

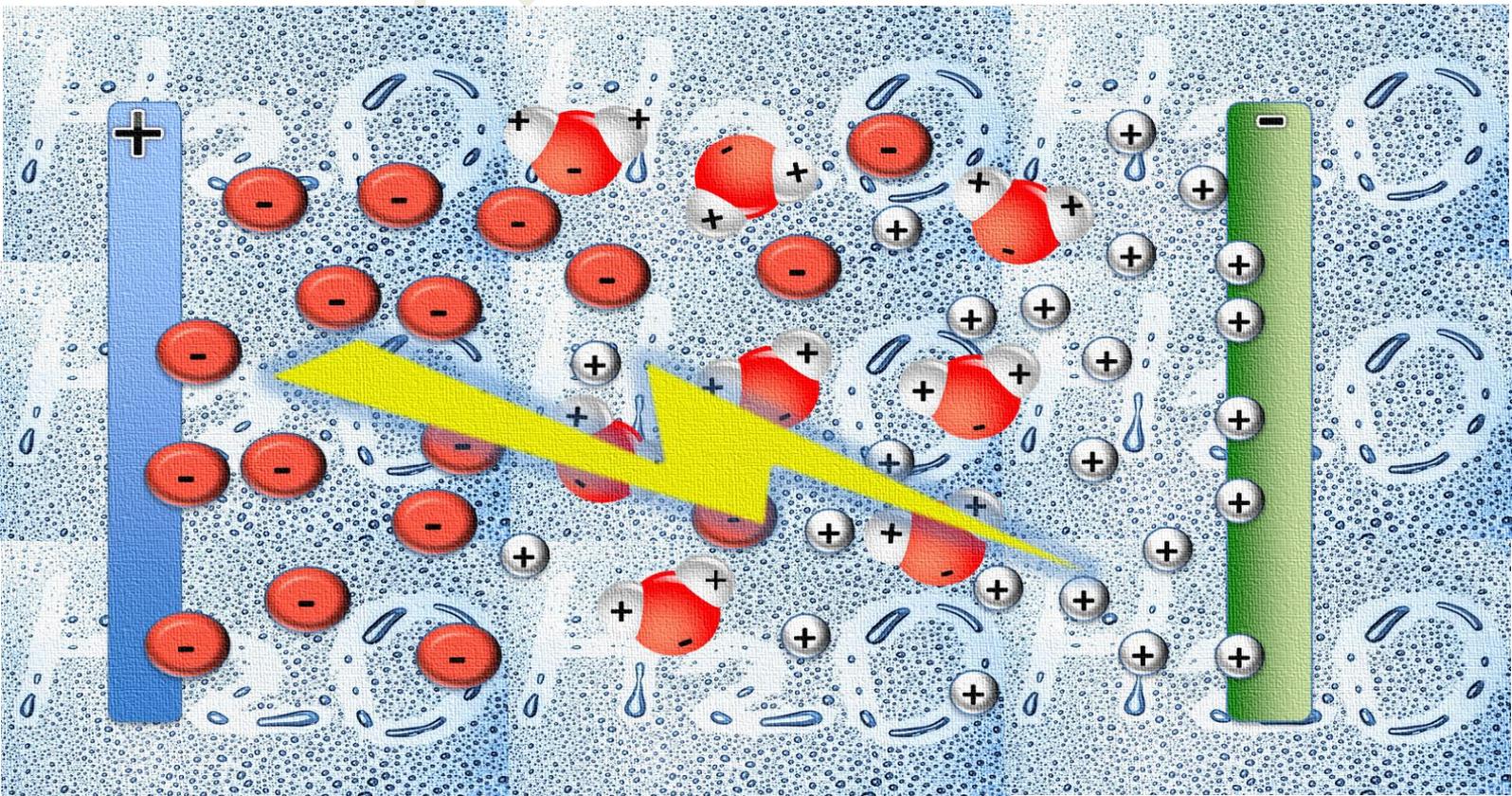
JRC SCIENCE FOR POLICY REPORT

EU HARMONISED TERMINOLOGY FOR LOW TEMPERATURE WATER ELECTROLYSIS FOR ENERGY STORAGE APPLICATIONS

Georgios Tsotridis; Alberto Pilenga

ISBN...

2018



This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

Contact information

Name: Georgios Tsotridis
Address: Westerduinweg 3, 1755 LE Petten, The Netherlands
Email: georgios.tsotridis@ec.europa.eu
Tel.: +31 22456 5656

JRC Science Hub

<https://ec.europa.eu/jrc>

JRCxxxxx

EUR xxxxx xx

Print	ISBN xxx-xx-xx-xxxxx-x	ISSN xxxx-xxxx	doi:xx.xxxxx/xxxxxx
PDF	ISBN xxx-xx-xx-xxxxx-x	ISSN xxxx-xxxx	doi:xx.xxxxx/xxxxxx

Luxembourg: Publications Office of the European Union, 2018
© European Union, 2018

The reuse of the document is authorised, provided the source is acknowledged and the original meaning or message of the texts are not distorted. The European Commission shall not be held liable for any consequences stemming from the reuse.

How to cite this report: Author(s), *Title*, EUR, doi

All images © European Union 2018: *The cover picture is an artistic impression of water electrolysis.*

Printed in 2018 (Belgium)



This report on "EU Harmonised Terminology for Low Temperature Water electrolysis for Energy Storage Applications" was carried out under the Framework Contract between the Joint Research Centre and the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU), Rolling Plan 2017.



EU HARMONISED TERMINOLOGY FOR LOW TEMPERATURE WATER
ELECTROLYSIS FOR ENERGY STORAGE APPLICATIONS



EU HARMONISED TERMINOLOGY FOR LOW TEMPERATURE WATER ELECTROLYSIS FOR ENERGY STORAGE APPLICATIONS

for FCH2JTC consultation



LIST OF CONTRIBUTORS

(in alphabetical order of their organisations)

for FCH2JU consultation



Aragon Hydrogen
Foundation

Laura Abadía Albás
Vanessa Gil



AREVA H₂Gen

AREVA H₂Gen

Fabien Auprêtre



CEA Commissariat à
l'énergie atomique et aux
énergies alternatives

Frederic Fouda-Onana



Deutsches Zentrum für
Luft- und Raumfahrt e. V.

