Aktsiaselts
ASA	Allmennaksjeselskap
ATEX	Appareils destinés à être utilisés en atmosphères explosibles
AWE	alkaline water electrolyser
AWI	approved working item
BoP	balance of plant
BPMEL	bipolar polymer membrane water electrolysis
BPMWE	bipolar polymer membrane water electrolyser
CC BY 4.0	Creative Commons Attribution 4.0 International
CEA	Commissariat à l’énergie atomique et aux énergies alternatives
CH	Switzerland
CH_2	compressed hydrogen
CHP	combined heat and power
Clean H_2 JU	Clean Hydrogen Joint Undertaking
CNR-ITAE	Consiglio Nazionale delle Ricerche - Istituto di Tecnologie Avanzate per l’Energia “Nicola Giordano”
DAQ	data acquisition
DC	direct current
DC/DC	direct current-to-direct current
DECHEMA	Gesellschaft für Chemische Technik und Biotechnologie e. V.
DFI	DECHEMA Forschungsinstitut Stiftung bügerlichen Rechts
DG	Directorate-General
DLR	Deutsches Zentrum für Luft- und Raumfahrt e. V.
doi	digital object identifier
DRI	direct reduction of iron
DTU	Danmarks Tekniske Universitet
e. V.	eingetragener Verein
EC	European Commission
EEA	European Economic Area
EHC	electrochemical hydrogen compressor
EMC	electromagnetic compatibility
EN	English
ENEA	Agenzia Nazionale per le Nuove tecnologie, l’Energia e lo Sviluppo economico sostenibile
EPI	energy performance indicator
ES	energy-storage
EU	European Union
EUR	EU Report
FBK	Fondazione Bruno Kessler
FCH2JU	Fuel Cells and Hydrogen second Joint Undertaking
FHa	Fundación para el Desarrollo de las Tecnologías del Hidrógeno en Aragón
FR	France
FZJ	Forschungszentrum Jülich GmbH
GHS	Green Hydrogen Systems A/S
GmbH	Gesellschaft mit beschränkter Haftung
H2I	hydrogen-to-industry
HHV	higher heating value
HTE	high-temperature electrolyser
HtM	hydrogen-to-mobility
HtP	hydrogen-to-power

HTSEL	high-temperature steam electrolysis
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEN	Instytut Energetyki - Instytut Badawczy
IFAM	Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung
IKTS	Fraunhofer-Institut für Keramische Technologien und Systeme
ISBN	international standard book number
ISO	International Organization for Standardization
IUPAC	International Union of Pure and Applied Chemistry
IWES	Fraunhofer-Institut für Windenergiesysteme
JCGM	Joint Committee for Guides in Metrology
JRC	Joint Research Centre
KIT	Karlsruher Institut für Technologie
KPI	key performance indicator
L	Luxembourg
$\mathbf{LH_2}$	liquefied hydrogen
LHV	lower heating value
LTWE	low-temperature water electrolysis
LUT	Lappeenranta-Lahti teknillinen yliopisto
LVD	Low-Voltage Directive
ML	machine learning
MPIM	Max-Planck-Institut für Dynamik komplexer technischer Systeme Magdeburg
NC	North Carolina
NG	natural gas
NPL	National Physical Laboratory
NTNU	Norges teknisk-naturvitenskapelige universitet
NY	New York
O-SOE	oxygen ion conducting solid oxide electrolyser
OHS	occupational health and safety
OJ	Official Journal of the European Union
Oy	Osakeyhtiö
P-SOE	proton conducting solid oxide electrolyser
P2C	power-to-chemical
P2F	power-to-fuel
P2G	power-to-gas
P2H2	power-to-hydrogen
P2L	power-to-liquid
P2M	power-to-mobility
P2X	power-to-X
PCCEL	proton conducting ceramic steam electrolysis
PCE	proton conducting ceramic electrolyser
PDF	portable document format
PED	Pressure Equipment Directive
PEM	proton exchange polymer membrane
PEMEL	proton exchange polymer membrane water electrolysis
PEMWE	proton exchange polymer membrane water electrolyser
PNR	pre-normative research
PoC	point of connection
PV	photovoltaic
PWR	Politechnika Wrocławska
QA	quality assurance
QC	quality control
R&D	research and development
R&D&I	research, development and innovation
R&I	research and innovation
RES	renewable energy source
RFB	redox flow battery
RHS	right hand side
rms	root mean square
rPCE	reversible proton conducting ceramic electrolyser
rPEMWE	reversible proton exchange polymer membrane water electrolyser

rSOE	reversible solid oxide electrolyser
SA	Société anonyme
SATP	standard ambient temperature and pressure
SI	Système International d'Unités
SINTEF	Stiftelsen for industriell og teknisk forskning
SOC	solid oxide cell
SOE	solid oxide electrolyser
SOEL	solid oxide steam electrolysis
SpA	Società per azioni
SRIA	strategic research and innovation agenda 2021-2027 of the Clean Hydrogen Partnership for Europe
TC	Technical Committee
TIP	test input parameter
TMA	technology monitoring and assessment
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TOP	test output parameter
TR	Technical Report
TUB	Technische Universität Berlin
UCD	University College Dublin
UCLM	Universidad de Castilla-La Mancha
URL	uniform resource locator
USA	United States of America
VRE	variable renewable energy
VSCHT	Vysoká Škola chemicko-technologická v Praze
WE	water electrolyser
WE system	water (steam) electrolyser system
WG	working group

List of Symbols

$\cos\varphi$	power factor
c_V	specific heat capacity at constant volume
c_p	specific heat capacity at constant pressure
c_p^i	specific heat at constant pressure of fluid i
c_p^j	specific heat at constant pressure of fluid j
c_V^j	specific heat at constant volume of fluid j
E_chem	chemical energy
E_compr	compression energy
E_el	electric energy
ε_e	specific energy consumption
$\varepsilon_\mathrm{e,n,sys}^0$	specific energy consumption per mole related to SATP conditions of a WE system
$\varepsilon_\mathrm{e,n,sys,l}^0$	instantaneous specific energy comsumption related to SATP conditions
ε_el	specific electric energy consumption
$\varepsilon_\mathrm{el,n,sys,l}^0$	instantaneous specific electric energy comsumption related to SATP conditions
$\varepsilon_\mathrm{el,m}$	specific electric energy consumption per unit mass
$\varepsilon_\mathrm{el,m,sys}^0$	specific electric energy consumption per unit mass related to SATP conditions of a WE system
$\varepsilon_\mathrm{el,m,sys}^\mathrm{p,T}$	specific electric energy consumption per unit mass related to hydrogen output conditions of a WE system
$\bar{\varepsilon}_\mathrm{el,m,sys}^\mathrm{p,T}$	average specific electric energy consumption per unit mass related to hydrogen output conditions
$\varepsilon_\mathrm{el,m,WE}^\mathrm{p,T}$	specific electric energy consumption per unit mass related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}_\mathrm{el,m,WE}^\mathrm{p,T}$	average specific electric energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$\varepsilon_\mathrm{el,n}$	specific electric energy consumption per mole
$\varepsilon_\mathrm{el,n,WE}^\mathrm{p,T}$	specific electric energy consumption related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}_\mathrm{el,n,WE}^\mathrm{p,T}$	average specific electric energy consumption of a WE/HTE related to hydrogen output conditions
$\tilde{\varepsilon}_\mathrm{el,n,WE}^\mathrm{p,T}$	pseudo-average specific electric energy consumption of a WE/HTE related to hydrogen output conditions calculated by equation (A.3.7d)
$\underline{\varepsilon}_\mathrm{el,n,WE}^\mathrm{p,T}$	pseudo-average specific electric energy consumption of a WE/HTE related to hydrogen output conditionsequation (A.3.7c)
$\varepsilon_\mathrm{el,n,WE,l}^\mathrm{p,T}$	instantaneous specific electric energy consumption of a WE/HTE related to hydrogen output conditions
$\tilde{\varepsilon}_\mathrm{el,n,sys}^\mathrm{p,T}$	pseudo-average specific electric energy consumption related to hydrogen output conditions calculated by equation (A.3.5d)
$\varepsilon_\mathrm{el,n,sys}^0$	specific electric energy consumption per mole related to SATP conditions of a WE system
$\bar{\varepsilon}_\mathrm{el,n,sys}^0$	average specific electric energy comsumption related to SATP conditions
$\underline{\varepsilon}_\mathrm{el,n,sys}^0$	pseudo-average specific electric energy comsumption related to SATP conditions calculated by equation (A.3.3a)
$\tilde{\varepsilon}_\mathrm{el,n,sys}^0$	pseudo-average specific electric energy comsumption related to SATP conditions calculated by equation (A.3.3b)
$\varepsilon_\mathrm{el,n,sys}^\mathrm{p,T}$	specific electric energy consumption per mole related to hydrogen output conditions of a WE system
$\bar{\varepsilon}_\mathrm{el,n,sys}^\mathrm{p,T}$	average specific electric energy consumption related to hydrogen output conditions
$\underline{\varepsilon}_\mathrm{el,n,sys}^\mathrm{p,T}$	pseudo-average specific electric energy consumption related to hydrogen output conditions calculated by equation (A.3.5c)
$\varepsilon_\mathrm{el,sys,l}^\mathrm{p,T}$	instantaneous specific electric energy consumption related to hydrogen output conditions
$\varepsilon_\mathrm{el,V}$	specific electric energy consumption per unit volume
$\varepsilon_\mathrm{el,V,sys}^0$	specific electric energy consumption per unit volume related to SATP conditions of a WE system
$\varepsilon_\mathrm{el,V,sys}^\mathrm{p,T}$	specific electric energy consumption per unit volume related to hydrogen output conditions of a WE system

$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,sys}}$	average specific electric energy consumption per unit volume related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$	specific electric energy consumption per unit volume related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,V,WE}}$	average specific electric energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
$\varepsilon_{\mathrm{e,m}}$	specific energy consumption per unit mass
$\varepsilon^{0}_{\mathrm{e,m,sys}}$	specific energy consumption per unit mass related to SATP conditions of a WE system
$\bar{\varepsilon}^{0}_{\mathrm{e,m,sys}}$	average specific energy comsumption per unit mass related to SATP conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$	specific energy consumption per unit mass related to hydrogen output conditions of a WE system
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,sys}}$	average specific energy consumption per unit mass related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$	specific energy consumption per unit mass related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,m,WE}}$	average specific energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$\varepsilon_{\mathrm{e,n}}$	specific energy consumption per mole
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$	specific energy consumption per mole related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$	average specific energy consumption of a WE/HTE related to hydrogen output conditions
$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$	pseudo-average specific energy consumption of a WE/HTE related to hydrogen output conditions calculated by equation (A.3.7b)
$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$	pseudo-average specific energy consumption of a WE/HTE related to hydrogen output conditions calculated by equation (A.3.7a)
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE,l}}$	instantaneous specific energy consumption of a WE/HTE related to hydrogen output conditions
$\bar{\varepsilon}^{0}_{\mathrm{e,n,sys}}$	average specific energy comsumption related to SATP conditions
$\underline{\varepsilon}^{0}_{\mathrm{e,n,sys}}$	pseudo-average specific energy comsumption related to SATP conditions calculated by equation (A.3.2a)
$\tilde{\varepsilon}^{0}_{\mathrm{e,n,sys}}$	pseudo-average specific energy comsumption related to SATP conditions calculated by equation (A.3.2b)
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$	specific energy consumption per mole related to hydrogen output conditions of a WE system
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$	average specific energy consumption related to hydrogen output conditions
$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$	pseudo-average specific energy consumption related to hydrogen output conditions calculated by equation (A.3.5a)
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys,l}}$	instantaneous specific energy consumption related to hydrogen output conditions
$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$	pseudo-average specific energy consumption related to hydrogen output conditions calculated by equation (A.3.5b)
$\varepsilon_{\mathrm{e,V}}$	specific energy consumption per unit volume
$\varepsilon^{0}_{\mathrm{e,V,sys}}$	specific energy consumption per unit volume related to SATP conditions of a WE system
$\bar{\varepsilon}^{0}_{\mathrm{e,V,sys}}$	average specific energy comsumption per unit volume related to SATP conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$	specific energy consumption per unit volume related to hydrogen output conditions of a WE system
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,sys}}$	average specific energy consumption per unit volume related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$	specific energy consumption per unit volume related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,V,WE}}$	average specific energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
$\varepsilon_{\mathrm{th}}$	specific thermal energy consumption
$\varepsilon^{0}_{\mathrm{th,n,sys,l}}$	instantaneous specific thermal energy comsumption related to SATP conditions
$\varepsilon_{\mathrm{th,m}}$	specific thermal energy consumption per unit mass
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$	specific thermal energy consumption per unit mass related to hydrogen output conditions of a WE system

$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,sys}}$	average specific thermal energy consumption per unit mass related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$	specific thermal energy consumption per unit mass related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,m,WE}}$	average specific thermal energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$\varepsilon_{\mathrm{th,m,sys}}$	specific thermal energy consumption per unit mass related to SATP conditions of a WE system
$\varepsilon_{\mathrm{th,n}}$	specific thermal energy consumption per mole
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$	specific thermal energy consumption per mole related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$	average specific thermal energy consumption of a WE/HTE related to hydrogen output conditions
$\tilde{\bar{\varepsilon}}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$	pseudo-average specific thermal energy consumption of a WE/HTE related to hydrogen output conditions calculated by equation (A.3.7f)
$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$	pseudo-average specific thermal energy consumption of a WE/HTE related to hydrogen output conditions calculated by equation (A.3.7e)
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE,l}}$	instantaneous specific thermal energy consumption of a WE/HTE related to hydrogen output conditions
$\varepsilon^{0}_{\mathrm{th,n,sys}}$	specific thermal energy consumption per mole related to SATP conditions of a WE system
$\bar{\varepsilon}^{0}_{\mathrm{th,n,sys}}$	average specific thermal energy comsumption related to SATP conditions
$\underline{\varepsilon}^{0}_{\mathrm{th,n,sys}}$	pseudo-average specific thermal energy comsumption related to SATP conditions calculated by equation (A.3.4a)
$\tilde{\bar{\varepsilon}}^{0}_{\mathrm{th,n,sys}}$	pseudo-average specific thermal energy comsumption related to SATP conditions calculated by equation (A.3.4b)
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$	specific thermal energy consumption per mole related to hydrogen output conditions of a WE system
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$	average specific thermal energy consumption related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys,l}}$	instantaneous specific thermal energy consumption related to hydrogen output conditions
$\tilde{\bar{\varepsilon}}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$	pseudo-average specific thermal energy consumption related to hydrogen output conditions calculated by equation (A.3.5f)
$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,sys}}$	pseudo-average specific thermal energy consumption related to hydrogen output conditions calculated by equation (A.3.5e)
$\varepsilon_{\mathrm{th,V}}$	specific thermal energy consumption per unit volume
$\varepsilon^{0}_{\mathrm{th,V,sys}}$	specific thermal energy consumption per unit volume related to SATP conditions of a WE system
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$	specific thermal energy consumption per unit volume related to hydrogen output conditions of a WE system
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,sys}}$	average specific thermal energy consumption per unit volume related to hydrogen output conditions
$\varepsilon^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$	specific thermal energy consumption per unit volume related to hydrogen output conditions of a WE/HTE
$\bar{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,V,WE}}$	average specific thermal energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
η_{e}	energy efficiency
$\eta_{\mathrm{HHV,e}}$	energy efficiency based on HHV
$\eta_{\mathrm{LHV,e}}$	energy efficiency based on LHV
$\eta^{0}_{\mathrm{HHV,e}}$	energy efficiency based on HHV related to SATP conditions
η_{el}	electrical efficiency
$\eta^{0}_{\mathrm{HHV,el}}$	electrical efficiency based on HHV related to SATP conditions
$\eta_{\mathrm{HHV,el}}$	electrical efficiency based on HHV
$\eta^{0}_{\mathrm{LHV,e}}$	energy efficiency based on LHV related to SATP conditions
$\eta^{0}_{\mathrm{LHV,el}}$	electrical efficiency based on LHV related to SATP conditions
$\eta_{\mathrm{LHV,el}}$	electrical efficiency based on LHV
$\eta_{\mathrm{HHV,el,sys}}$	electrical efficiency based on HHV of a WE system
$\eta^{0}_{\mathrm{HHV,el,sys}}$	electrical efficiency based on HHV related to SATP conditions of a WE system
$\bar{\eta}^{0}_{\mathrm{HHV,el,sys}}$	average electrical efficiency based on HHV of a WE system related to SATP conditions