Regine Reißner
Aldo Gago



Energy Research Centre
of Netherlands

Arhend Degroot
Frans van Berkel



Swiss Federal
Laboratories for Materials
Science and Technology

Ulrich Vogt
Wenbo Ju



Fraunhofer-Institut für
Mikrostruktur von
Werkstoffen und
Systemen

Dominik Härle



Fraunhofer-Institut für
Solare Energiesysteme

Tom Smolinka



HYDROGENICS

Jan Vaes



Industrie Haute
Technologie

Pablo Marcuello

 <p>UNIVERSITÉ PARIS SUD Comprendre le monde, construire l'avenir®</p>	<p>Institut de Chimie Moléculaire et des Matériaux d'Orsay – Université Paris-Sud</p>	<p>Pierre Millet</p>
 <p>um² UNIVERSITÉ MONTPELLIER 2 SCIENCES ET TECHNOLOGIES</p>  <p>HySPaC</p>	<p>Institut Européen des Membranes, Université de Montpellier</p>	<p>Claude Lamy</p>
 <p>Consiglio Nazionale delle Ricerche</p>  <p>ITAE</p>	<p>Istituto di Tecnologia Avanzate per L'Energia "Nicola Giordano"</p>	<p>Antonino Aricó</p>
 <p>ITM POWER</p>	<p>ITM power</p>	<p>Frederic Marchal Marcus Newborough</p>
 <p>Leibniz Universität Hannover</p>  <p>IFES</p>	<p>Institute for electric energy systems Leibniz Universität Hannover</p>	<p>Richard Hanke- Rauschenbach</p>
 <p>nel</p>	<p>Nel Hydrogen</p>	<p>Anders Søreng</p>
 <p>P V 3 TECHNOLOGIES</p>	<p>PV3 Technologies Ltd</p>	<p>Nicholas van Dijk</p>
 <p>SIEMENS</p>	<p>Siemens</p>	<p>Richard Wagner Manfred Waidhas</p>
 <p>SINTEF</p>	<p>SINTEF</p>	<p>Magnus Thomassen</p>
 <p>Z B T</p>	<p>Zentrum für BrennstoffzellenTechnik</p>	<p>Ivan Radev Sebastian Stypka</p>
 <p>ZSW</p>	<p>Zentrum für Sonnenenergie- und Wasserstoff-Forschung BW</p>	<p>Ludwig Jörissen</p>

TABLE OF CONTENTS

1	INTRODUCTION	1
2	LOW TEMPERATURE WATER ELECTROLYSIS TECHNOLOGIES	3
2.1	ALKALINE WATER ELECTROLYSIS (AWE) CELL	4
2.2	ANION EXCHANGE MEMBRANE WATER ELECTROLYSIS (AEMWE) CELL	4
2.3	PROTON EXCHANGE MEMBRANE WATER ELECTROLYSIS (PEMWE) CELL	4
2.4	ELECTROLYSIS STACK	4
2.5	PROTON EXCHANGE MEMBRANE WATER ELECTROLYSIS (PEMWE) SYSTEM	6
2.6	ALKALINE WATER ELECTROLYSIS (AWE) SYSTEM	8
2.7	ANION EXCHANGE MEMBRANE WATER ELECTROLYSIS (AEMWE) SYSTEM	10
3	TERMINOLOGY	10
3.1	AREA	11
3.2	AXIAL LOAD	11
3.3	CELL COMPONENTS	12
3.4	COOLANT	16
3.5	CURRENT	16
3.6	DEGRADATION	17
3.7	EFFICIENCY	20
3.8	ELECTRICAL POWER	53
3.9	GAS CROSSOVER	54
3.10	GAS LEAKAGE	54
3.11	GAS TIGHTNESS	54
3.12	GRID OR ELECTRICITY NETWORK	54
3.13	HEATING VALUE	65
3.14	HYDROGEN	66
3.15	KEY PERFORMANCE INDICATOR	66
3.16	OPERATING CONDITIONS	66
3.17	OPERATIONAL MODE	66
3.18	OPERATIONAL PARAMETERS	68
3.19	PRESSURE	71
3.20	PURITY OF GASES	71
3.21	RELIABILITY	72
3.22	RESISTANCE (ELECTRICAL)	72
3.23	SAFEGUARDING	72



3.24	TESTING	72
3.25	THERMAL MANAGEMENT SYSTEM	74
3.26	TIME.....	74
3.27	VOLTAGE	74
3.28	WATER.....	75
4	SYMBOLS.....	76
5	REFERENCES	78

for FCH2JU consultation

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to all participants and their respective organisations for their contributions in developing this terminology document for low temperature water electrolysis applications.

We would also like to thank the "Fuel Cell and Hydrogen second Joint Undertaking" (FCH2JU) Programme Office and in particular Dr. Nikolaos Lymperopoulos for the continuous support and encouragement we received throughout the different stages of this activity.

We would also like to express our gratitude to the "European Network of Transmission System Operators for Electricity" (ENTSOE), for granting permission of using extras from their glossary.

The authors would like to thank the International Electrotechnical Commission (IEC) for permission to reproduce Information from its International Standards. All such extracts are copyright of IEC, Geneva, Switzerland. All rights reserved⁽¹⁾

We would like to thank Pierre Millet Université Paris-Sud, Claude Lamy Université de Montpellier and Antonino Aricò Istituto di Tecnologie Avanzate per L'Energia, Messina for their fruitful discussion and support in preparing the efficiency part of the document.

⁽¹⁾ *Disclaimer*

Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced by the author, nor is IEC in any way responsible for the other content or accuracy therein.

IEC TS 62282-1 ed.3.0 "Copyright © 2013 IEC Geneva, Switzerland. www.iec.ch

1 INTRODUCTION

The energy transition towards low carbon technologies is a key political objective for the European Union which has defined a strategy to progressively decrease the CO₂ equivalent content throughout all the relevant power generation and distribution, industrial, transport and buildings sectors with the ultimate goal to decrease the greenhouse gas emissions to 80% below 1990 levels by 2050, with intermediate steps of 20% by 2020 and 40% by 2030.

In this context, hydrogen could play an important role having significant potential benefits to enable this transition to low carbon energy systems. Hydrogen in fact is not only considered as the ultimate cleaner energy carrier having no CO₂ emissions when burned but it is very versatile and therefore it could be used in a number of wide range industrial applications, such as use as feedstock in many industries (ammonia, refineries, etc.) to the fuel transportation sector.

The hydrogen production is still largely based on steam reforming of natural gas. Such type of production cannot be classified as renewable as it is linked to a fossil fuel as feedstock. Water would be a better source of hydrogen, but although the water electrolysis process is known for more than a century, today only 4% of the hydrogen is produced by this process due to the higher cost of production. However, recently the water electrolysis is receiving a new industrial attention as a possible relevant player in the emerging sustainable energy storage field, because electrolyzers could operate when electricity generation is available at very low prices or in excess of demand due to the introduction of renewable energy sources.

This report on "EU Harmonised Terminology for Low Temperature Water electrolysis for Energy Storage Applications" was carried out under the Framework Contract between the Joint Research Centre and the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU), Rolling Plan 2017.

This document is the result of a collaborative effort between industry partners, research organisations and academia participating in several Fuel Cell and Hydrogen second Joint Undertaking funded projects in Low Temperature Water Electrolysis applications.

The objectives of the report is to present to those involved in research and development a comprehensive and harmonised compendium of various terminology terms which are encountered in low temperature water electrolysis applications.

It provides clear definitions of module and system boundaries, for the three low water electrolysis technologies, namely Alkaline Water Electrolysis (AWE), Anion Exchange Membrane Water Electrolysis (AEMWE), and Proton Exchange Membrane Water Electrolysis (PEMWE). In addition, the report provides in alphabetical order a comprehensive list of appropriate terminology expressions used in various electrolysis applications such as various “electrochemical expressions”. It also presents a set of expressions frequently used within the “renewable energy storage sector” with “power distribution grid balancing” terminology expressions, where the electrolysis technology could play an important role.

To this respect, the document also makes reference of terminology expressions derived in other International Standards Drafting Organisations (SDOs) such as the International Electrotechnical Commission (IEC), as well under relevant European initiatives such as the European Network of Transmission System Operators for Electricity” (ENTSOE), and the Fuel Cells and Standardisation Network (FCTESTNET).

In addition, the document also provides an extensive account of science-based industry-endorsed definitions of Key Performance Indicators, such as definitions of various “efficiency” terms currently in use by research, academia and industry and provides a detailed methodology of the derivation of the relevant efficiency equations.

2 LOW TEMPERATURE WATER ELECTROLYSIS TECHNOLOGIES

Three different types of Low Temperature Water Electrolysis technologies are currently available as commercial products, namely Proton Exchange Membrane Water Electrolysis (PEMWE) that uses an acidic polymer electrolyte (and for this reason sometimes called also Polymer Electrolyte Membrane), Alkaline Water Electrolysis (AWE) (liquid electrolyte electrolysis) and most recently Anion Exchange Membrane Water Electrolysis (AEMWE).

The relevant differences among the three mentioned technologies are summarized in the table 1 below:

Table 1

State of the Art Low Temperature Water Electrolysis Technologies

Type	AEMWE	AWE	PEMWE
Charge carrier	OH ⁻	OH ⁻	H ⁺
Reactant	Water	Water	Water
Electrolyte	Anion exchange membrane	KOH 20-40 wt.% /water	Proton exchange membrane
Electrode	Ni, NiO, Co based catalyst	Raney Ni, Fe, Co, Mn,	Pt/C, IrO ₂
Current density	0.2-0.8 A/cm ²	0.2-0.5 A/cm ²	0.2-3.0 A/cm ²
Temperature	40-50 °C	40-90°C	20-80°C (*)
Pressure H₂ out	10 ⁵ – 30·10 ⁵ Pa	10 ⁵ – 30·10 ⁵ Pa	10 ⁵ –30·10 ⁵ Pa
Cathode reaction (HER)**	2H ₂ O(l)+2e ⁻ → H ₂ (g)+ 2 HO ⁻ (aq)	2H ₂ O(l)+2e ⁻ → H ₂ (g)+ 2 HO ⁻ (l)	2H ⁺ (aq) +2e ⁻ → H ₂ (g)
Anode reaction (OER)**	2 HO ⁻ (aq) → H ₂ O(l) +1/2 O ₂ (g)+ 2e ⁻	2 HO ⁻ (aq) → H ₂ O(l) +1/2 O ₂ (g)+ 2e ⁻	H ₂ O(l)→ 1/2 O ₂ (g)+ 2H ⁺ (aq) + 2e ⁻

(*) Research efforts are targeting temperatures up to 120°C

(**) (aq), (l) & (g) refers to aqueous, liquid and gaseous state

Each type of electrolyser is a combination and assembly of various parts that can be grouped in ascending order of complexity per individual technology as follows:

- Single cell (Electrolysis Cell)
- Stack (Electrolysis Stack)
- Electrolysis component or string
- Electrolysis system

2.1 ALKALINE WATER ELECTROLYSIS (AWE) CELL

An electrolysis set-up consisting of three functional elements: a cathode, a microporous diaphragm or membrane and an anode, which are embedded in an alkaline solution for hydrogen and oxygen production with the provision of electrical energy.

2.2 ANION EXCHANGE MEMBRANE WATER ELECTROLYSIS (AEMWE) CELL

An electrolysis cell consisting of three functional elements: a cathode, a solid hydroxyl exchange polymer membrane as electrolyte for the transport of hydroxides and an anode for hydrogen and oxygen production with the provision of external electrical energy as driving force in an electrochemical process

2.3 PROTON EXCHANGE MEMBRANE WATER ELECTROLYSIS (PEMWE) CELL

An electrolysis cell consisting of three functional elements: a cathode, a solid proton exchange polymer and an anode, which is able to produce hydrogen and oxygen from water electrochemical splitting by providing external electrical energy.

2.4 ELECTROLYSIS STACK

An electrolysis stack is an assembly of more than one electrolysis cell, mostly in a filter press arrangement and connected electrically either in parallel (scheme a, monopolar assembly), in full series (scheme b, bipolar assembly) or in series with a central anode (scheme c) and hydraulically in parallel. In addition to these cells an electrolysis stack consists of further components as separators, cooling plates, manifolds and a supporting structure.