$\eta^{0}_{\mathrm{HHV,\,el,\,sys,\,l}}$	instantaneous electrical efficiency based on HHV of a WE system related to SATP conditions
$\underline{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}$	pseudo-average electrical efficiency based on HHV of a WE system related to SATP conditions calculated by equation (A.3.3c)
$\tilde{\eta}^{0}_{\mathrm{HHV,\,el,\,sys}}$	pseudo-average electrical efficiency based on HHV of a WE system related to SATP conditions calculated by equation (A.3.3d)
$\eta^{0}_{\mathrm{LHV,\,el,\,sys}}$	electrical efficiency based on LHV related to SATP conditions of a WE system
$\bar{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$	average electrical efficiency based on LHV of a WE system related to SATP conditions
$\eta^{0}_{\mathrm{LHV,\,el,\,sys,\,l}}$	instantaneous electrical efficiency based on LHV of a WE system related to SATP conditions
$\underline{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$	pseudo-average electrical efficiency based on LHV of a WE system related to SATP conditions calculated by equation (A.3.3e)
$\tilde{\eta}^{0}_{\mathrm{LHV,\,el,\,sys}}$	pseudo-average electrical efficiency based on LHV of a WE system related to SATP conditions calculated by equation (A.3.3d)
$\eta^{0}_{\mathrm{HHV,\,e,\,sys}}$	energy efficiency based on HHV related to SATP conditions of a WE system
$\bar{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$	average energy efficiency based on HHV of a WE system related to SATP conditions
$\eta^{0}_{\mathrm{HHV,\,e,\,sys,\,l}}$	instantaneous energy efficiency based on HHV of a WE system related to SATP conditions
$\underline{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$	pseudo-average energy efficiency based on HHV of a WE system related to SATP conditions calculated by equation (A.3.2c)
$\tilde{\eta}^{0}_{\mathrm{HHV,\,e,\,sys}}$	pseudo-average energy efficiency based on HHV of a WE system related to SATP conditions calculated by equation (A.3.2d)
$\tilde{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$	pseudo-average energy efficiency based on LHV of a WE system calculated by equation (A.3.2f)
$\eta^{0}_{\mathrm{LHV,\,e,\,sys}}$	energy efficiency based on LHV related to SATP conditions of a WE system
$\bar{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$	average energy efficiency based on LHV of a WE system related to SATP conditions
$\eta^{0}_{\mathrm{LHV,\,e,\,sys,\,l}}$	instantaneous energy efficiency based on LHV of a WE system related to SATP conditions
$\underline{\eta}^{0}_{\mathrm{LHV,\,e,\,sys}}$	pseudo-average energy efficiency based on LHV of a WE system related to SATP conditions calculated by equation (A.3.2e)
E_{th}	thermal energy
γ	isentropic expansion factor
γ^{j}	isentropic expansion factor of fluid j
$\underline{q}^{\mathrm{f}}_{\mathrm{n}}$	pseudo-average molar flow rate of fuel calculated by equation (A.3.2j)
$\mathrm{H_2}$	molecular hydrogen
$\mathrm{HHV}^{\mathrm{f}}$	HHV of fuel
$\mathrm{HHV}_{\mathrm{H_2}}$	HHV of hydrogen
I	current
$I_{\mathrm{ac,\,sys}}$	alternating current of a WE system
I_{dc}	direct current
$I_{\mathrm{dc,\,WE}}$	direct current of a WE/HTE
$I_{\mathrm{dc,\,sys}}$	direct current of a WE system
I_{stack}	stack current
k	coverage factor
L	number of data point
$\mathrm{LHV}_{\mathrm{H_2}}$	LHV of hydrogen
m	mass
$m_{\mathrm{H_2}}$	molar mass of hydrogen
n	number of mole
P	power
p	pressure
p^{0}	standard ambient pressure
$P_{\mathrm{compr,\,in}}$	input power of compression
$P_{\mathrm{compr,\,in,\,j}}$	input power of compression of fluid j
$P_{\mathrm{compr,\,sys,\,in}}$	input power of compression of a WE system
$\bar{P}_{\mathrm{compr,\,sys,\,in}}$	average input power of compression of a WE system
$P_{\mathrm{compr,\,sys,\,in,\,j}}$	input power of compression of fluid j of a WE system
$\bar{P}_{\mathrm{compr,\,sys,\,in,\,j}}$	average input power of compression of fluid j of a WE system
$\underline{P}_{\mathrm{compr,\,sys,\,in,\,j}}$	pseudo-average input power of compression of fluid j of a WE system calculated by equation (A.3.2h) or equation (A.3.2i)

$P_{\mathrm{compr,\,sys,\,in,\,j,\,l}}$	instantaneous input power of compression of fluid j of a WE system
$P_{\mathrm{compr,\,sys,\,in,\,l}}$	instantaneous input power of compression of a WE system
$P_{\mathrm{compr,\,WE,\,in}}$	input power of compression of a WE/HTE
$\bar{P}_{\mathrm{compr,\,WE,\,in}}$	average input power of compression of a WE/HTE
$P_{\mathrm{compr,\,WE,\,in,\,j}}$	input power of compression of fluid j of a WE/HTE
$\bar{P}_{\mathrm{compr,\,WE,\,in,\,j}}$	average input power of compression of fluid j of a WE/HTE
$\underline{P}_{\mathrm{compr,\,WE,\,in,\,j}}$	pseudo-average input power of compression of fluid j of a WE/HTE calculated by equation (A.3.7h) or equation (A.3.7i)
$P_{\mathrm{compr,\,WE,\,in,\,j,\,l}}$	instantaneous input power of compression of fluid j of a WE/HTE
$P_{\mathrm{compr,\,WE,\,in,\,l}}$	instantaneous input power of compression of a WE/HT
P_{el}	electric power
$P_{\mathrm{el,\,1p,\,ac}}$	single-phase AC electric power
$P_{\mathrm{el,\,1p,\,ac,\,sys}}$	single-phase AC electric power of a WE system
$P_{\mathrm{el,\,3p,\,ac}}$	symmetrical three-phase AC electric power
$P_{\mathrm{el,\,3p,\,ac,\,sys}}$	symmetrical three-phase AC electric power of a WE system
$P_{\mathrm{el,\,ac}}$	AC electric power
$P_{\mathrm{el,\,ac,\,sys}}$	AC electric power of a WE system
$\bar{P}_{\mathrm{el,\,ac,\,sys}}$	average AC electric power of a WE system
$P_{\mathrm{el,\,ac,\,sys,\,l}}$	instantaneous AC electric power of a WE system
$P_{\mathrm{el,\,dc}}$	DC electric power
$P_{\mathrm{el,\,dc,\,sys}}$	DC electric power of a WE system
$\bar{P}_{\mathrm{el,\,dc,\,sys}}$	average DC electric power of a WE system
$P_{\mathrm{el,\,dc,\,sys,\,l}}$	instantaneous DC electric power of a WE system
$P_{\mathrm{el,\,dc,\,WE}}$	DC electric power of a WE/HTE
$\bar{P}_{\mathrm{el,\,dc,\,WE}}$	average DC electric power of a WE/HTE
$P_{\mathrm{el,\,dc,\,WE,\,l}}$	instantaneous DC electric power of a WE/HTE
$P_{\mathrm{el,\,in}}$	input electric power
$P_{\mathrm{el,\,sys}}$	electric power of a WE system
$\bar{P}_{\mathrm{el,\,sys}}$	average electric power of a WE system
$P_{\mathrm{el,\,sys,\,l}}$	instantaneous electric power of a WE system
p^{f}	pressure of fuel
p^{i}	pressure of fluid i
P_{in}	input power
p^{j}	pressure of fluid j
$\bar{p}^{\mathrm{j}}$	average pressure of fluid j
$p^{\mathrm{j}}_{\mathrm{l}}$	instantaneous pressure of fluid j
$p^{\mathrm{O_2}}_{\mathrm{out}}$	output pressure of oxygen
$p^{\mathrm{O_2}}_{\mathrm{WE,\,out}}$	output pressure of oxygen of a WE/HTE
$p_{\mathrm{out,\,H_2}}$	pressure of hydrogen
$p^{\mathrm{sg}}_{\mathrm{in}}$	input pressure of sweep gas
$p^{\mathrm{sg}}_{\mathrm{out}}$	output pressure of sweep gas
$p^{\mathrm{sg}}_{\mathrm{WE,\,in}}$	input pressure of sweep gas of a WE/HTE
$p^{\mathrm{sg}}_{\mathrm{WE,\,out}}$	output pressure of sweep gas of a WE/HTE
$p_{\mathrm{sys,\,H_2}}$	pressure of hydrogen of a WE system
$\bar{p}_{\mathrm{sys,\,H_2}}$	average pressure of hydrogen of a WE system
$p_{\mathrm{sys,\,H_2,\,l}}$	instantaneous pressure of hydrogen of a WE system
$P_{\mathrm{sys,\,in}}$	input power of a WE system
$\bar{P}_{\mathrm{sys,\,in}}$	average input power of a WE system
$P_{\mathrm{sys,\,in,\,l}}$	instantaneous input power of a WE system
$P_{\mathrm{th,\,in}}$	input thermal power
$P_{\mathrm{th,\,in,\,i}}$	input thermal power of fluid i
$P_{\mathrm{th,\,sys,\,in}}$	input thermal power of a WE system
$\bar{P}_{\mathrm{th,\,sys,\,in}}$	average input thermal power of a WE system
$P_{\mathrm{th,\,sys,\,in,\,i}}$	thermal power of fluid i of a WE system
$\bar{P}_{\mathrm{th,\,sys,\,in,\,i}}$	average input thermal power of fluid i of a WE system
$\underline{P}_{\mathrm{th,\,sys,\,in,\,i}}$	pseudo-average input thermal power of fluid i of a WE system calculated by equation (A.3.2g)
$P_{\mathrm{th,\,sys,\,in,\,i,\,l}}$	instantaneous input thermal power of fluid i of a WE system
$P_{\mathrm{th,\,sys,\,in,\,l}}$	instantaneous input thermal power of a WE system
$P_{\mathrm{th,\,WE,\,in}}$	input thermal power of a WE/HTE

$\bar{P}_{\mathrm{th,\,WE,\,in}}$	average input thermal power of a WE/HTE
$P_{\mathrm{th,\,WE,\,in,\,i}}$	thermal power of fluid i of a WE/HTE
$\bar{P}_{\mathrm{th,\,WE,\,in,\,i}}$	average input thermal power of fluid i of a WE/HTE
$\underline{P}_{\mathrm{th,\,WE,\,in,\,i}}$	pseudo-average input thermal power of fluid i of a WE/HTE calculated by equation (A.3.7g)
$P_{\mathrm{th,\,WE,\,in,\,i,\,l}}$	instantaneous input thermal power of fluid i of a WE/HTE
$P_{\mathrm{th,\,WE,\,in,\,l}}$	instantaneous input thermal power of a WE/HTE
p^{w}	pressure of water
$p^{\mathrm{i}}_{\mathrm{WE}}$	pressure of fluid i of a WE/HTE
$P_{\mathrm{WE,\,in}}$	input power of a WE/HTE
$\bar{P}_{\mathrm{WE,\,in}}$	average input power of a WE/HTE
$P_{\mathrm{WE,\,in,\,l}}$	instantaneous input power of a WE/HTE
$P^{\mathrm{p,\,T}}_{\mathrm{WE,\,in}}$	input power related to hydrogen output conditions of a WE/HTE
$p^{\mathrm{j}}_{\mathrm{WE}}$	pressure of fluid j of a WE/HTE
$\bar{p}^{\mathrm{j}}_{\mathrm{WE}}$	average pressure of fluid j of a WE/HTE
$p^{\mathrm{j}}_{\mathrm{WE,\,l}}$	instantaneous pressure of fluid j of a WE/HTE
$p_{\mathrm{WE,\,H_2}}$	pressure of hydrogen of a WE/HTE
$p^{\mathrm{w}}_{\mathrm{in}}$	input pressure of water
$p^{\mathrm{w}}_{\mathrm{out}}$	output pressure of water
$p^{\mathrm{w}}_{\mathrm{WE,\,in}}$	input pressure of water of a WE/HTE
$p^{\mathrm{w}}_{\mathrm{WE,\,out}}$	output pressure of water of a WE/HTE
q	flow rate
q_{m}	mass flow rate
$q^{\mathrm{f}}_{\mathrm{m}}$	mass flow rate of fuel
$q^{\mathrm{i}}_{\mathrm{m}}$	mass flow rate of fluid i
$\bar{q}^{\mathrm{i}}_{\mathrm{m}}$	average mass flow rate of fluid i
$q^{\mathrm{i}}_{\mathrm{m,\,l}}$	instantaneous mass flow rate of fluid i
$q^{\mathrm{O_2}}_{\mathrm{m,\,out}}$	output mass flow rate of oxygen
$q^{\mathrm{O_2}}_{\mathrm{m,\,WE,\,out}}$	mass flow rate of oxygen output of a WE/HTE
$q^{\mathrm{sg}}_{\mathrm{m,\,in}}$	input mass flow rate of sweep gas
$q^{\mathrm{sg}}_{\mathrm{m,\,out}}$	output mass flow rate of sweep gas
$q^{\mathrm{sg}}_{\mathrm{m,\,WE,\,in}}$	input mass flow rate of sweep gas of a WE/HTE
$q^{\mathrm{w}}_{\mathrm{m}}$	mass flow rate of water
$q^{\mathrm{i}}_{\mathrm{m,\,WE}}$	mass flow rate of fluid i of a WE/HTE
$\bar{q}^{\mathrm{i}}_{\mathrm{m,\,WE}}$	average mass flow rate of fluid j of a WE/HTE
$q^{\mathrm{i}}_{\mathrm{m,\,WE,\,l}}$	instantaneous mass flow rate of fluid j of a WE/HTE
$q^{\mathrm{w}}_{\mathrm{m,\,in}}$	input mass flow rate of water
$q^{\mathrm{w}}_{\mathrm{m,\,out}}$	output mass flow rate of water
$q^{\mathrm{w}}_{\mathrm{m,\,WE,\,in}}$	mass flow rate of water input of a WE/HTE
$q^{\mathrm{w}}_{\mathrm{m,\,WE,\,out}}$	mass flow rate of water output of a WE/HTE
q_{n}	molar flow rate
$q^{\mathrm{f}}_{\mathrm{n}}$	molar flow rate of fuel
$\bar{q}^{\mathrm{f}}_{\mathrm{n}}$	average molar flow rate of fuel
$q^{\mathrm{f}}_{\mathrm{n,\,l}}$	instantaneous molar flow rate of fuel
$q_{\mathrm{n,\,H_2}}$	molar flow rate of hydrogen
$q^{\mathrm{j}}_{\mathrm{n}}$	molar flow rate of fluid j
$\bar{q}^{\mathrm{j}}_{\mathrm{n}}$	average molar flow rate of fluid j
$q^{\mathrm{j}}_{\mathrm{n,\,l}}$	instantaneous molar flow rate of fluid j
$q_{\mathrm{n,\,out}}$	product gas molar flow rate
$\bar{q}_{\mathrm{n,\,out}}$	average output molar flow rate of hydrogen
$q_{\mathrm{n,\,out,\,H_2}}$	output molar flow rate of hydrogen
$q_{\mathrm{n,\,sys,\,H_2}}$	molar flow rate of hydrogen of a WE system
$q_{\mathrm{n,\,sys,\,out}}$	output molar flow rate of hydrogen of a WE system
$\bar{q}_{\mathrm{n,\,sys,\,out}}$	average output molar flow rate of hydrogen of a WE system
$q_{\mathrm{n,\,sys,\,out,\,H_2}}$	output molar flow rate of hydrogen of a WE system
$\bar{q}_{\mathrm{n,\,sys,\,out,\,H_2}}$	average output molar flow rate of hydrogen of a WE system
$\underline{q}_{\mathrm{n,\,sys,\,out,\,H_2}}$	pseudo-average output molar flow rate of hydrogen of a WE system calculated by equation (A.3.2k)
$q_{\mathrm{n,\,sys,\,out,\,H_2,\,l}}$	instantaneous output molar flow rate of hydrogen of a WE system
$q_{\mathrm{n,\,sys,\,out,\,l}}$	instantaneous output molar flow rate of hydrogen of a WE system

$q_{\mathrm{n,H_2}}^{\mathrm{WE}}$	molar flow rate of hydrogen of a WE/HTE
$\bar{q}_{\mathrm{n,H_2}}^{\mathrm{WE}}$	average molar flow rate of hydrogen of a WE/HTE
$\underline{q}_{\mathrm{n,H_2}}^{\mathrm{WE}}$	pseudo-average molar flow rate of hydrogen of a WE/HTE calculated by equation (A.3.7j)
$q_{\mathrm{n,H_2,l}}^{\mathrm{WE}}$	instantaneous molar flow rate of hydrogen of a WE/HTE
$q_{\mathrm{n,WE}}^{\mathrm{j}}$	molar flow rate of fluid j of a WE/HTE
$\bar{q}_{\mathrm{n,WE}}^{\mathrm{j}}$	average molar flow rate of fluid j of a WE/HTE
$q_{\mathrm{n,WE,l}}^{\mathrm{j}}$	instantaneous molar flow rate of fluid j of a WE/HTE
$q_{\mathrm{n,out}}^{\mathrm{WE}}$	output molar flow rate of hydrogen of a WE/HTE
$\bar{q}_{\mathrm{n,out}}^{\mathrm{WE}}$	average output molar flow rate of hydrogen of a WE/HTE
$q_{\mathrm{n,out,l}}^{\mathrm{WE}}$	instantaneous output molar flow rate of hydrogen of a WE/HTE
R_{g}	universal gas constant
$s^2\left(P_{\mathrm{el,ac,sys}}\right)$	standard variance of AC electric power of a WE system
$s^2\left(P_{\mathrm{el,ac,sys}}\right)$	standard variance of DC electric power of a WE system
$s^2\left(P_{\mathrm{el,dc,WE}}\right)$	standard variance of DC electric power of a WE/HTE
$s^2\left(p^{\mathrm{j}}\right)$	standard variance of pressure of fluid j
$s^2\left(p_{\mathrm{sys,H_2}}\right)$	standard variance of pressure of hydrogen of a WE system
$s^2\left(p_{\mathrm{WE}}^{\mathrm{j}}\right)$	standard variance of pressure of fluid j of a WE/HTE
$s^2\left(q_{\mathrm{m}}^{\mathrm{i}}\right)$	standard variance of mass flow rate of fluid i
$s^2\left(q_{\mathrm{m,WE}}^{\mathrm{i}}\right)$	standard variance of mass flow rate of fluid j of a WE/HTE
$s^2\left(q_{\mathrm{n}}^{\mathrm{f}}\right)$	standard variance of molar flow rate of fuel
$s^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)$	standard variance of molar flow rate of fluid j
$s^2\left(q_{\mathrm{n,sys,out}}\right)$	standard variance of molar flow rate of hydrogen of a WE system
	standard variance of molar flow rate of fluid j of a WE/HTE
$s^2\left(q_{\mathrm{n,WE,out}}\right)$	standard variance of output molar flow rate of product gas of a WE/HTE
$s_{\mathrm{r}}^2\left(p^{\mathrm{j}}\right)$	relative standard variance of pressure of fluid j
$s_{\mathrm{r}}^2\left(p_{\mathrm{sys,H_2}}\right)$	relative standard variance of pressure of hydrogen of a WE system
$s_{\mathrm{r}}^2\left(p_{\mathrm{WE}}^{\mathrm{j}}\right)$	relative standard variance of pressure of fluid j of a WE/HTE
$s_{\mathrm{r}}^2\left(q_{\mathrm{m}}^{\mathrm{i}}\right)$	relative standard variance of mass flow rate of fluid i
$s_{\mathrm{r}}^2\left(q_{\mathrm{m,WE}}^{\mathrm{i}}\right)$	relative standard variance of mass flow rate of fluid j of a WE/HTE
$s_{\mathrm{r}}^2\left(q_{\mathrm{n}}^{\mathrm{f}}\right)$	relative standard variance of molar flow rate of fuel
$s_{\mathrm{r}}^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)$	relative standard variance of molar flow rate of fluid j
$s_{\mathrm{r}}^2\left(q_{\mathrm{n,sys,out}}\right)$	relative standard variance of output molar flow rate of product gas of a WE system
$s_{\mathrm{r}}^2\left(q_{\mathrm{n,WE}}^{\mathrm{j}}\right)$	relative standard variance of molar flow rate of fluid j of a WE/HTE
$s_{\mathrm{r}}^2\left(q_{\mathrm{n,WE,out}}\right)$	relative standard variance of output molar flow rate of product gas of a WE/HTE
$s_{\mathrm{r}}^2\left(T^{\mathrm{i}}\right)$	relative standard variance of temperature of fluid i
$s_{\mathrm{r}}^2\left(T_{\mathrm{sys,H_2}}\right)$	relative standard variance of temperature of hydrogen of a WE system
$s_{\mathrm{r}}^2\left(T_{\mathrm{WE}}^{\mathrm{i}}\right)$	relative standard variance of temperature of fluid i of a WE/HTE
$s_{\mathrm{r}}^2\left(x_{\mathrm{n,sys,H_2}}\right)$	relative standard variance of molar concentration of hydrogen of a WE system
$s_{\mathrm{r}}^2\left(x_{\mathrm{n,WE,H_2}}\right)$	relative standard variance of molar concentration of hydrogen of a WE/HTE
$s^2\left(T^{\mathrm{i}}\right)$	standard variance of temperature of fluid i
$s^2\left(T_{\mathrm{sys,H_2}}\right)$	standard variance of temperature of hydrogen of a WE system
$s^2\left(T_{\mathrm{WE}}^{\mathrm{i}}\right)$	standard variance of temperature of fluid i of a WE/HTE
$s^2\left(x_{\mathrm{n,sys,H_2}}\right)$	standard variance of molar concentration of hydrogen of a WE system
$s^2\left(x_{\mathrm{n,H_2}}^{\mathrm{WE}}\right)$	standard variance of molar concentration of hydrogen of a WE/HTE
T	temperature
t	time
T^0	standard ambient temperature
T^{f}	temperature of fuel
$T_{\mathrm{H_2}}$	temperature of hydrogen
T^{i}	temperature of fluid i
$\bar{T}^{\mathrm{i}}$	average temperature of fluid i
$T_{\mathrm{l}}^{\mathrm{i}}$	instantaneous temperature of fluid i
T^{j}	temperature of fluid j
$T_{\mathrm{out}}^{\mathrm{O_2}}$	output temperature of oxygen
$T_{\mathrm{WE,out}}^{\mathrm{O_2}}$	output temperature of oxygen of a WE/HTE
$T_{\mathrm{in}}^{\mathrm{sg}}$	input temperature of sweep gas
$T_{\mathrm{out}}^{\mathrm{sg}}$	output temperature of sweep gas

$T^{\mathrm{sg}}_{\mathrm{WE,\,in}}$	input temperature of sweep gas of a WE/HTE
$T^{\mathrm{sg}}_{\mathrm{WE,\,out}}$	output temperature of sweep gas of a WE/HTE
$T_{\mathrm{sys,\,H_2}}$	temperature of hydrogen of a WE system
$\bar{T}_{\mathrm{sys,\,H_2}}$	average temperature of hydrogen of a WE system
$T_{\mathrm{sys,\,H_2,\,l}}$	instantaneous temperature of hydrogen of a WE system
T^{w}	temperature of water
$T_{\mathrm{WE,\,H_2}}$	temperature of hydrogen of a WE/HTE
$T^{\mathrm{i}}_{\mathrm{WE}}$	temperature of fluid i of a WE/HTE
$\bar{T}^{\mathrm{i}}_{\mathrm{WE}}$	average temperature of fluid i of a WE/HTE
$T^{\mathrm{i}}_{\mathrm{WE,\,l}}$	instantaneous temperature of fluid i of a WE/HTE
$T^{\mathrm{j}}_{\mathrm{WE}}$	temperature of fluid j of a WE/HTE
$T^{\mathrm{w}}_{\mathrm{in}}$	input temperature of water
$T^{\mathrm{w}}_{\mathrm{out}}$	output temperature of water
$T^{\mathrm{w}}_{\mathrm{WE,\,in}}$	temperature of water of a WE/HTE
$T^{\mathrm{w}}_{\mathrm{WE,\,out}}$	output temperature of water of a WE/HTE
U	voltage
u	standard uncertainty
s^2	standard variance
u_{c}^2	combined standard variance
$u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,\,sys}}\right)$	combined standard variance of specific energy comsumption related to SATP conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{el,\,sys}}\right)$	combined standard variance of specific electric energy comsumption related to SATP conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,m,\,sys}}\right)$	combined standard variance of specific electric energy consumption per unit mass related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,m,\,WE}}\right)$	combined standard variance of specific electric energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,sys}}\right)$	combined standard variance of specific electric energy consumption related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,n,\,WE}}\right)$	combined standard variance of specific electric energy consumption of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,V,\,sys}}\right)$	combined standard variance of specific electric energy consumption per unit volume related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{el,\,V,\,WE}}\right)$	combined standard variance of specific electric energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,\,m,\,sys}}\right)$	combined standard variance of specific energy consumption per unit mass related to SATP conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,m,\,sys}}\right)$	combined standard variance of specific energy consumption per unit mass related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,m,\,WE}}\right)$	combined standard variance of specific energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,sys}}\right)$	combined standard variance of specific energy consumption related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,n,\,WE}}\right)$	combined standard variance of specific energy consumption of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{e,\,V,\,sys}}\right)$	combined standard variance of specific energy consumption per unit volume related to SATP conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,V,\,sys}}\right)$	combined standard variance of specific energy consumption per unit volume related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{e,\,V,\,WE}}\right)$	combined standard variance of specific energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{0}_{\mathrm{th,\,sys}}\right)$	combined standard variance of specific thermal energy comsumption related to SATP conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{th,\,m,\,sys}}\right)$	combined standard variance of specific thermal energy consumption per unit mass related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{th,\,m,\,WE}}\right)$	combined standard variance of specific thermal energy consumption per unit mass of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^2\left(\varepsilon^{\mathrm{p,\,T}}_{\mathrm{th,\,sys}}\right)$	combined standard variance of specific thermal energy consumption related to hydrogen output conditions

$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,n,WE}}^{\mathrm{p,T}}\right)$	combined standard variance of specific thermal energy consumption of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,V,sys}}^{\mathrm{p,T}}\right)$	combined standard variance of specific thermal energy consumption per unit volume related to hydrogen output conditions
$u_{\mathrm{c}}^{2}\left(\varepsilon_{\mathrm{th,V,WE}}^{\mathrm{p,T}}\right)$	combined standard variance of specific thermal energy consumption per unit volume of a WE/HTE related to hydrogen output conditions
$u_{\mathrm{c}}^{2}\left(\eta_{\mathrm{HHV,el,sys}}^{0}\right)$	combined standard variance of electrical efficiency based on HHV of a WE system related to SATP conditions
$u_{\mathrm{c}}^{2}\left(\eta_{\mathrm{LHV,el,sys}}^{0}\right)$	combined standard variance of electrical efficiency based on LHV of a WE system related to SATP conditions
$u_{\mathrm{c}}^{2}\left(\eta_{\mathrm{HHV,e,sys}}^{0}\right)$	combined standard variance of energy efficiency based on HHV of a WE system related to SATP conditions
$u_{\mathrm{c}}^{2}\left(\eta_{\mathrm{LHV,e,sys}}^{0}\right)$	combined standard variance of energy efficiency based on LHV of a WE system related to SATP conditions
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,sys,in}}\right)$	combined standard variance of input power of compression of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,sys,in,j}}\right)$	combined standard variance of input power of compression of fluid j of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,WE,in}}\right)$	combined standard variance of input power of compression of a WE/HTE
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,WE,in,j}}\right)$	combined standard variance of input power of compression of fluid j of a WE/HTE
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{el,dc,WE}}\right)$	combined standard variance of DC electric power of a WE/HTE
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{el,sys}}\right)$	combined standard variance of electric power of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{sys,in}}\right)$	combined standard variance of input power of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,sys,in}}\right)$	combined standard variance of input thermal power of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,sys,in,i}}\right)$	combined standard variance of input thermal power of fluid i of a WE system
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,WE,in}}\right)$	combined standard variance of input thermal power of a WE/HTE
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,WE,in,i}}\right)$	combined standard variance of input thermal power of fluid i of a WE/HTE
$u_{\mathrm{c}}^{2}\left(P_{\mathrm{WE,in}}\right)$	combined standard variance of input power of a WE/HTE
$u_{\mathrm{c}}^{2}\left(q_{\mathrm{n,sys,out,H_2}}\right)$	combined standard variance of output molar flow rate of hydrogen of a WE system
$u_{\mathrm{c}}^{2}\left(q_{\mathrm{n,WE,H_2}}\right)$	combined standard variance of molar flow rate of hydrogen of a WE/HTE
u_{r}^{2}	relative combined standard variance
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{compr,sys,in}}\right)$	relative standard variance of input power of compression of a WE system
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{el,dc,WE}}\right)$	relative standard variance of DC electric power of a WE/HTE
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{el,sys}}\right)$	relative standard variance of electric power of a WE system
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{sys,in}}\right)$	relative standard variance of input power of a WE system
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{th,sys,in}}\right)$	relative standard variance of input thermal power of a WE system
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{th,WE,in}}\right)$	relative standard variance of input thermal power of a WE/HTE
$u_{\mathrm{r}}^{2}\left(P_{\mathrm{WE,in}}\right)$	relative standard variance of input power of a WE/HTE
$u_{\mathrm{r}}^{2}\left(q_{\mathrm{n,sys,out,H_2}}\right)$	relative standard variance of output molar flow rate of hydrogen of a WE system
U_{ac}	AC voltage
$U_{\mathrm{ac,sys}}$	AC voltage of a WE system
u_{c}	combined standard uncertainty
U_{dc}	DC voltage
	DC voltage of a WE/HTE
$U_{\mathrm{dc,sys}}$	DC voltage of a WE system
u_{r}	relative standard uncertainty
U_{stack}	stack voltage
V	volume
V_{m}	molar volume
$V_{\mathrm{m,H_2}}$	molar volume of hydrogen
$V_{\mathrm{m}}^{\mathrm{j}}$	molar volume of fluid j
$x_{\mathrm{n,H_2}}$	molar concentration of hydrogen
$x_{\mathrm{n,sys,H_2}}$	molar concentration of hydrogen of a WE system
$\bar{x}_{\mathrm{n,sys,H_2}}$	average molar concentration of hydrogen of a WE system
$x_{\mathrm{n,sys,H_2},l}$	instantaneous molar concentration of hydrogen of a WE system
$x_{\mathrm{n,H_2}}^{\mathrm{WE}}$	molar concentration of hydrogen of a WE/HTE
$\bar{x}_{\mathrm{n,H_2}}^{\mathrm{WE}}$	average molar concentration of hydrogen of a WE/HTE
$x_{\mathrm{n,H_2,l}}^{\mathrm{WE}}$	instantaneous molar concentration of hydrogen of a WE/HTE
$\bar{Z}$	average compressibility factor
$\bar{Z}^{\mathrm{j}}$	average compressibility factor of fluid j

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Annex A Test data post-processing

A.1 General

Calculations may readily be accomplished using spreadsheet software. The use of symbols for given parameters does not distinguish between SATP conditions and hydrogen output conditions except for the specific energy consumption, the specific electric energy consumption and the specific thermal energy consumption.

A.2 Instantaneous values of test parameters

A.2.1 General

Instantaneous values of test parameters whether measured or calculated are denoted by subscript $_\mathrm{l}$.

A.2.2 WE system tested under SATP conditions

The instantaneous values of the specific energy consumption per mole of hydrogen ($\varepsilon^0_\mathrm{e,\,n,\,sys}$), $\varepsilon^0_\mathrm{e,\,n,\,sys,\,l}$, see equation (3.2.1a), the specific electric energy consumption per mole of hydrogen ($\varepsilon^0_\mathrm{el,\,n,\,sys}$), $\varepsilon^0_\mathrm{el,\,n,\,sys,\,l}$, see equation (3.2.9) and the specific thermal energy consumption per mole of hydrogen ($\varepsilon^0_\mathrm{th,\,n,\,sys}$), $\varepsilon^0_\mathrm{th,\,n,\,sys,\,l}$, see equation (3.2.10), are respectively calculated as

$$\varepsilon^0_\mathrm{e,\,n,\,sys,\,l}\ \text{(kWh/mol)} \;=\; \frac{P_\mathrm{sys,\,in,\,l}\ \text{(kW)}}{q_\mathrm{n,\,sys,\,out,\,H_2,\,l}\ \text{(mol/h)}}, \tag{A.2.1a}$$

$$\varepsilon^0_\mathrm{el,\,n,\,sys,\,l}\ \text{(kWh/mol)} \;=\; \frac{P_\mathrm{el,\,sys,\,l}\ \text{(kW)}}{q_\mathrm{n,\,sys,\,out,\,H_2,\,l}\ \text{(mol/h)}} \quad \text{and} \tag{A.2.1b}$$

$$\varepsilon^0_\mathrm{th,\,n,\,sys,\,l}\ \text{(kWh/mol)} \;=\; \frac{P_\mathrm{th,\,sys,\,in,\,l}\ \text{(kW)}}{q_\mathrm{n,\,sys,\,out,\,H_2,\,l}\ \text{(mol/h)}}; \tag{A.2.1c}$$

$P_\mathrm{sys,\,in,\,l}$, $q_\mathrm{n,\,sys,\,out,\,H_2,\,l}$, $P_\mathrm{el,\,sys,\,l}$ and $P_\mathrm{th,\,sys,\,in,\,l}$ are respectively given by equation (A.2.1d), equation (A.2.1k), equation (A.2.1e) and equation (A.2.1f). The instantaneous value of the input power ($P_\mathrm{sys,\,in}$), $P_\mathrm{sys,\,in,\,l}$, is calculated as

$$P_\mathrm{sys,\,in,\,l}\ \text{(kW)} \;=\; P_\mathrm{el,\,sys,\,l}\ \text{(kW)} + P_\mathrm{th,\,sys,\,in,\,l}\ \text{(kW)} + P_\mathrm{compr,\,sys,\,in,\,l}\ \text{(kW)}; \tag{A.2.1d}$$

$P_\mathrm{el,\,sys,\,l}$, $P_\mathrm{th,\,sys,\,in,\,l}$ and $P_\mathrm{compr,\,sys,\,in,\,l}$ are respectively given by equation (A.2.1e), equation (A.2.1f) and equation (A.2.1g). The instantaneous value of the input electric power ($P_\mathrm{el,\,sys}$), $P_\mathrm{el,\,sys,\,l}$, is calculated as

$$P_\mathrm{el,\,sys,\,l}\ \text{(kW)} \;=\; P_\mathrm{el,\,ac,\,sys,\,l}\ \text{(kW)} + P_\mathrm{el,\,dc,\,sys,\,l}\ \text{(kW)}; \tag{A.2.1e}$$

$P_\mathrm{el,\,ac,\,sys,\,l}$ and $P_\mathrm{el,\,dc,\,sys,\,l}$ are the measured values of respectively the AC electric power ($P_\mathrm{el,\,ac,\,sys}$) and DC electric power ($P_\mathrm{el,\,dc,\,sys}$). The instantaneous value of the input thermal power ($P_\mathrm{th,\,sys,\,in,\,l}$), $P_\mathrm{th,\,sys,\,in,\,l}$, is calculated as

$$P_\mathrm{th,\,sys,\,in,\,l}\ \text{(kW)} \;=\; \mathrm{HHV}^\mathrm{f}\ \text{(kWh/mol)} \cdot q^\mathrm{f}_\mathrm{n,\,l}\ \text{(mol/h)} + \sum_\mathrm{i} P_\mathrm{th,\,sys,\,in,\,i,\,l}\ \text{(kW)}; \tag{A.2.1f}$$

$q^\mathrm{f}_\mathrm{n,\,l}$ is the measured value of the molar flow rate of fuel while $P_\mathrm{th,\,sys,\,in,\,i,\,l}$ is given by equation (A.2.1h). The instantaneous value of the input power of compression ($P_\mathrm{compr,\,sys,\,in}$), $P_\mathrm{compr,\,sys,\,in,\,l}$, is calculated as

$$P_\mathrm{compr,\,sys,\,in,\,l}\ \text{(kW)} \;=\; \sum_\mathrm{j} P_\mathrm{compr,\,sys,\,in,\,j,\,l}\ \text{(kW)}; \tag{A.2.1g}$$

$P_\mathrm{compr,\,sys,\,in,\,j,\,l}$ is given for incompressible and compressible fluid j by respectively equation (A.2.1i) and equation (A.2.1j). Note, the summation (A.2.1g) applies jointly to both type of fluids. The instantaneous value of the input thermal power of fluid i ($P_\mathrm{th,\,sys,\,in,\,i}$), $P_\mathrm{th,\,sys,\,in,\,i,\,l}$, is calculated as

$$P_\mathrm{th,\,sys,\,in,\,i,\,l}\ \text{(kW)} \;=\; q^\mathrm{i}_\mathrm{m,\,l}\ \text{(kg/s)} \cdot c^\mathrm{i}_\mathrm{p}\ \text{(kJ/(kg K))} \cdot \left(T^\mathrm{i}_\mathrm{l}\ \text{(K)} - T^0\ \text{(K)}\right); \tag{A.2.1h}$$

$q^\mathrm{i}_\mathrm{m,\,l}$ and T^i_l are the measured values of respectively the mass flow rate and temperature of fluid i. For the incompressible case, the instantaneous value of the input power of compression of fluid j ($P_\mathrm{compr,\,sys,\,in,\,j}$), $P_\mathrm{compr,\,sys,\,in,\,j,\,l}$, is calculated as

$$P_\mathrm{compr,\,sys,\,in,\,j,\,l}\ \text{(kW)} \;=\; \left(p^\mathrm{j}_\mathrm{l}\ \text{(kPa)} - p^0\ \text{(kPa)}\right) \cdot \frac{V^\mathrm{j}_\mathrm{m}\ (\mathrm{m^3/mol})}{3600\ \text{(s/h)}} \cdot q^\mathrm{j}_\mathrm{n,\,l}\ \text{(mol/h)}; \tag{A.2.1i}$$

$p^{\mathrm{j}}_{\mathrm{l}}$ and $q^{\mathrm{j}}_{\mathrm{n,l}}$ are the measured values of respectively the pressure and molar flow rate of fluid j. For the compressible case, the instantaneous value of the input power of compression of fluid j ($P_{\text{compr, sys, in, j}}$), $P_{\text{compr, sys, in, j, l}}$, is calculated as

$$P_{\text{compr, sys, in, j, l}}\ (\text{kW}) \;=\; \left(\frac{\gamma^{\mathrm{j}}}{\gamma^{\mathrm{j}}-1}\right) \frac{\bar{Z}^{\mathrm{j}} \cdot R_{\mathrm{g}}\ (\text{kJ/(mol K)}) \cdot T^{0}\ (\text{K}) \cdot q^{\mathrm{j}}_{\mathrm{n,l}}\ (\text{mol/h})}{3600\ (\text{s/h})} \left(\left(\frac{p^{\mathrm{j}}_{\mathrm{l}}\ (\text{kPa})}{p^{0}\ (\text{kPa})}\right)^{\frac{\gamma^{\mathrm{j}}-1}{\gamma^{\mathrm{j}}}} - 1\right). \quad \text{(A.2.1j)}$$

The instantaneous value of the molar flow rate of hydrogen ($q_{\text{n, sys, out, H}_2}$), $q_{\text{n, sys, out, H}_2\text{, l}}$, is calculated as

$$q_{\text{n, sys, out, H}_2\text{, l}}\ (\text{mol/h}) \;=\; x_{\text{n, sys, H}_2,\, l}\ (\text{mol/mol}) \cdot q_{\text{n, sys, out, l}}\ (\text{mol/h}); \quad \text{(A.2.1k)}$$

$x_{\text{n, sys, H}_2,\, l}$ and $q_{\text{n, sys, out, l}}$ are the measured values of respectively the molar concentration of hydrogen and product gas molar flow rate.