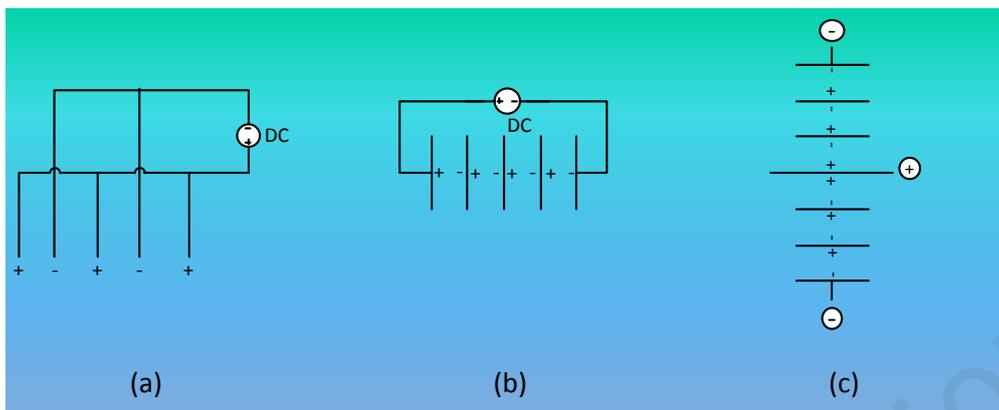


Figure 1

Schematic diagram showing various cell interconnection modes

Typical components of an Electrolysis stack are

- Membrane or diaphragm
- Electrodes (anode and cathode)
- Porous transport layers (PTL) or liquid gas diffusion layer (LGDL)
- Bipolar plate as separator plate between two adjacent electrolysis cells, sometimes with additional flow fields for an easier fluid distribution
- Cell frames and/or gaskets and/or sealing
- Current distributor
- End plates for mechanical compression
- Electrical terminals
- Balance of stack as tie bolts etc.

2.5 PROTON EXCHANGE MEMBRANE WATER ELECTROLYSIS (PEMWE) SYSTEM

A **PEMWE system**, whose typical scheme is depicted in Figure 2, is an assembly incorporating various number of components designed to operate the electrochemical conversion unit(s) (also called stack) at the intended operating conditions (temperature, pressure, water, supply of electrolyte and gas purity).

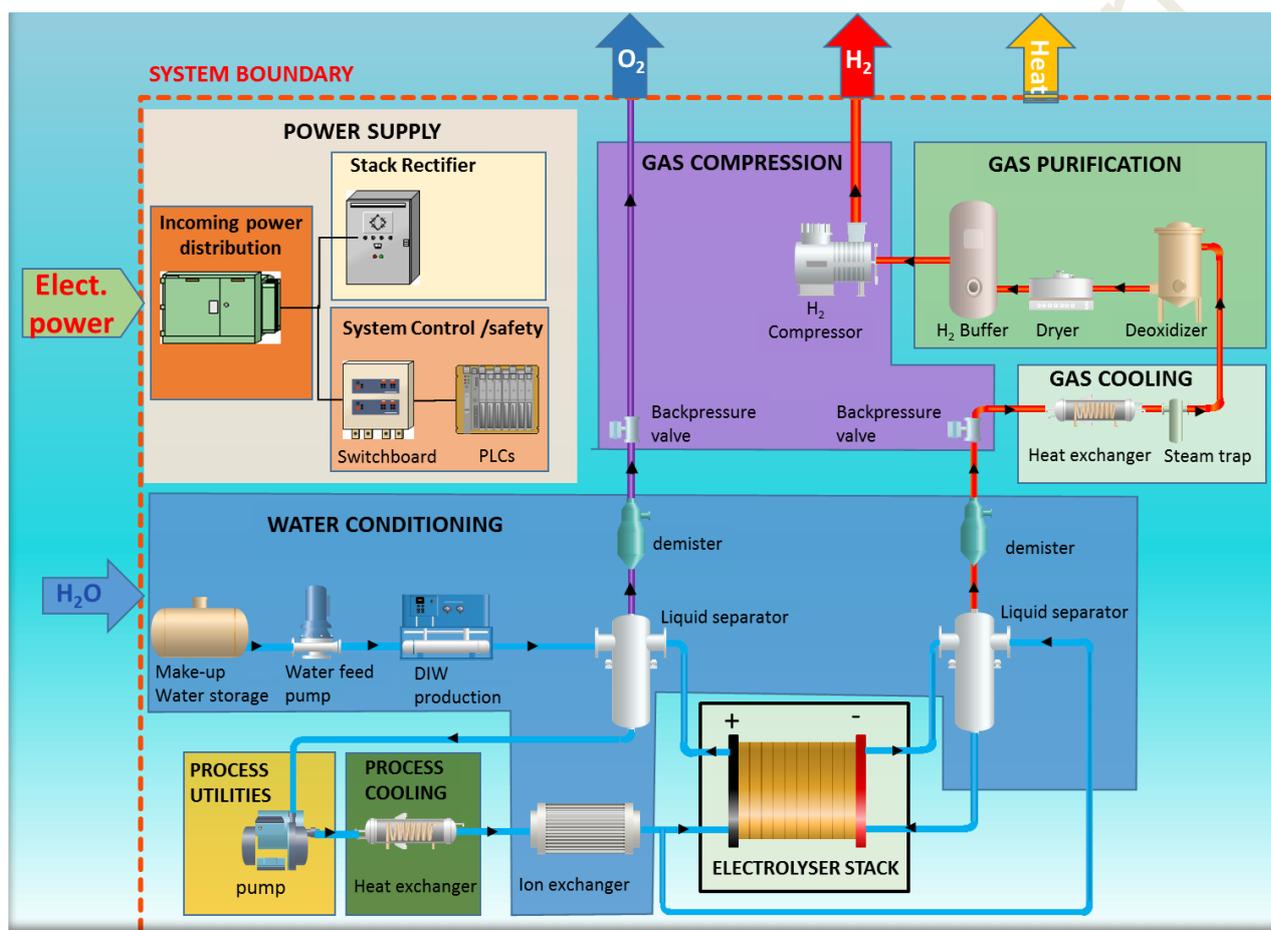


Figure 2

Schematic representation of the components of a PEMWE system

2.5.1 PEMWE COMPONENTS

The typical **components** of a **PEMWE** system are as follows:

- **POWER SUPPLY** which includes:
 - **Incoming power distribution** that consists of the grid connection and transformer to adjust the electricity from the transportation or distribution network to the operational requirements,
 - **Rectifier for stack operation,**