The instantaneous values of the energy efficiency based on HHV ($\eta^{0}_{\text{HHV, e, sys}}$), $\eta^{0}_{\text{HHV, e, sys, l}}$ and LHV of hydrogen ($\eta^{0}_{\text{LHV, e, sys}}$), $\eta^{0}_{\text{LHV, e, sys, l}}$, see equation (3.2.11), are respectively calculated as

$$\eta^{0}_{\text{HHV, e, sys, l}}\ (\%) \;=\; \frac{\text{HHV}_{\text{H}_2}\ (\text{kWh/mol})}{\varepsilon^{0}_{\text{e, n, sys, l}}\ (\text{kWh/mol})} \cdot 100\ \% \ \text{ and} \quad \text{(A.2.2a)}$$

$$\eta^{0}_{\text{LHV, e, sys, l}}\ (\%) \;=\; \frac{\text{LHV}_{\text{H}_2}\ (\text{kWh/mol})}{\varepsilon^{0}_{\text{e, n, sys, l}}\ (\text{kWh/mol})} \cdot 100\ \% \quad \text{(A.2.2b)}$$

$\varepsilon^{0}_{\text{e, n, sys, l}}$ is given by equation (A.2.1a).

The instantaneous values of the electrical efficiency based on HHV of a WE system ($\eta^{0}_{\text{HHV, el, sys}}$), $\eta^{0}_{\text{HHV, el, sys, l}}$ and LHV of hydrogen ($\eta^{0}_{\text{LHV, el, sys}}$), $\eta^{0}_{\text{LHV, el, sys, l}}$, see equation (3.2.12), are respectively calculated as

$$\eta^{0}_{\text{HHV, el, sys, l}}\ (\%) \;=\; \frac{\text{HHV}_{\text{H}_2}\ (\text{kWh/mol})}{\varepsilon^{0}_{\text{el, n, sys, l}}\ (\text{kWh/mol})} \cdot 100\ \% \;\approx\; 1,18 \cdot \eta^{0}_{\text{LHV, el, sys, l}}\ (\%) \ \text{ and} \quad \text{(A.2.3a)}$$

$$\eta^{0}_{\text{LHV, el, sys, l}}\ (\%) \;=\; \frac{\text{LHV}_{\text{H}_2}\ (\text{kWh/mol})}{\varepsilon^{0}_{\text{el, n, sys, l}}\ (\text{kWh/mol})} \cdot 100\ \% \;\approx\; 0,85 \cdot \eta^{0}_{\text{HHV, el, sys, l}}\ (\%); \quad \text{(A.2.3b)}$$

$\varepsilon^{0}_{\text{el, n, sys, l}}$ is given by equation (A.2.1b).

A.2.3 WE system tested under hydrogen output conditions

The instantaneous value of the specific energy consumption per mole of hydrogen ($\varepsilon^{\text{p, T}}_{\text{e, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{e, n, sys, l}}$, see equation (3.3.1a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{e, n, sys, l}}\ (\text{kWh/mol}) \;=\; \frac{P_{\text{sys, in, l}}\ (\text{kW})}{q_{\text{n, sys, out, H}_2\text{, l}}\ (\text{mol/h})}; \quad \text{(A.2.4a)}$$

$P_{\text{sys, in, l}}$ and $q_{\text{n, sys, out, H}_2\text{, l}}$ are respectively given by equation (A.2.1d) and equation (A.2.1k). The instantaneous value of the specific electric energy consumption per mole of hydrogen ($\varepsilon^{\text{p, T}}_{\text{el, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{el, sys, l}}$, see equation (3.3.2a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{el, sys, l}}\ (\text{kWh/mol}) \;=\; \frac{P_{\text{el, sys, l}}\ (\text{kW})}{q_{\text{n, sys, out, H}_2\text{, l}}\ (\text{mol/h})}; \quad \text{(A.2.4b)}$$

$P_{\text{el, sys, l}}$ and $q_{\text{n, sys, out, H}_2\text{, l}}$ are respectively given by equation (A.2.1e) and equation (A.2.1k). The instantaneous value of the specific thermal energy consumption per mole of hydrogen ($\varepsilon^{\text{p, T}}_{\text{th, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{th, n, sys, l}}$, see equation (3.3.3a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{th, n, sys, l}}\ (\text{kWh/mol}) \;=\; \frac{P_{\text{th, sys, in, l}}\ (\text{kW})}{q_{\text{n, sys, out, H}_2\text{, l}}\ (\text{mol/h})}; \quad \text{(A.2.4c)}$$

$P_{\text{th, sys, in, l}}$ and $q_{\text{n, sys, out, H}_2\text{, l}}$ are respectively given by equation (A.2.1f) and equation (A.2.1k).

A.2.4 WE/HTE tested under hydrogen output conditions

The instantaneous value of the specific energy consumption per mole of hydrogen ($\varepsilon^{0}_{\text{e, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{e, n, WE}}$, see equation (3.4.1a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{e, n, WE, l}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{WE, in, l}}\ \text{(kW)}}{q^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/h)}} \tag{A.2.5a}$$

$P_{\text{WE, in, l}}$ is given by equation (A.2.5d) and $q^{\text{WE}}_{\text{n, H}_2\text{, l}}$ is given by equation (A.2.5j). The instantaneous value of the specific electric energy consumption per mole of hydrogen ($\varepsilon^{0}_{\text{el, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{el, n, sys}}$, see equation (3.4.4a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{el, n, WE, l}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{el, dc, WE, l}}\ \text{(kW)}}{q^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/h)}}; \tag{A.2.5b}$$

$P_{\text{el, dc, WE, l}}$ is the measured value of the DC electric power ($P_{\text{el, dc, WE}}$) and $q^{\text{WE}}_{\text{n, H}_2\text{, l}}$ is given by equation (A.2.5j). The instantaneous value of the specific thermal energy consumption per mole of hydrogen ($\varepsilon^{0}_{\text{th, n, sys}}$), $\varepsilon^{\text{p, T}}_{\text{th, n, WE}}$, see equation (3.4.5a), is calculated as

$$\varepsilon^{\text{p, T}}_{\text{th, n, WE, l}}\ \text{(kWh/mol)} \ = \ \frac{P_{\text{th, WE, in, l}}\ \text{(kW)}}{q^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/h)}}; \tag{A.2.5c}$$

$P_{\text{th, WE, in, l}}$ is given by equation (A.2.5e) and $q^{\text{WE}}_{\text{n, H}_2\text{, l}}$ is given by equation (A.2.5j). The instantaneous value of the input power ($P_{\text{WE, in}}$), $P_{\text{compr, WE, in, l}}$, is calculated as

$$P_{\text{WE, in, l}}\ \text{(kW)} \ = \ P_{\text{el, dc, WE, l}}\ \text{(kW)} + P_{\text{th, WE, in, l}}\ \text{(kW)} + P_{\text{compr, WE, in, l}}\ \text{(kW)}; \tag{A.2.5d}$$

$P_{\text{el, dc, WE, l}}$ is the measured value of the DC electric power ($P_{\text{el, dc, WE}}$) while $P_{\text{th, WE, in, l}}$ and $P_{\text{compr, WE, in, l}}$ are respectively given by equation (A.2.5e) and equation (A.2.5f). The instantaneous value of the input thermal power ($P_{\text{th, WE, in}}$), $P_{\text{th, WE, in, l}}$, is calculated as

$$P_{\text{th, WE, in, l}}\ \text{(kW)} \ = \ \sum_{\text{i}} P_{\text{th, WE, in, i, l}}\ \text{(kW)}; \tag{A.2.5e}$$

$P_{\text{th, WE, in, i, l}}$ is given by equation (A.2.5g). The instantaneous value of the input power of compression ($P_{\text{compr, WE, in}}$), $P_{\text{compr, WE, in, l}}$, is calculated as

$$P_{\text{compr, WE, in, l}}\ \text{(kW)} \ = \ \sum_{\text{j}} P_{\text{compr, WE, in, j, l}}\ \text{(kW)}; \tag{A.2.5f}$$

$P_{\text{compr, WE, in, j, l}}$ is given for incompressible and compressible fluid j by respectively equation (A.2.5h) and equation (A.2.5i). Note, the summation (A.2.5f) applies jointly to both type of fluids. The instantaneous value of the input thermal power of fluid i ($P_{\text{th, WE, in, i}}$), $P_{\text{th, WE, in, i, l}}$, is calculated as

$$P_{\text{th, WE, in, i, l}}\ \text{(kW)} \ = \ q^{\text{i}}_{\text{m, WE, l}}\ \text{(kg/s)} \cdot c^{\text{i}}_{\text{p}}\ \text{(kJ/(kg K))} \cdot \left(T^{\text{i}}_{\text{WE, l}}\ \text{(K)} - T^{0}\ \text{(K)}\right); \tag{A.2.5g}$$

$q^{\text{i}}_{\text{m, WE, l}}$ and $T^{\text{i}}_{\text{WE, l}}$ are the measured values of respectively the mass flow rate and temperature of fluid i. For the incompressible case, the instantaneous value of the input power of compression of fluid j ($P_{\text{compr, WE, in, j}}$), $P_{\text{compr, WE, in, j, l}}$, is calculated as

$$P_{\text{compr, WE, in, j, l}}\ \text{(kW)} \ = \ \left(p^{\text{j}}_{\text{WE, l}}\ \text{(kPa)} - p^{0}\ \text{(kPa)}\right) \cdot \frac{V^{\text{j}}_{\text{m}}\ \text{(m}^3\text{/mol)}}{3600\ \text{(s/h)}} \cdot q^{\text{j}}_{\text{n, WE, l}}\ \text{(mol/h)}; \tag{A.2.5h}$$

$p^{\text{j}}_{\text{WE, l}}$ and $q^{\text{j}}_{\text{n, WE, l}}$ are the measured values of respectively the pressure and molar flow rate of fluid j. For the compressible case, the instantaneous value of the input power of compression of fluid j ($P_{\text{compr, WE, in, j}}$), $P_{\text{compr, WE, in, j, l}}$, is calculated as

$$P_{\text{compr, WE, in, j, l}}\ \text{(kW)} \ = \ \left(\frac{\gamma^{\text{j}}}{\gamma^{\text{j}} - 1}\right) \frac{\bar{Z}^{\text{j}} \cdot R_{\text{g}}\ \text{(kJ/(mol K))} \cdot T^{0}\ \text{(K)} \cdot q^{\text{j}}_{\text{n, WE, l}}\ \text{(mol/h)}}{3600\ \text{(s/h)}} \left(\left(\frac{p^{\text{j}}_{\text{WE, l}}\ \text{(kPa)}}{p^{0}\ \text{(kPa)}}\right)^{\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}} - 1\right). \tag{A.2.5i}$$

The instantaneous value of the molar flow rate of hydrogen ($q^{\text{WE}}_{\text{n, H}_2}$), $q^{\text{WE}}_{\text{n, H}_2\text{, l}}$, is calculated as

$$q^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/h)} \ = \ x^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/mol)} \cdot q^{\text{WE}}_{\text{n, out, l}}\ \text{(mol/h)}; \tag{A.2.5j}$$

$x^{\text{WE}}_{\text{n, H}_2\text{, l}}$ and $q^{\text{WE}}_{\text{n, out, l}}$ are the measured values of respectively the molar concentration of hydrogen and product gas molar flow rate.

A.3 Mean values of test parameters

A.3.1 General

Average values (arithmetic means) of test parameters are denoted by overhead ¯. Pseudo-averages of test parameters are denoted either by underline _ or overhead ˜.

A.3.2 WE system tested under SATP conditions

The average of the input power of a WE system to the tested WE system ($P_{\text{sys, in}}$), $\bar{P}_{\text{sys, in}}$, see equation (3.2.2), is calculated as

$$\bar{P}_{\text{sys, in}}\ (\text{kW}) \ = \ \bar{P}_{\text{el, sys}}\ (\text{kW}) + \bar{P}_{\text{th, sys, in}}\ (\text{kW}) + \bar{P}_{\text{compr, sys, in}}\ (\text{kW}); \tag{A.3.1a}$$

$\bar{P}_{\text{el, sys}}$, $\bar{P}_{\text{th, sys, in}}$ and $\bar{P}_{\text{compr, sys, in}}$ are respectively given by equation (A.3.1b), equation (A.3.1e) and equation (A.3.1f). The average of the input electric power ($P_{\text{el, sys}}$), $\bar{P}_{\text{el, sys}}$, is calculated as

$$\bar{P}_{\text{el, sys}}\ (\text{kW}) \ = \ \bar{P}_{\text{el, ac, sys}}\ (\text{kW}) + \bar{P}_{\text{el, dc, sys}}\ (\text{kW}); \tag{A.3.1b}$$

$\bar{P}_{\text{el, ac, sys}}$ and $\bar{P}_{\text{el, dc, sys}}$ are respectively given by equation (A.3.1c) and equation (A.3.1d). The averages of the AC electric power ($P_{\text{el, ac, sys}}$), $\bar{P}_{\text{el, ac, sys}}$ and DC electric power ($P_{\text{el, dc, sys}}$), $\bar{P}_{\text{el, dc, sys}}$, are respectively calculated as

$$\bar{P}_{\text{el, ac, sys}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{el, ac, sys, l}}\ (\text{kW}) \ \text{ and} \tag{A.3.1c}$$

$$\bar{P}_{\text{el, dc, sys}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{el, dc, sys, l}}\ (\text{kW}); \tag{A.3.1d}$$

$P_{\text{el, ac, sys, l}}$ and $P_{\text{el, dc, sys, l}}$ are the measured values of respectively the AC electric power and DC electric power. The average of the input thermal power ($P_{\text{th, sys, in}}$), $\bar{P}_{\text{th, sys, in}}$ is calculated as

$$\bar{P}_{\text{th, sys, in}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} \left(\text{HHV}^{\text{f}}\ (\text{kWh/mol}) \cdot q^{\text{f}}_{\text{n, l}}\ (\text{mol/h}) + \sum_{\text{i}} P_{\text{th, sys, in, i, l}}\ (\text{kW}) \right); \tag{A.3.1e}$$

$q^{\text{f}}_{\text{n, l}}$ is the measured value of the molar flow rate of fuel while $P_{\text{th, sys, in, i, l}}$ is given by equation (A.2.1h). The average of the input power of compression ($P_{\text{compr, sys, in}}$), $\bar{P}_{\text{compr, sys, in}}$ is calculated as

$$\bar{P}_{\text{compr, sys, in}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} \left(\sum_{\text{j}} P_{\text{compr, sys, in, j, l}}\ (\text{kW}) \right); \tag{A.3.1f}$$

$P_{\text{compr, sys, in, j, l}}$ is given for incompressible and compressible fluid j by respectively equation (A.2.1i) and equation (A.2.1j). Note, the summation (A.3.1f) applies jointly to both type of fluids. The averages of the input thermal power of fluid i ($P_{\text{th, sys, in, i}}$), $\bar{P}_{\text{th, sys, in, i}}$ and input power of compression of fluid j ($P_{\text{compr, sys, in, j}}$), $\bar{P}_{\text{compr, sys, in, j}}$, are respectively calculated as

$$\bar{P}_{\text{th, sys, in, i}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{th, sys, in, i, l}}\ (\text{kW}) \ \text{ and} \tag{A.3.1g}$$

$$\bar{P}_{\text{compr, sys, in, j}}\ (\text{kW}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{compr, sys, in, j, l}}\ (\text{kW}); \tag{A.3.1h}$$

$P_{\text{th, sys, in, i, l}}$ is given by equation (A.2.1h) and $P_{\text{compr, sys, in, j, l}}$ is given for incompressible and compressible fluid j by respectively equation (A.2.1i) and equation (A.2.1j). The average of the molar flow rate of fuel (q^{f}_{n}), $\bar{q}^{\text{f}}_{\text{n}}$, is calculated as

$$\bar{q}^{\text{f}}_{\text{n}}\ (\text{mol/h}) \ = \ \frac{1}{L}\sum_{\text{l=1}}^{L} q^{\text{f}}_{\text{n, l}}\ (\text{mol/h}); \tag{A.3.1i}$$

$q^{\mathrm{f}}_{\mathrm{n,l}}$ is the measured value of the molar flow rate of fuel. The averages of the mass flow rate ($q^{\mathrm{i}}_{\mathrm{m}}$), $\bar{q}^{\mathrm{i}}_{\mathrm{m}}$ and temperature of fluid i (T^{i}), $\bar{T}^{\mathrm{i}}$, are respectively calculated as

$$\bar{q}^{\mathrm{i}}_{\mathrm{m}}\ \text{(kg/s)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} q^{\mathrm{i}}_{\mathrm{m,l}}\ \text{(kg/s)} \ \text{ and} \tag{A.3.1j}$$

$$\bar{T}^{\mathrm{i}}\ \text{(K)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} T^{\mathrm{i}}_{\mathrm{l}}\ \text{(K);} \tag{A.3.1k}$$

$q^{\mathrm{i}}_{\mathrm{m,l}}$ and $T^{\mathrm{i}}_{\mathrm{l}}$ are the measured values of respectively the mass flow rate and temperature of fluid i. The averages of the pressure ($p_{\mathrm{sys,H_2}}$), $\bar{p}_{\mathrm{sys,H_2}}$ and temperature of hydrogen ($T_{\mathrm{sys,H_2}}$), $\bar{T}_{\mathrm{sys,H_2}}$, are respectively calculated as

$$\bar{p}_{\mathrm{sys,H_2}}\ \text{(kPa)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} p_{\mathrm{sys,H_2,l}}\ \text{(kPa)} \ \text{ and} \tag{A.3.1l}$$

$$\bar{T}_{\mathrm{sys,H_2}}\ \text{(K)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} T_{\mathrm{sys,H_2,l}}\ \text{(K);} \tag{A.3.1m}$$

$p_{\mathrm{sys,H_2,l}}$ and $T_{\mathrm{sys,H_2,l}}$ are the measured values of respectively the pressure and temperature of hydrogen. The averages of the pressure (p^{j}), $\bar{p}^{\mathrm{j}}$ and molar flow rate of fluid j ($q^{\mathrm{j}}_{\mathrm{n}}$), $\bar{q}^{\mathrm{j}}_{\mathrm{n}}$, are respectively calculated as

$$\bar{p}^{\mathrm{j}}\ \text{(kPa)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} p^{\mathrm{j}}_{\mathrm{l}}\ \text{(kPa)} \ \text{ and} \tag{A.3.1n}$$

$$\bar{q}^{\mathrm{j}}_{\mathrm{n}}\ \text{(mol/h)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} q^{\mathrm{j}}_{\mathrm{n,l}}\ \text{(mol/h);} \tag{A.3.1o}$$

$p^{\mathrm{j}}_{\mathrm{l}}$ and $q^{\mathrm{j}}_{\mathrm{n,l}}$ are the measured values of respectively the pressure and molar flow rate of fluid j. The averages of the molar flow rate of hydrogen ($q_{\mathrm{n,sys,out,H_2}}$), $\bar{q}_{\mathrm{n,sys,out,H_2}}$, molar concentration of hydrogen ($x_{\mathrm{n,H_2}}$), $\bar{x}_{\mathrm{n,sys,H_2}}$ and product gas molar flow rate ($q_{\mathrm{n,sys,out}}$), $\bar{q}_{\mathrm{n,sys,out}}$, are respectively calculated as

$$\bar{q}_{\mathrm{n,sys,out,H_2}}\ \text{(mol/h)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} x_{\mathrm{n,sys,H_2},\,l}\ \text{(mol/mol)} \cdot q_{\mathrm{n,sys,out,l}}\ \text{(mol/h),} \tag{A.3.1p}$$

$$\bar{x}_{\mathrm{n,sys,H_2}}\ \text{(mol/h)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} x_{\mathrm{n,sys,H_2},\,l}\ \text{(mol/mol)} \ \text{ and} \tag{A.3.1q}$$

$$\bar{q}_{\mathrm{n,sys,out}}\ \text{(mol/h)} \ = \ \frac{1}{L}\sum_{\mathrm{l}=1}^{L} q_{\mathrm{n,sys,out,l}}\ \text{(mol/h);} \tag{A.3.1r}$$

$x_{\mathrm{n,sys,H_2},\,l}$ and $q_{\mathrm{n,sys,out,l}}$ are the measured values of respectively the molar concentration of hydrogen and product gas molar flow rate.