- **System control board** for other auxiliary components of the electrolysis system including automatic control system to operate the system according to manufacturer's specification. It includes safety sensors, process parameter measuring devices, piping and valves, plc's, data I/O, PC.
- **WATER CONDITIONING** for the necessary treatment of the water supplied and recovered that is composed by:
 - Make-up water tank
 - Water feed pump
 - De-Ionized Water production unit (DIW)
 - Anodic circulation loop consisting of:
 - Water purification unit – mostly an ion exchange resin bed – used to keep the water quality at the desired level, to minimize the risk of chemical contamination of the stack;
 - Oxygen / water separator vessel used for a first separation of residual liquid water in the gases outlet stream;
 - Demisters used for further removal of small liquid water droplets from the gas outlet stream.
 - Cathodic circulation loop consisting at least of:
 - a hydrogen / water separator vessel and subsequent demister and sometimes an additional circulation pump for defined thermal management of the cathode side.
- **ELECTROLYSER STACK** that is the core of the system where water is electrochemically converted into hydrogen and oxygen by means of a DC current. It comprises one or more PEMWE stack(s) connected either in series or parallel mode.
- **PROCESS UTILITIES** consisting of the elements using power for the operation like the water recirculation pump enabling a continuous flow of water into the stack for the electrochemical reaction itself and for the thermal management of the stack; process value measuring devices (i.e. pressure sensor, flow meter, gas sensors)
- **PROCESS COOLING** consisting of heat exchanger(s) for the thermal management of the pumped water to remove heat out of the circulation loop and to keep the stack at the proper temperature range.
- **GAS COOLING** consisting of heat exchanger(s) for the thermal management of the gases produced during the electrolysis process.
- **GAS PURIFICATION** to clean the hydrogen product stream to the desired level of quality consisting of:
 - De-oxidation stage, to recombine catalytically residual traces of oxygen that could be present due to cross-over effects;
 - Gas dryer to remove residual moisture down to the ppm level;
 - Buffer tank for compensation of variable hydrogen production.
- **GAS COMPRESSION** composed of:
 - Pressure control valve for hydrogen and oxygen to operate the EL system at the desired pressure level (either pressure balanced or differential pressure).
 - Compressor, to bring the gas pressure at the specified value.
 - High pressure storage tank(s) for the final storage of the gas produced by the electrolyser.

2.6 ALKALINE WATER ELECTROLYSIS (AWE) SYSTEM

The principle layout of an **AWE system** is shown in Figure 3. The utmost noticeable difference compared to PEMWE systems is that in this case the electrolyte is an aqueous alkaline solution formed by KOH with a concentration of approx. 20-30% in deionized water called Lye. The anode and cathode electrodes are immersed in this solution separated by a diaphragm. This solution is caustic and this shall be taken into consideration for the selection of the proper material for the components that are or may get in contact with Lye solution.

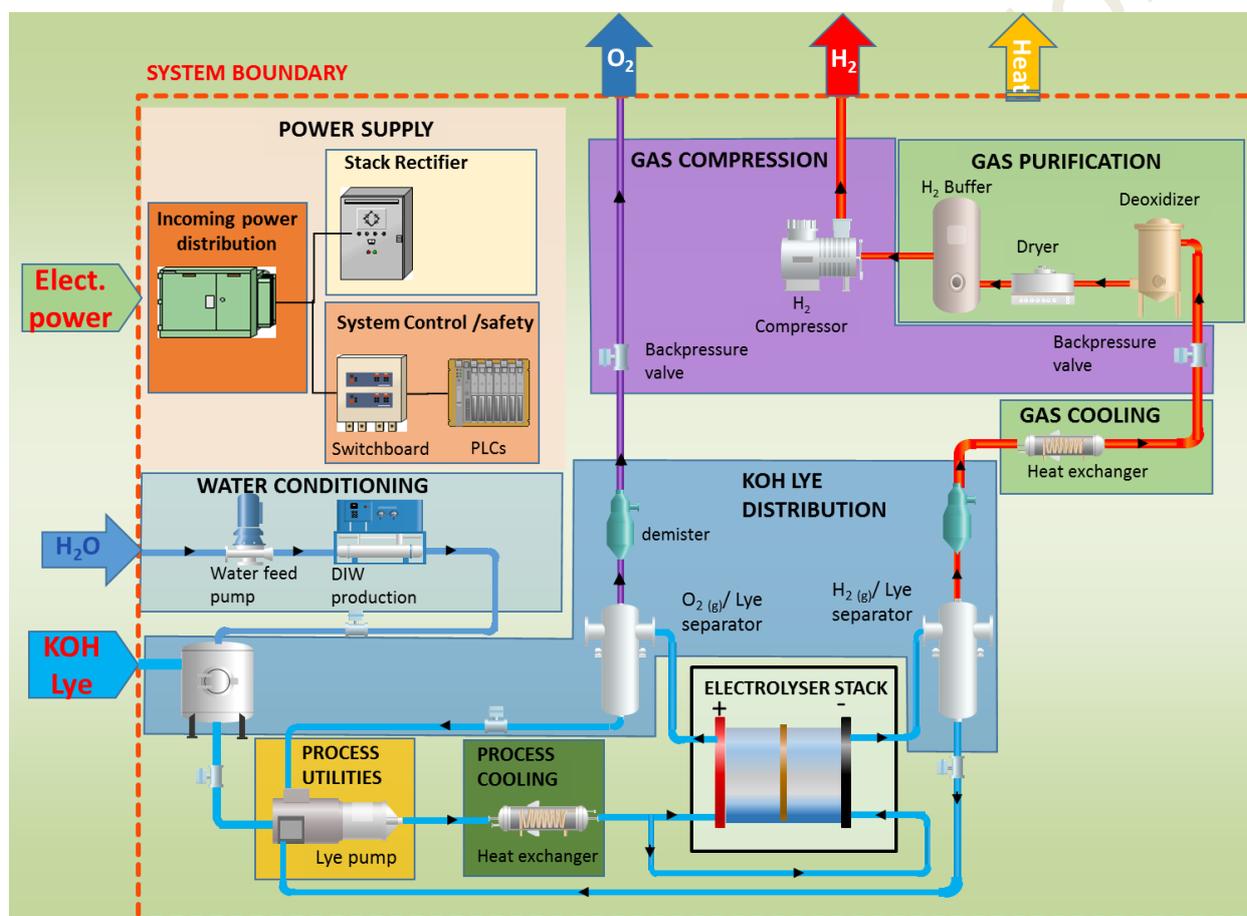


Figure 3

Schematic representation of the components of an AWE system

2.6.1 AWE COMPONENTS

The typical **AWE components** include the following items:

- **POWER SUPPLY**, see 2.5.1
- **WATER CONDITIONING**
 - Alkaline electrolysis stack
 - Lye supply/recirculation system is used to provide a continuous electrolyte flow into the stack for the electrochemical reaction and thermal management. The main components are:
 - Lye recirculation pump
 - Lye heat exchanger
 - Gas/lye separator, used for a first separation of residual liquid in the produced gases outlet stream.
 - Demisters and scrubbers are devices for further removal of water and lye aerosols from the gases outlet stream.
- **ELECTROLYSER STACK**, see 2.5.1
- **PROCESS UTILITIES**, see 2.5.1
- **PROCESS COOLING**, see 2.5.1
- **GAS COOLING**, see 2.5.1
- **GAS PURIFICATION**, see 2.5.1
- **GAS COMPRESSION**, see 2.5.1

2.7 ANION EXCHANGE MEMBRANE WATER ELECTROLYSIS (AEMWE) SYSTEM

An **AEMWE system** is an assembly essentially similar to a PEMWE system but the type of stack technology used is based on the anion exchange membrane instead of ion exchange membrane.

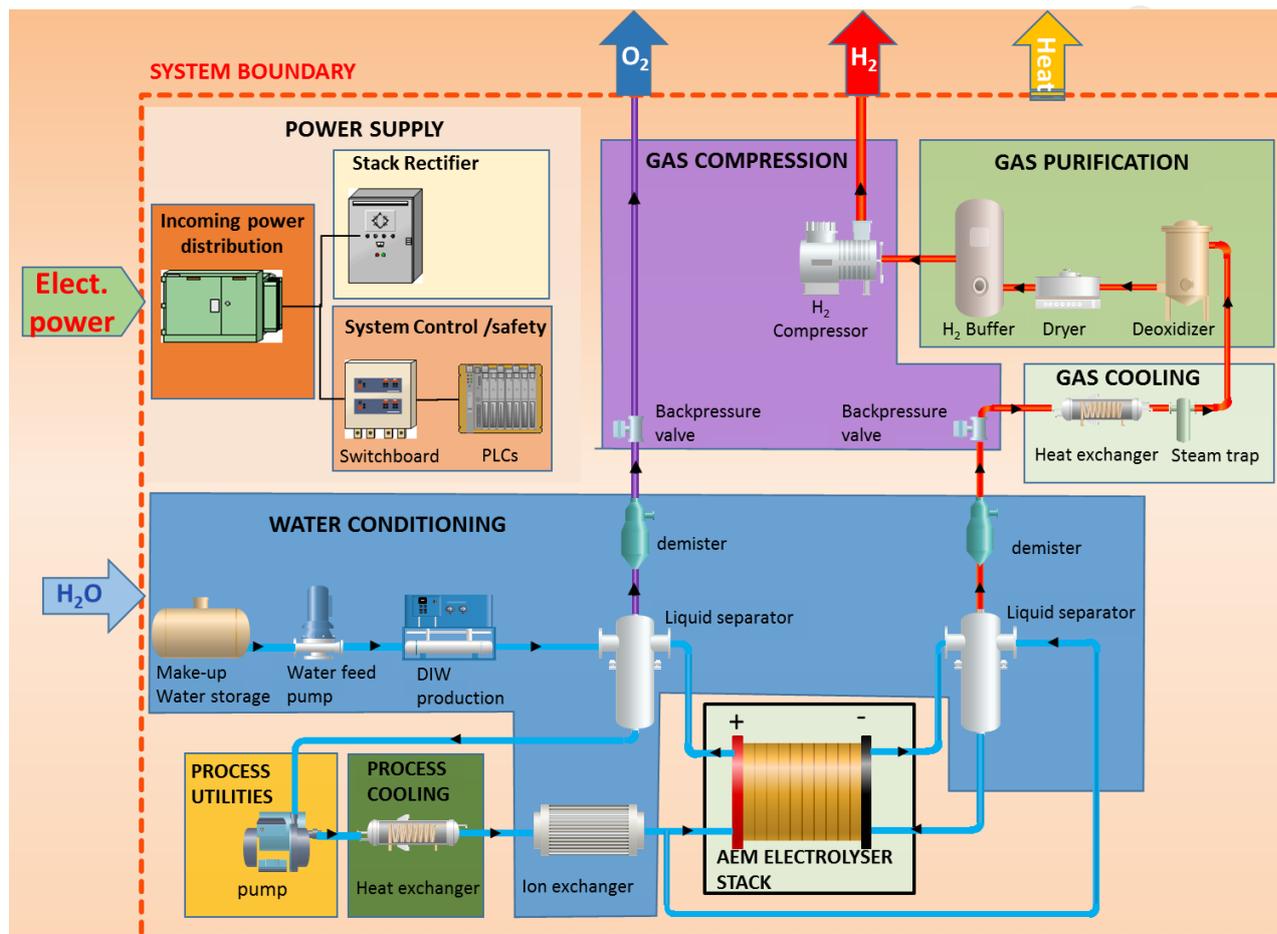


Figure 4

Schematic representation of the components of an AEMWE system

2.7.1 AEMWE COMPONENTS

As above mentioned the components are equivalent to the ones described for the PEMWE system in 2.5.1 with only the difference related to the stack technology.

3 TERMINOLOGY

3.1 AREA

3.1.1 ACTIVE AREA

It is the geometric area of the electrode which is perpendicular to the direction of the current flow and is available for electrochemical reaction [Units: m²].⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.1.2 CELL AREA

Geometric area of the bipolar plate perpendicular to the direction of current flow.⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.1.3 GEOMETRIC ELECTRODE AREA

Geometric electrode area is the largest area of the electrode projected on a plane [Units: m²].

3.1.4 EFFECTIVE AREA

See equivalent definition of active area.

3.1.5 ELECTROCHEMICAL SURFACE AREA (ECSA)

Electrochemical surface area is the real surface area of an electrocatalyst accessible to an electrochemical process due to its open porous structure.

It is presented as electrochemical surface area per unit mass (or volume) of the catalyst or per geometric electrode area [Units: m²/g, m²/m³, m²/m²].

3.1.6 SPECIFIC SURFACE AREA

Electrochemical surface area per unit mass (or volume) of the catalyst

The specific surface area corresponds to the area of an electrocatalyst accessible to reactants due to its open porous structure, per unit mass (or volume, or electrode geometric area) of the catalyst⁽¹⁾ [Units: m²/g, m²/m³].⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.2 AXIAL LOAD

Compressive load applied to the end plates of an electrolysis cell or stack to assure contact and/or gas tightness⁽²⁾ [Units: Pa].

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3 CELL COMPONENTS

3.3.1 BIPOLAR PLATE

Electrical conductive and gas tight plate separating individual cells in a single cell or stack, acting as reagent flow distributor and current distributor and providing mechanical support for the electrodes or membrane electrode assembly. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.2 CATALYST

Substance that increases the rate of a reaction without being consumed itself. The catalyst lowers the activation energy of the reaction, allowing for an increase in the reaction rate, or to proceed at a lower temperature or overpotential. A catalyst that promotes an electrochemical reaction is termed an 'electrocatalyst'. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.3 CATALYST COATED MEMBRANE (CCM)

Specific configuration of a membrane electrode assembly (for PEMWE and AEMWE cell) where the catalyst layers are coated directly as electrodes onto the membrane.

3.3.3.1 CATALYST LAYER (CL)

Layer adjacent to the membrane on either side of the membrane comprising of electro catalyst particles and ionomer with co-existing ionic and electronic conductivity. This layer comprises the spatial region where the electrochemical reactions may take place. ⁽⁴⁾

3.3.3.2 CATALYST LOADING

Amount of catalyst incorporated per unit electrode geometric area, specified either per anode or cathode separately, or combined anode and cathode loading [Units: g/cm²]. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.3.3 CATALYST POISONING

Inhibition of the catalyst properties by adsorbate substances (poisons). ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.3.4 ELECTROCATALYST

An electrocatalyst is a catalyst that participates in and accelerates/catalyses an electrochemical reaction.

For low temperature water electrolysis the electrocatalyst can be built up as porous bulk catalyst or consists of a catalyst dispersed on support particles like carbon powder or titanium sub-oxides which increase the ECSA of the catalyst.

3.3.3.5 ELECTROCATALYST SUPPORT

Component of an electrode that is the support of the electrocatalyst, and serves as porous and electrically conductive medium. It also leads to a higher ECSA of the catalyst and a reduced loading of electrocatalyst in the electrode. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.4 CLAMPING PLATE

See equivalent definition of end plate 3.3.8.

3.3.5 COMPRESSION END PLATE

See equivalent definition of end plate 3.3.8.

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.6 ELECTRODE

Electronic conductor through which an electric current enters or leaves the electrochemical cell as the result of an electrochemical reaction. ⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.3.6.1 ANODE

Electrode at which the water oxidation reaction (electron loss) occurs leading to the Oxygen Evolution Reaction (OER).

3.3.6.2 CATHODE

Electrode at which the water reduction reaction (electron gain) occurs leading to the Hydrogen Evolution Reaction (HER) reduction.

3.3.6.3 ELECTRODE POTENTIAL

Difference between the internal electric potential of the electrode (electronic conductor) and electrolyte (ionic conductor).

3.3.7 ELECTROLYTE

The electrolyte is the medium for charge transfer between the electrodes in an electrochemical cell.

It is a ionic conductor (e. g. solution, solid, molten salt or gas) in which the electric current is carried by ionic species (cations and anions). The respective transference number characterises the fraction of the current carried either by cations or anions. In an electrochemical cell the charge transfer reactions (e.g. OER or HER) take place at the interface between the electrode and the electrolyte.

The nature of the electrolyte is the main distinctive feature of the different fuel cell technologies and determines the useful operating temperature range. ⁽⁴⁾

3.3.7.1 LIQUID ELECTROLYTE LEAKAGE

Undesired escape of liquid electrolyte from a cell/stack. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.7.2 ELECTROLYTE LOSS

Any decrease with respect to the initial electrolyte content in an electrolyser system. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.7.3 ELECTROLYTE MATRIX

Insulating gas-tight cell component with a properly tailored pore structure that retains the liquid electrolyte. ⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.3.7.4 ELECTROLYTE MIGRATION

Ion transport mechanism resulting from electrical potential gradients affecting electrolyte local concentration.

3.3.7.5 ELECTROLYTE RESERVOIR

A component of liquid electrolyte module. A proper amount of liquid electrolyte is stored therein with the purpose to replenish electrolyte losses over the cell life. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.8 END PLATE

Component located on either end of the electrolyser cell or stack serving to transmit the required compression to the stacked cells to allow proper electrical contact and to avoid fluids leaks. The end plate may comprise ports, ducts or manifolds for the conveyance of fluids (reactants, coolant, cable wiring) to/from the cell or stack. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.3.9 GASKET

Component that prevents exchange of fluids between two or more compartments of a device, or leakage of fluids from a device to the outside. ⁽⁴⁾

3.3.10 IONOMER SOLUTION

Dispersion of ion conductive polymer in water or in water and low aliphatic alcohols. It is used in the manufacturing of electrocatalytic layers to increase the electrode-electrolyte interface area by ensuring better contact between the electrocatalyst particles and the ion conducting polymer membrane.

3.3.11 LIQUID/GAS DIFFUSION LAYER (LGDL)

Diffusion porous layer facilitating the mass transport of reactants and removal of reaction products. It is made of a porous medium or a combination of different porous media forming adjacent layers or a composite layer.

3.3.12 MEMBRANE

The separating layer that acts as electrolyte (an ion-exchanger) as well as a barrier film separating H₂/O₂ gases and electronic conducting materials of the anode and cathode compartments of the AEM or PEM electrolyser.⁽⁴⁾

3.3.12.1 ANION EXCHANGE MEMBRANE (AEM)

Polymer based Membrane with **anion** conductivity which serves as electrolyte and separator between the anode and the cathode.

3.3.12.2 PROTON EXCHANGE MEMBRANE (PEM)

Polymer based Membrane with **proton** conductivity which serves as electrolyte and separator between the anode and the cathode.

3.3.13 MEMBRANE ELECTRODE ASSEMBLY (MEA)

Assembly of CCM with thin porous transport layers and edge reinforcement membranes. Its geometric area includes active (see 3.1.1) and non-active areas.