Two different pseudo-averages of the specific energy consumption per mole of hydrogen ($\varepsilon^{0}_{\mathrm{e,n,sys}}$), $\underline{\varepsilon}^{0}_{\mathrm{e,n,sys}}$ and $\tilde{\varepsilon}^{0}_{\mathrm{e,n,sys}}$, are respectively calculated as

$$\underline{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ \text{(kWh/mol)} \ = \ \frac{\bar{P}_{\mathrm{sys,in}}\ \text{(kW)}}{\underline{q}_{\mathrm{n,sys,out,H_2}}\ \text{(mol/h)}} \ \text{ and} \tag{A.3.2a}$$

$$\tilde{\varepsilon}^{0}_{\mathrm{e,n,sys}}\ \text{(kWh/mol)} \ = \ \frac{\bar{P}_{\mathrm{sys,in}}\ \text{(kW)}}{\bar{q}_{\mathrm{n,sys,out,H_2}}\ \text{(mol/h)}}; \tag{A.3.2b}$$

$\bar{P}_{\text{sys, in}}$, $\underline{q}_{\text{n, sys, out, H}_2}$ and $\bar{q}_{\text{n, sys, out, H}_2}$ are respectively given by equation (A.3.1a), equation (A.3.2k) and equation (A.3.1p). Accordingly, two different pseudo-averages of the energy efficiency based on HHV of hydrogen ($\eta^0_{\text{HHV, e}}$), $\underline{\eta}^0_{\text{HHV, e, sys}}$ and $\tilde{\eta}^0_{\text{HHV, e, sys}}$, are respectively calculated as

$$\underline{\eta}^0_{\text{HHV, e, sys}}\ (\%) \;=\; \frac{\text{HHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\underline{\varepsilon}^0_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%\ \text{ and} \tag{A.3.2c}$$

$$\tilde{\eta}^0_{\text{HHV, e, sys}}\ (\%) \;=\; \frac{\text{HHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\tilde{\varepsilon}^0_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%; \tag{A.3.2d}$$

$\underline{\varepsilon}^0_{\text{e, n, sys}}$ and $\tilde{\varepsilon}^0_{\text{e, n, sys}}$ are respectively given by equation (A.3.2a) and equation (A.3.2b). Correspondingly, two different pseudo-averages of the energy efficiency based on LHV of hydrogen ($\eta^0_{\text{LHV, e}}$), $\underline{\eta}^0_{\text{LHV, e, sys}}$ and $\tilde{\eta}^0_{\text{LHV, e, sys}}$, are respectively calculated as

$$\underline{\eta}^0_{\text{LHV, e, sys}}\ (\%) \;=\; \frac{\text{LHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\underline{\varepsilon}^0_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%\ \text{ and} \tag{A.3.2e}$$

$$\tilde{\eta}^0_{\text{LHV, e, sys}}\ (\%) \;=\; \frac{\text{LHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\tilde{\varepsilon}^0_{\text{e, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%; \tag{A.3.2f}$$

$\underline{\varepsilon}^0_{\text{e, n, sys}}$ and $\tilde{\varepsilon}^0_{\text{e, n, sys}}$ are respectively given by equation (A.3.2a) and equation (A.3.2b). The pseudo-average of the input thermal power of fluid i ($P_{\text{th, sys, in, i}}$), $\underline{P}_{\text{th, sys, in, i}}$, is calculated as

$$\underline{P}_{\text{th, sys, in, i}}\ \text{(kW)} \;=\; \bar{q}^{\text{i}}_{\text{m}}\ \text{(kg/s)} \cdot c^{\text{i}}_{\text{p}}\ \text{(kJ/(kg K))} \cdot \left(\bar{T}^{\text{i}}\ \text{(K)} - T^0\ \text{(K)}\right); \tag{A.3.2g}$$

$\bar{q}^{\text{i}}_{\text{m}}$ and $\bar{T}^{\text{i}}$ are respectively given by equation (A.3.1j) and equation (A.3.1k). For the incompressible case, the pseudo-average of the input power of compression of fluid j ($P_{\text{compr, sys, in, j}}$), $\underline{P}_{\text{compr, sys, in, j}}$, is calculated as

$$\underline{P}_{\text{compr, sys, in, j}}\ \text{(kW)} \;=\; \left(\bar{p}^{\text{j}}\ \text{(kPa)} - p^0\ \text{(kPa)}\right) \cdot \frac{V^{\text{j}}_{\text{m}}\ (\text{m}^3\text{/mol})}{3600\ \text{(s/h)}} \cdot \bar{q}^{\text{j}}_{\text{n}}\ \text{(mol/h)}; \tag{A.3.2h}$$

$\bar{p}^{\text{j}}$ and $\bar{q}^{\text{j}}_{\text{n}}$ are respectively given by equation (A.3.1n) and equation (A.3.1o). For the compressible case, the pseudo-average of the input power of compression of fluid j ($P_{\text{compr, sys, in, j}}$), $\underline{P}_{\text{compr, sys, in, j}}$, is calculated as

$$\underline{P}_{\text{compr, sys, in, j}}\ \text{(kW)} \;=\; \left(\frac{\gamma^{\text{j}}}{\gamma^{\text{j}} - 1}\right) \frac{\bar{Z}^{\text{j}} \cdot R_{\text{g}}\ \text{(kJ/(mol K))} \cdot T^0\ \text{(K)} \cdot \bar{q}^{\text{j}}_{\text{n}}\ \text{(mol/h)}}{3600\ \text{(s/h)}} \left(\left(\frac{\bar{p}^{\text{j}}\ \text{(kPa)}}{p^0\ \text{(kPa)}}\right)^{\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}} - 1\right). \tag{A.3.2i}$$

The pseudo-averages of the molar flow rate of fuel (q^{f}_{n}), $\underline{q}^{\text{f}}_{\text{n}}$ and hydrogen ($q_{\text{n, sys, out, H}_2}$), $\underline{q}_{\text{n, sys, out, H}_2}$, are respectively calculated as

$$\underline{q}^{\text{f}}_{\text{n}}\ \text{(mol/h)} \;=\; \text{HHV}^{\text{f}}\ \text{(kWh/mol)} \cdot \bar{q}^{\text{f}}_{\text{n}}\ \text{(mol/h)}\ \text{ and} \tag{A.3.2j}$$

$$\underline{q}_{\text{n, sys, out, H}_2}\ \text{(mol/h)} \;=\; \bar{x}_{\text{n, sys, H}_2}\ \text{(mol/mol)} \cdot \bar{q}_{\text{n, sys, out}}\ \text{(mol/h)}; \tag{A.3.2k}$$

$\bar{q}^{\text{f}}_{\text{n}}$, $\bar{x}_{\text{n, sys, H}_2}$ and $\bar{q}_{\text{n, sys, out}}$ are respectively given by equation (A.3.1i), equation (A.3.1q) and equation (A.3.1r).

Two different pseudo-averages of the specific electric energy consumption per mole of hydrogen ($\varepsilon^0_{\text{el, n, sys}}$), $\underline{\varepsilon}^0_{\text{el, n, sys}}$ and $\tilde{\varepsilon}^0_{\text{el, n, sys}}$, are respectively calculated as

$$\underline{\varepsilon}^0_{\text{el, n, sys}}\ \text{(kWh/mol)} \;=\; \frac{\bar{P}_{\text{el, sys}}\ \text{(kW)}}{\underline{q}_{\text{n, sys, out, H}_2}\ \text{(mol/h)}}\ \text{ and} \tag{A.3.3a}$$

$$\tilde{\varepsilon}^0_{\text{el, n, sys}}\ \text{(kWh/mol)} \;=\; \frac{\bar{P}_{\text{el, sys}}\ \text{(kW)}}{\bar{q}_{\text{n, sys, out, H}_2}\ \text{(mol/h)}}; \tag{A.3.3b}$$

$\bar{P}_{\text{el, sys}}$, $\underline{q}_{\text{n, sys, out, H}_2}$ and $\bar{q}_{\text{n, sys, out, H}_2}$ are respectively given by equation (A.3.1b), equation (A.3.2k) and equation (A.3.1p). Accordingly, two different pseudo-averages of the electrical efficiency based on HHV of hydrogen ($\eta^0_{\text{HHV, el}}$), $\underline{\eta}^0_{\text{HHV, el, sys}}$ and $\tilde{\eta}^0_{\text{HHV, el, sys}}$, are respectively calculated as

$$\underline{\eta}^0_{\text{HHV, el, sys}}\ (\%) \;=\; \frac{\text{HHV}_{\text{H}_2}\ \text{(kWh/mol)}}{\underline{\varepsilon}^0_{\text{el, n, sys}}\ \text{(kWh/mol)}} \cdot 100\ \%\ \text{ and} \tag{A.3.3c}$$

$$\tilde{\eta}^{0}_{\mathrm{HHV,el,sys}}\ (\%) \;=\; \frac{\mathrm{HHV}_{\mathrm{H_2}}\ (\mathrm{kWh/mol})}{\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}\cdot 100\ \%; \qquad \text{(A.3.3d)}$$

$\underline{\varepsilon}^{0}_{\mathrm{el,n,sys}}$ and $\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}$ are respectively given by equation (A.3.3a) and equation (A.3.3b). Correspondingly, two different pseudo-averages of the electrical efficiency based on LHV of hydrogen ($\eta^{0}_{\mathrm{LHV,el}}$), $\underline{\eta}^{0}_{\mathrm{LHV,el,sys}}$ and $\tilde{\eta}^{0}_{\mathrm{LHV,el,sys}}$, are respectively calculated as

$$\underline{\eta}^{0}_{\mathrm{LHV,el,sys}}\ (\%) \;=\; \frac{\mathrm{LHV}_{\mathrm{H_2}}\ (\mathrm{kWh/mol})}{\underline{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}\cdot 100\ \%\ \text{ and} \qquad \text{(A.3.3e)}$$

$$\tilde{\eta}^{0}_{\mathrm{LHV,el,sys}}\ (\%) \;=\; \frac{\mathrm{LHV}_{\mathrm{H_2}}\ (\mathrm{kWh/mol})}{\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol})}\cdot 100\ \%; \qquad \text{(A.3.3f)}$$

$\underline{\varepsilon}^{0}_{\mathrm{el,n,sys}}$ and $\tilde{\varepsilon}^{0}_{\mathrm{el,n,sys}}$ are respectively given by equation (A.3.3a) and equation (A.3.3b).

Two different pseudo-averages of the specific thermal energy consumption per mole of hydrogen ($\varepsilon^{0}_{\mathrm{th,n,sys}}$), $\underline{\varepsilon}^{0}_{\mathrm{th,n,sys}}$ and $\tilde{\varepsilon}^{0}_{\mathrm{th,n,sys}}$, are respectively calculated as

$$\underline{\varepsilon}^{0}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{th,sys,in}}\ (\mathrm{kW})}{\underline{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \qquad \text{(A.3.4a)}$$

$$\tilde{\varepsilon}^{0}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{th,sys,in}}\ (\mathrm{kW})}{\bar{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}; \qquad \text{(A.3.4b)}$$

$\bar{P}_{\mathrm{th,sys,in}}$, $\underline{q}_{\mathrm{n,sys,out,H_2}}$ and $\bar{q}_{\mathrm{n,sys,out,H_2}}$ are respectively given by equation (A.3.1e), equation (A.3.2k) and equation (A.3.1p).

A.3.3 WE system tested under hydrogen output conditions

Two different pseudo-averages of the specific energy consumption per mole of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$), $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}$, are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{sys,in}}\ (\mathrm{kW})}{\underline{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \qquad \text{(A.3.5a)}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{sys,in}}\ (\mathrm{kW})}{\bar{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}; \qquad \text{(A.3.5b)}$$

$\bar{P}_{\mathrm{sys,in}}$, $\underline{q}_{\mathrm{n,sys,out,H_2}}$ and $\bar{q}_{\mathrm{n,sys,out,H_2}}$ are respectively given by equation (A.3.1a), equation (A.3.2k) and equation (A.3.1p). Two different pseudo-averages of the specific electric energy consumption per mole of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$), $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}$, are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{el,sys}}\ (\mathrm{kW})}{\underline{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \qquad \text{(A.3.5c)}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{el,sys}}\ (\mathrm{kW})}{\bar{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}; \qquad \text{(A.3.5d)}$$

$\bar{P}_{\mathrm{el,sys}}$, $\underline{q}_{\mathrm{n,sys,out,H_2}}$ and $\bar{q}_{\mathrm{n,sys,out,H_2}}$ are respectively by equation (A.3.1b), equation (A.3.2k) and equation (A.3.1p). Two different pseudo-averages of the specific thermal energy consumption per mole of generated hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$) namely $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,sys}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}$ are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{th,sys,in}}\ (\mathrm{kW})}{\underline{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \qquad \text{(A.3.5e)}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,sys}}\ (\mathrm{kWh/mol}) \;=\; \frac{\bar{P}_{\mathrm{th,sys,in}}\ (\mathrm{kW})}{\bar{q}_{\mathrm{n,sys,out,H_2}}\ (\mathrm{mol/h})}; \qquad \text{(A.3.5f)}$$

$\bar{P}_{\mathrm{th,sys,in}}$, $\underline{q}_{\mathrm{n,sys,out,H_2}}$ and $\bar{q}_{\mathrm{n,sys,out,H_2}}$ are respectively given by equation (A.3.1e), equation (A.3.2k) and equation (A.3.1p).

A.3.4 WE/HTE tested under hydrogen output conditions

The average of the input power to the tested WE/HTE ($P^{\text{p,T}}_{\text{WE, in}}$), $\bar{P}_{\text{WE, in}}$, see equation (3.4.2a), $\bar{P}_{\text{WE, in}}$, is calculated as

$$\bar{P}_{\text{WE, in}}\ \text{(kW)} \;=\; \bar{P}_{\text{el, dc, WE}}\ \text{(kW)} + \bar{P}_{\text{th, WE, in}}\ \text{(kW)} + \bar{P}_{\text{compr, WE, in}}\ \text{(kW)}; \tag{A.3.6a}$$

$\bar{P}_{\text{el, dc, WE}}$, $\bar{P}_{\text{th, WE, in}}$ and $\bar{P}_{\text{compr, WE, in}}$ are respectively given by equation (A.3.6b), equation (A.3.6c) and equation (A.3.6d). The averages of the DC electric power ($P_{\text{el, dc, WE}}$), $\bar{P}_{\text{el, dc, WE}}$, input thermal power ($P_{\text{th, WE, in}}$), $\bar{P}_{\text{th, WE, in}}$ and input power of compression ($P_{\text{compr, WE, in}}$), $\bar{P}_{\text{compr, WE, in}}$, are respectively calculated as

$$\bar{P}_{\text{el, dc, WE}}\ \text{(kW)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{el, dc, WE, l}}\ \text{(kW)}, \tag{A.3.6b}$$

$$\bar{P}_{\text{th, WE, in}}\ \text{(kW)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{th, WE, in, l}}\ \text{(kW)}\ \text{ and} \tag{A.3.6c}$$

$$\bar{P}_{\text{compr, WE, in}}\ \text{(kW)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{compr, WE, in, l}}\ \text{(kW)}; \tag{A.3.6d}$$

$P_{\text{el, dc, WE, l}}$ is the measured value of the DC electric power while $P_{\text{th, WE, in, l}}$ and $P_{\text{compr, WE, in, l}}$are respectively given by equation (A.2.5e) and equation (A.2.5f). The averages of the input thermal power of fluid i ($P_{\text{th, WE, in, i}}$), $\bar{P}_{\text{th, WE, in, i}}$ and input power of compression of fluid j ($P_{\text{compr, WE, in, j}}$), $\bar{P}_{\text{compr, WE, in, j}}$, are respectively calculated as

$$\bar{P}_{\text{th, WE, in, i}}\ \text{(kW)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{th, WE, in, i, l}}\ \text{(kW)}\ \text{ and} \tag{A.3.6e}$$

$$\bar{P}_{\text{compr, WE, in, j}}\ \text{(kW)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} P_{\text{compr, WE, in, j, l}}\ \text{(kW)}; \tag{A.3.6f}$$

$P_{\text{th, WE, in, i, l}}$ is given by equation (A.2.5g) and $P_{\text{compr, WE, in, j, l}}$ is given for incompressible and compressible fluid j by respectively equation (A.2.5h) and equation (A.2.5i). The averages of the mass flow rate ($q^{\text{i}}_{\text{m, WE}}$), $\bar{q}^{\text{i}}_{\text{m, WE}}$ and temperature of fluid i (T^{i}_{WE}), T^{i}_{WE}, are respectively calculated as

$$\bar{q}^{\text{i}}_{\text{m, WE}}\ \text{(kg/s)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} q^{\text{i}}_{\text{m, WE, l}}\ \text{(kg/s)}\ \text{ and} \tag{A.3.6g}$$

$$\bar{T}^{\text{i}}_{\text{WE}}\ \text{(K)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} T^{\text{i}}_{\text{WE, l}}\ \text{(K)}; \tag{A.3.6h}$$

$q^{\text{i}}_{\text{m, WE, l}}$ and $T^{\text{i}}_{\text{WE, l}}$ are the measured values of respectively the mass flow rate and temperature of fluid i. The averages of the pressure (p^{j}_{WE}), $\bar{p}^{\text{j}}_{\text{WE}}$ and molar flow rate of fluid j ($q^{\text{j}}_{\text{n, WE}}$), $q^{\text{j}}_{\text{n, WE}}$, are respectively calculated as

$$\bar{p}^{\text{j}}_{\text{WE}}\ \text{(kPa)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} p^{\text{j}}_{\text{WE, l}}\ \text{(kPa)}\ \text{ and} \tag{A.3.6i}$$

$$\bar{q}^{\text{j}}_{\text{n, WE}}\ \text{(mol/h)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} q^{\text{j}}_{\text{n, WE, l}}\ \text{(mol/h)}; \tag{A.3.6j}$$

$p^{\text{j}}_{\text{WE, l}}$ and $q^{\text{j}}_{\text{n, WE, l}}$ are the measured values of respectively the pressure and molar flow rate of fluid j. The averages of the molar flow rate of hydrogen ($q^{\text{WE}}_{\text{n, H}_2}$), $\bar{q}^{\text{WE}}_{\text{n, H}_2}$, molar concentration of hydrogen ($x^{\text{WE}}_{\text{n, H}_2}$), $\bar{x}^{\text{WE}}_{\text{n, H}_2}$ and product gas molar flow rate ($q^{\text{WE}}_{\text{n, out}}$), $\bar{q}^{\text{WE}}_{\text{n, out}}$, are respectively calculated as

$$\bar{q}^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/h)} \;=\; \frac{1}{L}\sum_{\text{l=1}}^{L} x^{\text{WE}}_{\text{n, H}_2\text{, l}}\ \text{(mol/mol)} \cdot q^{\text{WE}}_{\text{n, out, l}}\ \text{(mol/h)}, \tag{A.3.6k}$$

$$\bar{x}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/mol}) = \frac{1}{L}\sum_{\mathrm{l}=1}^{L} x^{\mathrm{WE}}_{\mathrm{n,H_2,l}}\ (\mathrm{mol/mol})\ \text{ and} \tag{A.3.6l}$$

$$\bar{q}^{\mathrm{WE}}_{\mathrm{n,out}}\ (\mathrm{mol/h}) = \frac{1}{L}\sum_{\mathrm{l}=1}^{L} q^{\mathrm{WE}}_{\mathrm{n,out,l}}\ (\mathrm{mol/h}); \tag{A.3.6m}$$

$x^{\mathrm{WE}}_{\mathrm{n,H_2,l}}$ and $q^{\mathrm{WE}}_{\mathrm{n,out,l}}$ are the measured value of respectively the molar concentration of hydrogen and product gas molar flow rate.

Two different pseudo-averages of the specific energy consumption per mole of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$) namely $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}$ are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{WE,in}}\ (\mathrm{kW})}{\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \tag{A.3.7a}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{e,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{WE,in}}\ (\mathrm{kW})}{\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}; \tag{A.3.7b}$$

$\bar{P}_{\mathrm{WE,in}}$, $\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ and $\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ are respectively given by equation (A.3.6a), equation (A.3.7j) and equation (A.3.6k). Two different pseudo-averages of the specific electric energy consumption per mole of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$) namely $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}$ are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{el,dc,WE}}\ (\mathrm{kW})}{\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \tag{A.3.7c}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{el,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{el,dc,WE}}\ (\mathrm{kW})}{\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}; \tag{A.3.7d}$$

$\bar{P}_{\mathrm{el,dc,WE}}$, $\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ and $\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ are respectively given by equation (A.3.6b), equation (A.3.7j) and equation (A.3.6k). Two different pseudo-averages of the specific thermal energy consumption per mole of hydrogen ($\varepsilon^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$) namely $\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$ and $\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}$ are respectively calculated as

$$\underline{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{th,WE,in}}\ (\mathrm{kW})}{\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}\ \text{ and} \tag{A.3.7e}$$

$$\tilde{\varepsilon}^{\mathrm{p,T}}_{\mathrm{th,n,WE}}\ (\mathrm{kWh/mol}) = \frac{\bar{P}_{\mathrm{th,WE,in}}\ (\mathrm{kW})}{\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}\ (\mathrm{mol/h})}; \tag{A.3.7f}$$

$\bar{P}_{\mathrm{th,WE,in}}$, $\underline{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ and $\bar{q}^{\mathrm{WE}}_{\mathrm{n,H_2}}$ are respectively given by equation (A.3.6c), equation (A.3.7j) and equation (A.3.6k). The pseudo-average of the input thermal power related to fluid i ($P_{\mathrm{th,WE,in,i}}$), $\underline{P}_{\mathrm{th,WE,in,i}}$, is calculated as

$$\underline{P}_{\mathrm{th,WE,in,i}}\ (\mathrm{kW}) = \bar{q}^{\mathrm{i}}_{\mathrm{m,WE}}\ (\mathrm{kg/s}) \cdot c^{\mathrm{i}}_{\mathrm{p}}\ (\mathrm{kJ/(kg\ K)}) \cdot \left(\bar{T}^{\mathrm{i}}_{\mathrm{WE}}\ (\mathrm{K}) - T^0\ (\mathrm{K})\right); \tag{A.3.7g}$$

$\bar{q}^{\mathrm{i}}_{\mathrm{m,WE}}$ and $\bar{T}^{\mathrm{i}}_{\mathrm{WE}}$ are respectively given by equation (A.3.6g) and equation (A.3.6h). For the incompressible case, the pseudo-average of the input power of compression related to fluid j ($P_{\mathrm{compr,WE,in,j}}$), $\underline{P}_{\mathrm{compr,WE,in,j}}$, is calculated as

$$\underline{P}_{\mathrm{compr,WE,in,j}}\ (\mathrm{kW}) = \left(\bar{p}^{\mathrm{j}}_{\mathrm{WE}}\ (\mathrm{kPa}) - p^0\ (\mathrm{kPa})\right) \cdot \frac{V^{\mathrm{j}}_{\mathrm{m}}\ (\mathrm{m^3/mol})}{3600\ (\mathrm{s/h})} \cdot \bar{q}^{\mathrm{j}}_{\mathrm{n,WE}}\ (\mathrm{mol/h}); \tag{A.3.7h}$$

$\bar{p}^{\mathrm{j}}_{\mathrm{WE}}$ and $\bar{q}^{\mathrm{j}}_{\mathrm{n,WE}}$ are respectively given by equation (A.3.6i) and equation (A.3.6j). For the compressible case, the pseudo-average of the input power of compression related to fluid j ($P_{\mathrm{compr,WE,in,j}}$), $\underline{P}_{\mathrm{compr,WE,in,j}}$, is calculated as

$$\underline{P}_{\mathrm{compr,WE,in,j}}\ (\mathrm{kW}) = \left(\frac{\gamma^{\mathrm{j}}}{\gamma^{\mathrm{j}}-1}\right) \frac{\bar{Z}^{\mathrm{j}} \cdot R_{\mathrm{g}}\ (\mathrm{kJ/(mol\ K)}) \cdot T^0\ (\mathrm{K}) \cdot \bar{q}^{\mathrm{j}}_{\mathrm{n,WE}}\ (\mathrm{mol/h})}{3600\ (\mathrm{s/h})} \left(\left(\frac{\bar{p}^{\mathrm{j}}_{\mathrm{WE}}\ (\mathrm{kPa})}{p^0\ (\mathrm{kPa})} \right)^{\frac{\gamma^{\mathrm{j}}-1}{\gamma^{\mathrm{j}}}} - 1 \right).$$

(A.3.7i)

The pseudo-average of the molar flow rate of hydrogen ($q^{\text{WE}}_{\text{n, H}_2}$), $\underline{q}^{\text{WE}}_{\text{n, H}_2}$, is calculated as

$$\underline{q}^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/h)} \ = \ \bar{x}^{\text{WE}}_{\text{n, H}_2}\ \text{(mol/mol)} \cdot \bar{q}^{\text{WE}}_{\text{n, out}}\ \text{(mol/h)}; \tag{A.3.7j}$$

$\bar{x}^{\text{WE}}_{\text{n, H}_2}$ and $\bar{q}_{\text{n, out}}$ are respectively given by equation (A.3.6l) and equation (A.3.6m).

A.4 Standard variances of test parameters

A.4.1 General

For test parameters, the standard uncertainty (u) and the combined standard uncertainty (u_{c}) each multiplied by the coverage factor or multiplier, k=3, are respectively given by

$$ku \ = \ 3\sqrt{s^2}\ \text{and} \tag{A.4.1a}$$

$$ku_{\text{c}} \ = \ 3\sqrt{u^2_{\text{c}}}; \tag{A.4.1b}$$

s^2 is the standard variance of a measured test parameter and u^2_{c} is the combined standard variance of a calculated test parameter (JCGM, 2008). All test parameters are assumed uncorrelated. The relative standard uncertainty of a test parameter (u_{r}) is the positive square root of its relative combined standard variance (u^2_{r}) (JCGM, 2008).

A.4.2 WE system

The combined standard variance of the input power of a WE system of the tested WE system ($P_{\text{sys, in}}$), $u^2_{\text{c}}\left(P_{\text{sys, in}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{sys, in}}\right)\ \text{(kW)}^2 \ = \ u^2_{\text{c}}\left(P_{\text{el, sys}}\right)\ \text{(kW)}^2 + u^2_{\text{c}}\left(P_{\text{th, sys, in}}\right)\ \text{(kW)}^2 + u^2_{\text{c}}\left(P_{\text{compr, sys, in}}\right)\ \text{(kW)}^2; \tag{A.4.2a}$$

$u^2_{\text{c}}\left(P_{\text{el, sys}}\right)$, $u^2_{\text{c}}\left(P_{\text{th, sys, in}}\right)$ and $u^2_{\text{c}}\left(P_{\text{compr, sys, in}}\right)$ are respectively given by equation (A.4.2b), equation (A.4.2c) and equation (A.4.2d). The combined standard variance of the electric power ($P_{\text{el, sys}}$), $u^2_{\text{c}}\left(P_{\text{el, sys}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{el, sys}}\right)\ \text{(kW)}^2 \ = \ s^2\left(P_{\text{el, ac, sys}}\right)\ \text{(kW)}^2 + s^2\left(P_{\text{el, ac, sys}}\right)\ \text{(kW)}^2; \tag{A.4.2b}$$

$s^2\left(P_{\text{el, ac, sys}}\right)$ and $s^2\left(P_{\text{el, ac, sys}}\right)$ are respectively given by equation (A.4.3a) and equation (A.4.3b). The combined standard variance of the input thermal power ($P_{\text{th, sys, in}}$), $u^2_{\text{c}}\left(P_{\text{th, sys, in}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{th, sys, in}}\right)\ \text{(kW)}^2 \ = \ \Big(\text{HHV}^{\text{f}}\ \text{(kWh/mol)} \cdot \underline{q}^{\text{f}}_{\text{n}}\ \text{(mol/h)}\Big)^2\ s^2_{\text{r}}\left(q^{\text{f}}_{\text{n}}\right) + \sum_{\text{i}} u^2_{\text{c}}\left(P_{\text{th, sys, in, i}}\right)\ \text{(kW)}^2; \tag{A.4.2c}$$

$\underline{q}^{\text{f}}_{\text{n}}$, $s^2_{\text{r}}\left(q^{\text{f}}_{\text{n}}\right)$ and $u^2_{\text{c}}\left(P_{\text{th, sys, in, i}}\right)$ are respectively given by equation (A.3.2j), equation (A.4.4e) and equation (A.4.2e). The combined standard variance of the input power of compression ($P_{\text{compr, sys, in}}$), $u^2_{\text{c}}\left(P_{\text{compr, sys, in}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{compr, sys, in}}\right)\ \text{(kW)}^2 \ = \ \sum_{\text{j}} u^2_{\text{c}}\left(P_{\text{compr, sys, in, j}}\right)\ \text{(kW)}^2; \tag{A.4.2d}$$

$u^2_{\text{c}}\left(P_{\text{compr, sys, in, j}}\right)$ is given for incompressible and compressible fluid j by respectively equation (A.4.2f) and equation (A.4.2g). Note, the summation (A.4.2d) applies jointly to both type of fluids. The combined standard variance of the input thermal power of fluid i ($P_{\text{th, sys, in, i}}$), $u^2_{\text{c}}\left(P_{\text{th, sys, in, i}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{th, sys, in, i}}\right)\ \text{(kW)}^2 \ = \ \left(\underline{P}_{\text{th, sys, in, i}}\ \text{(kW)}^2\right)^2 \left(s^2_{\text{r}}\left(q^{\text{i}}_{\text{m}}\right) + s^2_{\text{r}}\left(T^{\text{i}}\right)\right); \tag{A.4.2e}$$

$\underline{P}_{\text{th, sys, in, i}}$, $s^2_{\text{r}}\left(q^{\text{i}}_{\text{m}}\right)$ and $s^2_{\text{r}}\left(T^{\text{i}}\right)$ are respectively given by equation (A.3.2g), equation (A.4.4f) and equation (A.4.4g). For the incompressible case, the combined standard variance of the input power of compression of fluid j ($P_{\text{compr, sys, in, j}}$), $u^2_{\text{c}}\left(P_{\text{compr, sys, in, j}}\right)$, is calculated as

$$u^2_{\text{c}}\left(P_{\text{compr, sys, in, j}}\right)\ \text{(kW)}^2 \ = \ \left(\underline{P}_{\text{compr, sys, in, j}}\ \text{(kW)}^2\right)^2 \left(s^2_{\text{r}}\left(p^{\text{j}}\right) + s^2_{\text{r}}\left(q^{\text{j}}_{\text{n}}\right)\right); \tag{A.4.2f}$$

$\underline{P}_{\mathrm{compr,\,sys,\,in,\,j}}$, $s_{\mathrm{r}}^2\left(p^{\mathrm{j}}\right)$ and $s_{\mathrm{r}}^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)$ are respectively given by equation (A.3.2h), equation (A.4.4h) and equation (A.4.4i). For the compressible case, the combined standard variance of the input power of compression of fluid j ($P_{\mathrm{compr,\,sys,\,in,\,j}}$), $u_{\mathrm{c}}^2\left(P_{\mathrm{compr,\,sys,\,in,\,j}}\right)$, is calculated as

$$u_{\mathrm{c}}^2\left(P_{\mathrm{compr,\,sys,\,in,\,j}}\right)\,(\mathrm{kW})^2 \;=\; \left(\underline{P}_{\mathrm{compr,\,sys,\,in,\,j}}\,(\mathrm{kW})^2\right)^2\left(\left(\frac{\gamma^{\mathrm{j}}-1}{\gamma^{\mathrm{j}}}\right)^2 s_{\mathrm{r}}^2\left(p^{\mathrm{j}}\right)+s_{\mathrm{r}}^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)\right)\,; \tag{A.4.2g}$$

$\underline{P}_{\mathrm{compr,\,sys,\,in,\,j}}$ is given by equation (A.3.2i). The combined standard variance of the molar flow rate of hydrogen ($q_{\mathrm{n,\,sys,\,out,\,H_2}}$), $u_{\mathrm{c}}^2\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right)$, is calculated as

$$u_{\mathrm{c}}^2\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right)\,(\mathrm{mol/h})^2 \;=\; \left(\underline{q}_{\mathrm{n,\,sys,\,out,\,H_2}}\,(\mathrm{mol/h})\right)^2\left(s_{\mathrm{r}}^2\left(x_{\mathrm{n,\,sys,\,H_2}}\right)+s_{\mathrm{r}}^2\left(q_{\mathrm{n,\,sys,\,out}}\right)\right)\,; \tag{A.4.2h}$$

$\underline{q}_{\mathrm{n,\,sys,\,out,\,H_2}}$, $s_{\mathrm{r}}^2\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$ and $s_{\mathrm{r}}^2\left(q_{\mathrm{n,\,sys,\,out}}\right)$ are respectively given by equation (A.3.2k), equation (A.4.4m) and equation (A.4.4n). The standard variances of the AC electric power ($P_{\mathrm{el,\,ac,\,sys}}$), $s^2\left(P_{\mathrm{el,\,ac,\,sys}}\right)$ and DC electric power ($P_{\mathrm{el,\,dc,\,sys}}$), $s^2\left(P_{\mathrm{el,\,ac,\,sys}}\right)$, are respectively calculated as

$$s^2\left(P_{\mathrm{el,\,ac,\,sys}}\right)\,(\mathrm{kW})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(P_{\mathrm{el,\,ac,\,sys,\,l}}\,(\mathrm{kW})-\bar{P}_{\mathrm{el,\,ac,\,sys}}\,(\mathrm{kW})\right)^2 \;\text{ and} \tag{A.4.3a}$$

$$s^2\left(P_{\mathrm{el,\,ac,\,sys}}\right)\,(\mathrm{kW})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(P_{\mathrm{el,\,dc,\,sys,\,l}}\,(\mathrm{kW})-\bar{P}_{\mathrm{el,\,dc,\,sys}}\,(\mathrm{kW})\right)^2; \tag{A.4.3b}$$

$P_{\mathrm{el,\,ac,\,sys,\,l}}$ and $P_{\mathrm{el,\,dc,\,sys,\,l}}$ are the measured values of respectively the AC electric power and DC electric power while $\bar{P}_{\mathrm{el,\,ac,\,sys}}$ and $\bar{P}_{\mathrm{el,\,dc,\,sys}}$ are respectively given by equation (A.3.1c) and equation (A.3.1d). The standard variance of the molar flow rate of fuel ($q_{\mathrm{n}}^{\mathrm{f}}$), $s^2\left(q_{\mathrm{n}}^{\mathrm{f}}\right)$, is calculated as

$$s^2\left(q_{\mathrm{n}}^{\mathrm{f}}\right)\,(\mathrm{mol/h})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(q_{\mathrm{n,\,l}}^{\mathrm{f}}\,(\mathrm{mol/h})-\bar{q}_{\mathrm{n}}^{\mathrm{f}}\,(\mathrm{mol/h})\right)^2; \tag{A.4.3c}$$

$q_{\mathrm{n,\,l}}^{\mathrm{f}}$ is the measured value of the molar flow rate of fuel and $\bar{q}_{\mathrm{n}}^{\mathrm{f}}$ is given by equation (A.3.1i). The standard variances of the mass flow rate ($q_{\mathrm{m}}^{\mathrm{i}}$), $s^2\left(q_{\mathrm{m}}^{\mathrm{i}}\right)$ and temperature of fluid i (T^{i}), $s^2\left(T^{\mathrm{i}}\right)$, are respectively calculated as

$$s^2\left(q_{\mathrm{m}}^{\mathrm{i}}\right)\,(\mathrm{kg/s})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(q_{\mathrm{m,\,l}}^{\mathrm{i}}\,(\mathrm{kg/s})-\bar{q}_{\mathrm{m}}^{\mathrm{i}}\,(\mathrm{kg/s})\right)^2 \;\text{ and} \tag{A.4.3d}$$

$$s^2\left(T^{\mathrm{i}}\right)\,(\mathrm{K})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(T_{\mathrm{l}}^{\mathrm{i}}\,(\mathrm{K})-\bar{T}^{\mathrm{i}}\,(\mathrm{K})\right)^2; \tag{A.4.3e}$$

$q_{\mathrm{m,\,l}}^{\mathrm{i}}$ and $T_{\mathrm{l}}^{\mathrm{i}}$ are the measured values of respectively the mass flow rate and temperature of fluid i while $\bar{q}_{\mathrm{m}}^{\mathrm{i}}$ and $\bar{T}^{\mathrm{i}}$ are respectively given by equation (A.3.1j) and equation (A.3.1k). The standard variances of the pressure (p^{j}), $s^2\left(p^{\mathrm{j}}\right)$ and molar flow rate of fluid j ($q_{\mathrm{n}}^{\mathrm{j}}$), $s^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)$, are respectively calculated as

$$s^2\left(p^{\mathrm{j}}\right)\,(\mathrm{kPa})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(p_{\mathrm{l}}^{\mathrm{j}}\,(\mathrm{kPa})-\bar{p}^{\mathrm{j}}\,(\mathrm{kPa})\right)^2 \;\text{ and} \tag{A.4.3f}$$

$$s^2\left(q_{\mathrm{n}}^{\mathrm{j}}\right)\,(\mathrm{mol/h})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(q_{\mathrm{n,\,l}}^{\mathrm{j}}\,(\mathrm{mol/h})-\bar{q}_{\mathrm{n}}^{\mathrm{j}}\,(\mathrm{mol/h})\right)^2; \tag{A.4.3g}$$

$p_{\mathrm{l}}^{\mathrm{j}}$ and $q_{\mathrm{n,\,l}}^{\mathrm{j}}$ are the measured values of respectively the pressure and molar flow rate of fluid j while $\bar{p}^{\mathrm{j}}$ and $\bar{q}_{\mathrm{n}}^{\mathrm{j}}$ are respectively given by equation (A.3.1n) and equation (A.3.1o). The standard variances of the pressure ($p_{\mathrm{sys,\,H_2}}$), $s^2\left(p_{\mathrm{sys,\,H_2}}\right)$ and temperature of hydrogen ($T_{\mathrm{sys,\,H_2}}$), $s^2\left(T_{\mathrm{sys,\,H_2}}\right)$, are respectively calculated as

$$s^2\left(p_{\mathrm{sys,\,H_2}}\right)\,(\mathrm{kPa})^2 \;=\; \frac{1}{L-1}\sum_{\mathrm{l}=1}^{L}\left(p_{\mathrm{sys,\,H_2,\,l}}\,(\mathrm{kPa})-\bar{p}_{\mathrm{sys,\,H_2}}\,(\mathrm{kPa})\right)^2 \;\text{ and} \tag{A.4.3h}$$

$$s^2\left(T_{\mathsf{sys,H_2}}\right)(\mathsf{K})^2 = \frac{1}{L-1}\sum_{\mathsf{l=1}}^{L}\left(T_{\mathsf{sys,H_2,l}}(\mathsf{K}) - \bar{T}_{\mathsf{sys,H_2}}(\mathsf{K})\right)^2; \tag{A.4.3i}$$

$p_{\mathsf{sys,H_2,l}}$ and $T_{\mathsf{sys,H_2,l}}$ are the measured values of respectively the pressure and temperature of hydrogen while $\bar{p}_{\mathsf{sys,H_2}}$ and $\bar{T}_{\mathsf{sys,H_2}}$ are respectively given by equation (A.3.1l) and equation (A.3.1m). The standard variances of the molar concentration of hydrogen $(x_{\mathsf{n,sys,H_2}})$, $s^2\left(x_{\mathsf{n,sys,H_2}}\right)$ and product gas molar flow rate $(q_{\mathsf{n,sys,out}})$, $s^2\left(q_{\mathsf{n,sys,out}}\right)$, are respectively calculated as

$$s^2\left(x_{\mathsf{n,sys,H_2}}\right)(\mathsf{mol/mol})^2 = \frac{1}{L-1}\sum_{\mathsf{l=1}}^{L}\left(x_{\mathsf{n,sys,H_2},l}(\mathsf{mol/mol}) - \bar{x}_{\mathsf{n,sys,H_2}}(\mathsf{mol/mol})\right)^2 \text{ and} \tag{A.4.3j}$$

$$s^2\left(q_{\mathsf{n,sys,out}}\right)(\mathsf{mol/h})^2 = \frac{1}{L-1}\sum_{\mathsf{l=1}}^{L}\left(q_{\mathsf{n,sys,out,l}}(\mathsf{mol/h}) - \bar{q}_{\mathsf{n,sys,out}}(\mathsf{mol/h})\right)^2; \tag{A.4.3k}$$

$x_{\mathsf{n,sys,H_2},l}$ and $q_{\mathsf{n,sys,out,l}}$ are the measured values of respectively the molar concentration of hydrogen and product gas molar flow rate while $\bar{x}_{\mathsf{n,sys,H_2}}$ and $\bar{q}_{\mathsf{n,sys,out}}$ are respectively given by equation (A.3.1q) and equation (A.3.1r).

The relative standard variances of the input power $(P_{\mathsf{sys,in}})$, $u_{\mathsf{r}}^2\left(P_{\mathsf{sys,in}}\right)$, electric power $(P_{\mathsf{el,sys}})$, $u_{\mathsf{r}}^2\left(P_{\mathsf{el,sys}}\right)$, input thermal power $(P_{\mathsf{th,sys,in}})$, $u_{\mathsf{r}}^2\left(P_{\mathsf{th,sys,in}}\right)$ and input power of compression $(P_{\mathsf{compr,sys,in}})$, $u_{\mathsf{r}}^2\left(P_{\mathsf{compr,sys,in}}\right)$, are respectively calculated as

$$u_{\mathsf{r}}^2\left(P_{\mathsf{sys,in}}\right) = \frac{u_{\mathsf{c}}^2\left(P_{\mathsf{sys,in}}\right)(\mathsf{kW})^2}{\left(\bar{P}_{\mathsf{sys,in}}(\mathsf{kW})\right)^2}, \tag{A.4.4a}$$

$$u_{\mathsf{r}}^2\left(P_{\mathsf{el,sys}}\right) = \frac{u_{\mathsf{c}}^2\left(P_{\mathsf{el,sys}}\right)(\mathsf{kW})^2}{\left(\bar{P}_{\mathsf{el,sys}}(\mathsf{kW})\right)^2}, \tag{A.4.4b}$$

$$u_{\mathsf{r}}^2\left(P_{\mathsf{th,sys,in}}\right) = \frac{u_{\mathsf{c}}^2\left(P_{\mathsf{th,sys,in}}\right)(\mathsf{kW})^2}{\left(\bar{P}_{\mathsf{th,sys,in}}(\mathsf{kW})\right)^2} \text{ and} \tag{A.4.4c}$$

$$u_{\mathsf{r}}^2\left(P_{\mathsf{compr,sys,in}}\right) = \frac{u_{\mathsf{c}}^2\left(P_{\mathsf{compr,sys,in}}\right)(\mathsf{kW})^2}{\left(\bar{P}_{\mathsf{compr,sys,in}}(\mathsf{kW})\right)^2}; \tag{A.4.4d}$$

$u_{\mathsf{c}}^2\left(P_{\mathsf{sys,in}}\right)$, $\bar{P}_{\mathsf{sys,in}}$, $u_{\mathsf{c}}^2\left(P_{\mathsf{el,sys}}\right)$, $\bar{P}_{\mathsf{el,sys}}$, $u_{\mathsf{c}}^2\left(P_{\mathsf{th,sys,in}}\right)$, $\bar{P}_{\mathsf{th,sys,in}}$, $u_{\mathsf{c}}^2\left(P_{\mathsf{compr,sys,in}}\right)$ and $\bar{P}_{\mathsf{compr,sys,in}}$ are respectively given by equation (A.4.2a), equation (A.3.1a), equation (A.4.2b), equation (A.3.1b), equation (A.4.2c), equation (A.3.1e), equation (A.4.2d) and equation (A.3.1f). The relative combined standard variance of the molar flow rate of fuel $(q_{\mathsf{n}}^{\mathsf{f}})$, $s_{\mathsf{r}}^2\left(q_{\mathsf{n}}^{\mathsf{f}}\right)$, is calculated as

$$s_{\mathsf{r}}^2\left(q_{\mathsf{n}}^{\mathsf{f}}\right) = \frac{s^2\left(q_{\mathsf{n}}^{\mathsf{f}}\right)(\mathsf{mol/h})^2}{\left(\bar{q}_{\mathsf{n}}^{\mathsf{f}}(\mathsf{mol/h})\right)^2}; \tag{A.4.4e}$$

$s^2\left(q_{\mathsf{n}}^{\mathsf{f}}\right)$ and $\bar{q}_{\mathsf{n}}^{\mathsf{f}}$ are respectively given by equation (A.4.3c) and equation (A.3.1i). The relative standard variances of the mass flow rate $(q_{\mathsf{m}}^{\mathsf{i}})$, $s_{\mathsf{r}}^2\left(q_{\mathsf{m}}^{\mathsf{i}}\right)$ and temperature of fluid i (T^{i}), $s_{\mathsf{r}}^2\left(T^{\mathsf{i}}\right)$, are respectively calculated as

$$s_{\mathsf{r}}^2\left(q_{\mathsf{m}}^{\mathsf{i}}\right) = \frac{s^2\left(q_{\mathsf{m}}^{\mathsf{i}}\right)(\mathsf{kg/s})^2}{\left(\bar{q}_{\mathsf{m}}^{\mathsf{i}}(\mathsf{kg/s})\right)^2} \text{ and} \tag{A.4.4f}$$

$$s_{\mathsf{r}}^2\left(T^{\mathsf{i}}\right) = \frac{s^2\left(T^{\mathsf{i}}\right)(\mathsf{K})^2}{\left(\bar{T}^{\mathsf{i}}(\mathsf{K})\right)^2}; \tag{A.4.4g}$$

$s^2\left(q_{\mathsf{m}}^{\mathsf{i}}\right)$, $\bar{q}_{\mathsf{m}}^{\mathsf{i}}$, $s^2\left(T^{\mathsf{i}}\right)$ and $\bar{T}^{\mathsf{i}}$ are respectively given by equation (A.4.3d), equation (A.3.1j), equation (A.4.3e) and equation (A.3.1k). The relative standard variances of the pressure (p^{j}), $s_{\mathsf{r}}^2\left(p^{\mathsf{j}}\right)$ and molar flow rate of fluid j $(q_{\mathsf{n}}^{\mathsf{j}})$, $s_{\mathsf{r}}^2\left(q_{\mathsf{n}}^{\mathsf{j}}\right)$, are respectively calculated as

$$s_{\mathsf{r}}^2\left(p^{\mathsf{j}}\right) = \frac{s^2\left(p^{\mathsf{j}}\right)(\mathsf{kPa})^2}{\left(\bar{p}^{\mathsf{j}}(\mathsf{kPa})\right)^2} \text{ and} \tag{A.4.4h}$$

$$s_{\mathrm{r}}^{2}\left(q_{\mathrm{n}}^{\mathrm{j}}\right) \;=\; \frac{s^{2}\left(q_{\mathrm{n}}^{\mathrm{j}}\right)\ (\text{mol/h})^{2}}{\left(\bar{q}_{\mathrm{n}}^{\mathrm{j}}\ (\text{mol/h})\right)^{2}} \quad \text{and} \tag{A.4.4i}$$

$s^{2}\left(p^{\mathrm{j}}\right)$, $\bar{p}^{\mathrm{j}}$, $s^{2}\left(q_{\mathrm{n}}^{\mathrm{j}}\right)$ and $\bar{q}_{\mathrm{n}}^{\mathrm{j}}$ are respectively given by equation (A.4.3f), equation (A.3.1n), equation (A.4.3g) and equation (A.3.1o). The relative standard variances of the pressure ($p_{\mathrm{sys,\,H_2}}$), $s_{\mathrm{r}}^{2}\left(p_{\mathrm{sys,\,H_2}}\right)$ and temperature of hydrogen ($T_{\mathrm{sys,\,H_2}}$), $s_{\mathrm{r}}^{2}\left(T_{\mathrm{sys,\,H_2}}\right)$, are respectively calculated as

$$s_{\mathrm{r}}^{2}\left(p_{\mathrm{sys,\,H_2}}\right) \;=\; \frac{s^{2}\left(p_{\mathrm{sys,\,H_2}}\right)\ (\text{kPa})^{2}}{\left(\bar{p}_{\mathrm{sys,\,H_2}}\ (\text{kPa})\right)^{2}} \quad \text{and} \tag{A.4.4j}$$

$$s_{\mathrm{r}}^{2}\left(T_{\mathrm{sys,\,H_2}}\right) \;=\; \frac{s^{2}\left(T_{\mathrm{sys,\,H_2}}\right)\ (\text{K})^{2}}{\left(\bar{T}_{\mathrm{sys,\,H_2}}\ (\text{K})\right)^{2}}; \tag{A.4.4k}$$

$s^{2}\left(p_{\mathrm{sys,\,H_2}}\right)$, $\bar{p}_{\mathrm{sys,\,H_2}}$, $s^{2}\left(T_{\mathrm{sys,\,H_2}}\right)$ and $\bar{T}_{\mathrm{sys,\,H_2}}$ are respectively given by equation (A.4.3h), equation (A.3.1l), equation (A.4.3i) and equation (A.3.1m). The relative combined standard variance of the molar flow rate of hydrogen ($q_{\mathrm{n,\,sys,\,out,\,H_2}}$), $u_{\mathrm{r}}^{2}\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right)$, is calculated as

$$u_{\mathrm{r}}^{2}\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right) \;=\; \frac{u_{\mathrm{c}}^{2}\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right)\ (\text{mol/mol})^{2}}{\left(\bar{q}_{\mathrm{n,\,sys,\,out,\,H_2}}\ (\text{mol/mol})\right)^{2}}, \tag{A.4.4l}$$

$u_{\mathrm{c}}^{2}\left(q_{\mathrm{n,\,sys,\,out,\,H_2}}\right)$ and $\bar{q}_{\mathrm{n,\,sys,\,out,\,H_2}}$ are respectively given by equation (A.4.2h) and equation (A.3.1p). The relative standard variances of the molar concentration of hydrogen ($x_{\mathrm{n,\,sys,\,H_2}}$), $s_{\mathrm{r}}^{2}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$ and product gas molar flow rate ($q_{\mathrm{n,\,sys,\,out}}$), $s_{\mathrm{r}}^{2}\left(q_{\mathrm{n,\,sys,\,out}}\right)$, are respectively calculated as

$$s_{\mathrm{r}}^{2}\left(x_{\mathrm{n,\,sys,\,H_2}}\right) \;=\; \frac{s^{2}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)\ (\text{mol/mol})^{2}}{\left(\bar{x}_{\mathrm{n,\,sys,\,H_2}}\ (\text{mol/mol})\right)^{2}} \quad \text{and} \tag{A.4.4m}$$

$$s_{\mathrm{r}}^{2}\left(q_{\mathrm{n,\,sys,\,out}}\right) \;=\; \frac{s^{2}\left(q_{\mathrm{n,\,sys,out}}\right)\ (\text{mol/h})^{2}}{\left(\bar{q}_{\mathrm{n,\,sys,\,out}}\ (\text{mol/h})\right)^{2}}; \tag{A.4.4n}$$

$s^{2}\left(x_{\mathrm{n,\,sys,\,H_2}}\right)$, $\bar{x}_{\mathrm{n,\,sys,\,H_2}}$, $s^{2}\left(q_{\mathrm{n,\,sys,out}}\right)$ and $\bar{q}_{\mathrm{n,\,sys,\,out}}$ are respectively given by equation (A.4.3j), equation (A.3.1q), equation (A.4.3k) and equation (A.3.1r).

A.4.3 WE/HTE

The combined standard variance of the input power of a WE/HTE of the tested WE/HTE ($P_{\mathrm{WE,\,in}}$), $u_{\mathrm{c}}^{2}\left(P_{\mathrm{WE,\,in}}\right)$, is calculated as

$$u_{\mathrm{c}}^{2}\left(P_{\mathrm{WE,\,in}}\right)\ (\text{kW})^{2} \;=\; s^{2}\left(P_{\mathrm{el,\,dc,\,WE}}\right)\ (\text{kW})^{2} + u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in}}\right)\ (\text{kW})^{2} + u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in}}\right)\ (\text{kW})^{2}; \tag{A.4.5a}$$

$s^{2}\left(P_{\mathrm{el,\,dc,\,WE}}\right)$, $u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in}}\right)$ and $u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in}}\right)$ are respectively given by equation (A.4.6a), equation (A.4.5b) and equation (A.4.5c). The combined standard variance of the input thermal power ($P_{\mathrm{th,\,WE,\,in}}$), $u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in}}\right)$ is calculated as

$$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in}}\right)\ (\text{kW})^{2} \;=\; \sum_{\mathrm{i}} u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in,\,i}}\right)\ (\text{kW})^{2}; \tag{A.4.5b}$$

$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in,\,i}}\right)$ is given by equation (A.4.5d). The combined standard variance of the input power of compression ($P_{\mathrm{compr,\,WE,\,in}}$), $u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in}}\right)$, is calculated as

$$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in}}\right)\ (\text{kW})^{2} \;=\; \sum_{\mathrm{i}} u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in,\,j}}\right)\ (\text{kW})^{2}; \tag{A.4.5c}$$

$u_{\mathrm{c}}^{2}\left(P_{\mathrm{compr,\,WE,\,in,\,j}}\right)$ is given for incompressible and compressible fluid j by respectively equation (A.4.5e) and equation (A.4.5f). Note, the summation (A.4.5c) applies jointly to both type of fluids. The combined standard variance of the input thermal power of fluid i ($P_{\mathrm{th,\,WE,\,in,\,i}}$), $u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in,\,i}}\right)$, is calculated as

$$u_{\mathrm{c}}^{2}\left(P_{\mathrm{th,\,WE,\,in,\,i}}\right)\ (\text{kW})^{2} \;=\; \left(\underline{P}_{\mathrm{th,\,WE,\,in,\,i}}\ (\text{kW})\right)^{2}\left(s_{\mathrm{r}}^{2}\left(q_{\mathrm{m,\,WE}}^{\mathrm{i}}\right) + s_{\mathrm{r}}^{2}\left(T_{\mathrm{WE}}^{\mathrm{i}}\right)\right); \tag{A.4.5d}$$

$\underline{P}_{\text{th, WE, in, i}}$, $s_{\text{r}}^2\left(q^{\text{i}}_{\text{m, WE}}\right)$ and $s_{\text{r}}^2\left(T^{\text{i}}_{\text{WE}}\right)$ are respectively given by equation (A.3.7g), equation (A.4.7d) and equation (A.4.7e). For the incompressible case, the combined standard variance of the input power of compression of fluid j ($P_{\text{compr, WE, in, j}}$), $u_{\text{c}}^2\left(P_{\text{compr, WE, in, j}}\right)$, is calculated as

$$u_{\text{c}}^2\left(P_{\text{compr, WE, in, j}}\right)\ (\text{kW})^2 \;=\; \left(\underline{P}_{\text{compr, WE, in, j}}\ (\text{kW})\right)^2 \left(s_{\text{r}}^2\left(p^{\text{j}}_{\text{WE}}\right) + s_{\text{r}}^2\left(q^{\text{j}}_{\text{n, WE}}\right)\right); \tag{A.4.5e}$$

$\underline{P}_{\text{compr, WE, in, j}}$, $s_{\text{r}}^2\left(p^{\text{j}}_{\text{WE}}\right)$ and $s_{\text{r}}^2\left(q^{\text{j}}_{\text{n, WE}}\right)$ are respectively given by equation (A.3.7h), equation (A.4.7f) and equation (A.4.7g). For the compressible case, the combined standard variance of the input power of compression of fluid j ($P_{\text{compr, WE, in, j}}$), $u_{\text{c}}^2\left(P_{\text{compr, WE, in, j}}\right)$, is calculated as

$$u_{\text{c}}^2\left(P_{\text{compr, WE, in, j}}\right)\ (\text{kW})^2 \;=\; \left(\underline{P}_{\text{compr, WE, in, j}}\ (\text{kW})\right)^2 \left(\left(\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}\right)^2 s_{\text{r}}^2\left(p^{\text{j}}_{\text{WE}}\right) + s_{\text{r}}^2\left(q^{\text{j}}_{\text{n, WE}}\right)\right); \tag{A.4.5f}$$

$\underline{P}_{\text{compr, WE, in, j}}$ is given by equation (A.3.7i). The combined standard variance of the molar flow rate of hydrogen ($q^{\text{WE}}_{\text{n, H}_2}$), $u_{\text{c}}^2\left(q_{\text{n, WE, H}_2}\right)$, is calculated as

$$u_{\text{c}}^2\left(q_{\text{n, WE, H}_2}\right)\ (\text{mol/h})^2 \;=\; \left(\underline{q}^{\text{WE}}_{\text{n, H}_2}\ (\text{mol/h})\right)^2 \left(s_{\text{r}}^2\left(x_{\text{n, WE, H}_2}\right) + s_{\text{r}}^2\left(q_{\text{n, WE, out}}\right)\right); \tag{A.4.5g}$$

$\underline{q}^{\text{WE}}_{\text{n, H}_2}$, $s_{\text{r}}^2\left(x_{\text{n, WE, H}_2}\right)$ and $s_{\text{r}}^2\left(q_{\text{n, WE, out}}\right)$ are respectively given by equation (A.3.7j), equation (A.4.7h) and equation (A.4.7i). The standard variance of the DC electric power ($P_{\text{el, dc, WE}}$), $s^2\left(P_{\text{el, dc, WE}}\right)$, is calculated as

$$s^2\left(P_{\text{el, dc, WE}}\right)\ (\text{kW})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(P_{\text{el, dc, WE, l}}\ (\text{kW}) - \bar{P}_{\text{el, dc, WE}}\ (\text{kW})\right)^2; \tag{A.4.6a}$$

$P_{\text{el, dc, WE, l}}$ is the measured value of the DC electric power while $\bar{P}_{\text{el, dc, WE}}$ is given by equation (A.3.6b). The standard variances of the mass flow rate ($q^{\text{i}}_{\text{m, WE}}$), $s^2\left(q^{\text{i}}_{\text{m, WE}}\right)$ and temperature of fluid i (T^{i}_{WE}), $s^2\left(T^{\text{i}}_{\text{WE}}\right)$, are respectively calculated as

$$s^2\left(q^{\text{i}}_{\text{m, WE}}\right)\ (\text{kg/s})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(q^{\text{i}}_{\text{m, WE, l}}\ (\text{kg/s}) - \bar{q}^{\text{i}}_{\text{m, WE}}\ (\text{kg/s})\right)^2 \quad \text{and} \tag{A.4.6b}$$

$$s^2\left(T^{\text{i}}_{\text{WE}}\right)\ (\text{K})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(T^{\text{i}}_{\text{WE, l}}\ (\text{K}) - \bar{T}^{\text{i}}_{\text{WE}}\ (\text{K})\right)^2; \tag{A.4.6c}$$

$q^{\text{i}}_{\text{m, WE, l}}$ and $T^{\text{i}}_{\text{WE, l}}$ are the measured values of respectively the mass flow rate and temperature of fluid i while $\bar{q}^{\text{i}}_{\text{m, WE}}$ and $\bar{T}^{\text{i}}_{\text{WE}}$ are respectively given by equation (A.3.6g) and equation (A.3.6h). The standard variances of the pressure (p^{j}_{WE}), $s^2\left(p^{\text{j}}_{\text{WE}}\right)$ and molar flow rate of fluid j ($q^{\text{j}}_{\text{n, WE}}$), $s^2\left(q^{\text{j}}_{\text{n, WE}}\right)$, are respectively calculated as

$$s^2\left(p^{\text{j}}_{\text{WE}}\right)\ (\text{kg/s})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(p^{\text{j}}_{\text{WE, l}}\ (\text{kPa}) - \bar{p}^{\text{j}}_{\text{WE}}\ (\text{kPa})\right)^2 \quad \text{and} \tag{A.4.6d}$$

$$s^2\left(q^{\text{j}}_{\text{n, WE}}\right)\ (\text{mol/h})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(q^{\text{j}}_{\text{n, WE, l}}\ (\text{mol/h}) - \bar{q}^{\text{j}}_{\text{n, WE}}\ (\text{mol/h})\right)^2; \tag{A.4.6e}$$

$p^{\text{j}}_{\text{WE, l}}$ and $q^{\text{j}}_{\text{n, WE, l}}$ are the measured values of respectively the pressure and molar flow rate of fluid j while $\bar{p}^{\text{j}}_{\text{WE}}$ and $\bar{q}^{\text{j}}_{\text{n, WE}}$ are respectively given by equation (A.3.6i) and equation (A.3.6j). The standard variances of the molar concentration of hydrogen ($x^{\text{WE}}_{\text{n, H}_2}$), $s^2\left(x^{\text{WE}}_{\text{n, H}_2}\right)$ and product gas molar flow rate ($q^{\text{WE}}_{\text{n, out}}$), $s^2\left(q_{\text{n, WE, out}}\right)$, are respectively calculated as

$$s^2\left(x^{\text{WE}}_{\text{n, H}_2}\right)\ (\text{mol/mol})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(x^{\text{WE}}_{\text{n, H}_2\text{, l}}\ (\text{mol/mol}) - \bar{x}^{\text{WE}}_{\text{n, H}_2}\ (\text{mol/mol})\right)^2 \quad \text{and} \tag{A.4.6f}$$

$$s^2\left(q_{\text{n, WE, out}}\right)\ (\text{mol/h})^2 \;=\; \frac{1}{L-1}\sum_{\text{l}=1}^{L}\left(q^{\text{WE}}_{\text{n, out, l}}\ (\text{mol/h}) - \bar{q}^{\text{WE}}_{\text{n, out}}\ (\text{mol/h})\right)^2; \tag{A.4.6g}$$

$x^{\mathsf{WE}}_{\mathsf{n,H_2,l}}$ and $q^{\mathsf{WE}}_{\mathsf{n,out,l}}$ are respectively the measured values of the molar concentration of hydrogen and product gas molar flow rate while $\bar{x}^{\mathsf{WE}}_{\mathsf{n,H_2}}$ and $\bar{q}^{\mathsf{WE}}_{\mathsf{n,out}}$ are respectively given by equation (A.3.6l) and equation (A.3.6m).

The relative standard variances of the input power ($P_{\mathsf{WE,in}}$), $u^2_{\mathsf{r}}\left(P_{\mathsf{WE,in}}\right)$, DC electric power ($P_{\mathsf{el,dc,WE}}$), $u^2_{\mathsf{r}}\left(P_{\mathsf{el,dc,WE}}\right)$ and input thermal power ($P_{\mathsf{th,WE,in}}$), $u^2_{\mathsf{r}}\left(P_{\mathsf{th,WE,in}}\right)$, are respectively calculated as

$$u^2_{\mathsf{r}}\left(P_{\mathsf{WE,in}}\right) = \frac{u^2_{\mathsf{c}}\left(P_{\mathsf{WE,in}}\right)\,\mathsf{(kW)^2}}{\left(\bar{P}_{\mathsf{WE,in}}\,\mathsf{(mol/h)}\right)^2}, \tag{A.4.7a}$$

$$u^2_{\mathsf{r}}\left(P_{\mathsf{el,dc,WE}}\right) = \frac{s^2\left(P_{\mathsf{el,dc,WE}}\right)\,\mathsf{(kW)^2}}{\left(\bar{P}_{\mathsf{el,dc,WE}}\,\mathsf{(mol/h)}\right)^2} \text{ and} \tag{A.4.7b}$$

$$u^2_{\mathsf{r}}\left(P_{\mathsf{th,WE,in}}\right) = \frac{u^2_{\mathsf{c}}\left(P_{\mathsf{th,WE,in}}\right)\,\mathsf{(kW)^2}}{\left(\bar{P}_{\mathsf{th,WE,in}}\,\mathsf{(mol/h)}\right)^2}; \tag{A.4.7c}$$

$u^2_{\mathsf{c}}\left(P_{\mathsf{WE,in}}\right)$, $\bar{P}_{\mathsf{WE,in}}$, $u^2_{\mathsf{c}}\left(P_{\mathsf{el,dc,WE}}\right)$, $\bar{P}_{\mathsf{el,dc,WE}}$, $u^2_{\mathsf{c}}\left(P_{\mathsf{th,WE,in}}\right)$ and $\bar{P}_{\mathsf{th,WE,in}}$ are respectively given by equation (A.4.5a), equation (A.3.6a), equation (A.4.6a), equation (A.3.6b), equation (A.4.5b) and equation (A.3.6c). The relative standard variances of the mass flow rate ($q^{\mathsf{i}}_{\mathsf{m,WE}}$), $s^2_{\mathsf{r}}\left(q^{\mathsf{i}}_{\mathsf{m,WE}}\right)$ and temperature of fluid i ($T^{\mathsf{i}}_{\mathsf{WE}}$), $s^2_{\mathsf{r}}\left(T^{\mathsf{i}}_{\mathsf{WE}}\right)$, are respectively calculated as

$$s^2_{\mathsf{r}}\left(q^{\mathsf{i}}_{\mathsf{m,WE}}\right) = \frac{s^2\left(q^{\mathsf{i}}_{\mathsf{m,WE}}\right)\,\mathsf{(kg/s)^2}}{\left(\bar{q}^{\mathsf{i}}_{\mathsf{m,WE}}\,\mathsf{(kg/s)}\right)^2} \text{ and} \tag{A.4.7d}$$

$$s^2_{\mathsf{r}}\left(T^{\mathsf{i}}_{\mathsf{WE}}\right) = \frac{s^2\left(T^{\mathsf{i}}_{\mathsf{WE}}\right)\,\mathsf{(K)^2}}{\left(\bar{T}^{\mathsf{i}}_{\mathsf{WE}}\,\mathsf{(K)}\right)^2}; \tag{A.4.7e}$$

$s^2\left(q^{\mathsf{i}}_{\mathsf{m,WE}}\right)$, $\bar{q}^{\mathsf{i}}_{\mathsf{m,WE}}$, $s^2\left(T^{\mathsf{i}}_{\mathsf{WE}}\right)$ and $\bar{T}^{\mathsf{i}}_{\mathsf{WE}}$ are respectively given by equation (A.4.6b), equation (A.3.6g), equation (A.4.6c) and equation (A.3.6h). The relative standard variances of the pressure ($p^{\mathsf{j}}_{\mathsf{WE}}$), $s^2_{\mathsf{r}}\left(p^{\mathsf{j}}_{\mathsf{WE}}\right)$ and molar flow rate of fluid j ($q^{\mathsf{j}}_{\mathsf{n,WE}}$), $s^2_{\mathsf{r}}\left(q^{\mathsf{j}}_{\mathsf{n,WE}}\right)$, are respectively calculated as

$$s^2_{\mathsf{r}}\left(p^{\mathsf{j}}_{\mathsf{WE}}\right) = \frac{s^2\left(p^{\mathsf{j}}_{\mathsf{WE}}\right)\,\mathsf{(kPa)^2}}{\left(\bar{p}^{\mathsf{j}}_{\mathsf{WE}}\,\mathsf{(kPa)}\right)^2} \text{ and} \tag{A.4.7f}$$

$$s^2_{\mathsf{r}}\left(q^{\mathsf{j}}_{\mathsf{n,WE}}\right) = \frac{s^2\left(q^{\mathsf{j}}_{\mathsf{n,WE}}\right)\,\mathsf{(K)^2}}{\left(\bar{q}^{\mathsf{j}}_{\mathsf{n,WE}}\,\mathsf{(K)}\right)^2}; \tag{A.4.7g}$$

$s^2\left(p^{\mathsf{j}}_{\mathsf{WE}}\right)$, $\bar{p}^{\mathsf{j}}_{\mathsf{WE}}$, $s^2\left(q^{\mathsf{j}}_{\mathsf{n,WE}}\right)$ and $\bar{q}^{\mathsf{j}}_{\mathsf{n,WE}}$ are respectively given by equation (A.4.6d), equation (A.3.6i), equation (A.4.6e) and equation (A.3.6j). The relative standard variances of the molar concentration of hydrogen ($x^{\mathsf{WE}}_{\mathsf{n,H_2}}$), $s^2_{\mathsf{r}}\left(x_{\mathsf{n,WE,H_2}}\right)$ and product gas molar flow rate ($q^{\mathsf{WE}}_{\mathsf{n,out}}$), $s^2_{\mathsf{r}}\left(q_{\mathsf{n,WE,out}}\right)$, are respectively calculated as

$$s^2_{\mathsf{r}}\left(x_{\mathsf{n,WE,H_2}}\right) = \frac{s^2\left(x^{\mathsf{WE}}_{\mathsf{n,H_2}}\right)\,\mathsf{(mol/mol)^2}}{\left(\bar{x}^{\mathsf{WE}}_{\mathsf{n,H_2}}\,\mathsf{(mol/mol)}\right)^2} \text{ and} \tag{A.4.7h}$$

$$s^2_{\mathsf{r}}\left(q_{\mathsf{n,WE,out}}\right) = \frac{s^2\left(q_{\mathsf{n,WE,out}}\right)\,\mathsf{(mol/h)^2}}{\left(\bar{q}^{\mathsf{WE}}_{\mathsf{n,out}}\,\mathsf{(mol/h)}\right)^2}; \tag{A.4.7i}$$

$s^2\left(x^{\mathsf{WE}}_{\mathsf{n,H_2}}\right)$, $\bar{x}^{\mathsf{WE}}_{\mathsf{n,H_2}}$, $s^2\left(x^{\mathsf{WE}}_{\mathsf{n,H_2}}\right)$, $\bar{x}^{\mathsf{WE}}_{\mathsf{n,H_2}}$, $s^2\left(q_{\mathsf{n,WE,out}}\right)$ and $\bar{q}^{\mathsf{WE}}_{\mathsf{n,out}}$ are respectively given by equation (A.4.6f), equation (A.3.6l), equation (A.4.6g) and equation (A.3.6m).

Annex B Test report

B.1 General

The test report shall accurately, clearly and objectively present all relevant information to demonstrate whether or not the objective(s) of the test is/are attained. As a minimum requirement, the test report shall contain a title page (see section B.2) and a summary report (see section B.3) with the measured or estimated TIPs and TOPs at least as mean values along with their (combined) standard uncertainties.

B.2 Title page

The titlepage shall present the following information:

(a) report identification, *i. e.* report number (optional),

(b) type of report (summary, detailed or full),

(c) author(s) of the report,

(d) entity issuing the report with name and address,

(e) date of the report,

(f) person(s) conducting the test when different from the report author(s),

(g) organisation conducting the test when different from report issuing entity,

(h) date and time per test run,

(i) location per test run when different from the address of the report issuing entity,

(j) descriptive name per test and

(k) identification (model name, serial number, type and specification) of the WE/HTE and/or system tested including manufacturer.

The titlepage may be followed by a contents page before the summary report.

B.3 Summary report

The summary report shall include the following information:

(i) test objective(s),

(ii) description of the test(s) with sufficient information on the measurement set-up (see section 6) including operating conditions such as input power (P_{in}), pressure and temperature of hydrogen,

(iii) all relevant test parameters (see section 5) and test results (see section 8.2) and

(iv) as appropriate, conclusion(s) including graphical presentation of test results and discussion with remark(s) and/or observation(s).

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