3.3.14 POROUS TRANSPORT LAYER (PTL)

See equivalent definition of liquid/gas diffusion layer 3.3.11

3.3.15 SEPARATOR PLATE

See equivalent definition of bipolar plate.3.3.1

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.3.16 SINGLE ELECTROLYSIS CELL

Basic unit of an electrolysis device composed of three functional elements namely, cathode, electrolyte and anode, that are capable to break up chemical compounds by

applied electrical energy to produce reduced and oxidized compounds. In a water electrolysis cell hydrogen and oxygen are generated by electrochemical splitting of de-ionized water or water in alkaline aqueous solutions by providing external electrical energy.

3.3.17 SPACER

An electrically insulating component spaces two opposite electrodes and provides space for the flow of electrolyte between the electrodes.

3.3.18 WATER SEPARATOR

Device that condenses and separates water vapour in the gas discharged from the cell/system.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.4 COOLANT

A fluid used to control heat transfer between various media and components.⁽⁴⁾ Heat dissipated to the atmosphere through the cooling circuit of the system, typically by an air-to-liquid heat exchanger.⁽⁴⁾

3.5 CURRENT

3.5.1 CURRENT DENSITY

A vector-point function describing the magnitude and direction of charge flow, i.e. the current intensity per unit area [Units: A/m²].⁽⁴⁾

3.5.2 CURRENT RAMP RATE

The rate at which the amount of electric current change over time. [Units: A/s].

3.5.3 LEAKAGE CURRENT

Electric current in an unwanted conductive path other than a short-circuit [Units: A].⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.5.4 NOMINAL CURRENT

Electric current value associated to the nominal design point as specified by the manufacturer [Units: A].

3.5.5 OVERLOAD CURRENT

See Rated current 3.5.6

3.5.6 RATED CURRENT

Maximum continuous electric current as specified by the manufacturer, at which the electrolyser system has been designed to operate [Units: A].⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.5.7 SPECIFIC CURRENT DENSITY

Current per unit electrocatalyst surface active area at a given cell voltage [Units: A/m²].

3.5.8 VOLUMETRIC CURRENT DENSITY

A vector-point function describing the magnitude and direction of charge flow, i.e. the current intensity per unit volume [Units: A/m³].

3.6 DEGRADATION

3.6.1 DEGRADATION RATE

Rate of change of a measurable quantity over time. The degradation rate can be used to measure both reversible (non-permanent) and irreversible (permanent) losses in cell performance. Mostly the degradation rate refers to the cell voltage.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.6.2 CELL VOLTAGE DEGRADATION RATE

The cell voltage degradation is an increase in the cell voltage due to deterioration processes inside an electrolysis cell. The cell voltage evolution rate is the most used expression to describe the degradation rate of an electrolysis cell and is defined as an average cell voltage increase per time unit [Units: $\mu\text{V/h}$ or $[\mu\text{V}/1,000 \text{ h}]$].

3.6.2.1 INITIAL CELL VOLTAGE DEGRADATION RATE

Voltage rate of change during the initial part of a test or operation phase, when this time is excluded from the operation cell voltage degradation time.

It is expressed as absolute voltage difference divided by the initial test time

$$\Delta U_{\text{in}} = (|U_{t_{\text{start}}} - U_{t_0}|) / (t_{\text{start}} - t_0)$$

Where t_{start} is the start time of degradation measurement and t_0 is the start time of test/operation.

3.6.2.2 OPERATION CELL VOLTAGE DEGRADATION RATE

Voltage rate of change during a defined experiment time.

It is expressed as absolute voltage difference divided by operation time

$$\Delta U_{op} = (|U_{t_{end}} - U_{t_{start}}|) / (t_{end} - t_{start})$$

Where t_{start} is the starting time of degradation measurement and t_{end} is the time of the end of the test.

T_{start} shall be given as offset time from the operation test start t_0 defined as zero.

3.6.3 DURABILITY

The ability to withstand wear, pressure, or damage within the defined operational settings.

3.6.4 EFFICIENCY DEGRADATION RATE

Efficiency degradation is defined as the decrease of the overall efficiency over time referred to the initial efficiency level and expressed in percentage per unit of time [Units: %/h].

3.6.5 PERFORMANCE DEGRADATION RATE

Decrease of hydrogen productivity over time referred to the initial productivity under constant operating conditions of load, temperature and pressure, expressed in percentage per unit of time [Units: %/h].

3.6.5.1 CELL LIFETIME

Duration of the time interval under operating conditions between the first start up and until the cell voltage, at defined conditions, goes above the specified maximum acceptable voltage⁽²⁾ [Units: h].

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.6.5.2 STACK LIFETIME

Life time of stack is defined as the life-span of the stack when the process relevant (i.e. hydrogen production rate, or hydrogen production efficiency) performance loss with time has reached 20% compared to its initial performance (BoL = beginning of life) or when the average cell potential has reached the cut-off voltage defined by the manufacturer. This condition is indicated as End of Life (EoL).

The life time is expressed in operating hours at nominal load. This is related to the steady-state operation at the nominal operating point [Units: h].

3.6.6 STABILITY FACTOR

Parameter to assess the stability characteristics defined as the reciprocal of the product of the voltage increase rate (operation cell voltage degradation) and the initial cell overvoltage versus the thermoneutral potential (~ 1.47 V at 80 °C).

Stability Factor (**SF**) = $1 / [\Delta U_{op} \cdot (U_{cell} - U_{tn})_{t_{start}}]$

[Units: $h \cdot V^{-2}$].

for FCH2JU consultation

3.7 EFFICIENCY

3.7.1 GENERAL CONSIDERATIONS ON EFFICIENCY

In this section, a critical review of the different definitions of the efficiency of the water electrolysis reactions (at cell, stack, component and system level) found in the literature is provided. The discussion is applicable to near-ambient temperature technologies such as PEM, alkaline and anion-membranes only.

From a thermodynamic viewpoint, the water electrolysis cells, stacks and systems can be seen as energy conversion devices. The energy efficiency of such devices is defined as the ratio between the useful chemical energy output (the hydrogen/oxygen energy content) and the energy input (electricity and heat). The efficiency factors or descriptors thus obtained offer a common and practical way to characterize such conversion devices, assess the quality of the conversion process and compare the results among them.

The following figure 5 provides a schematic overview of mass and energy flows across the boundaries of the system under consideration and the environment.

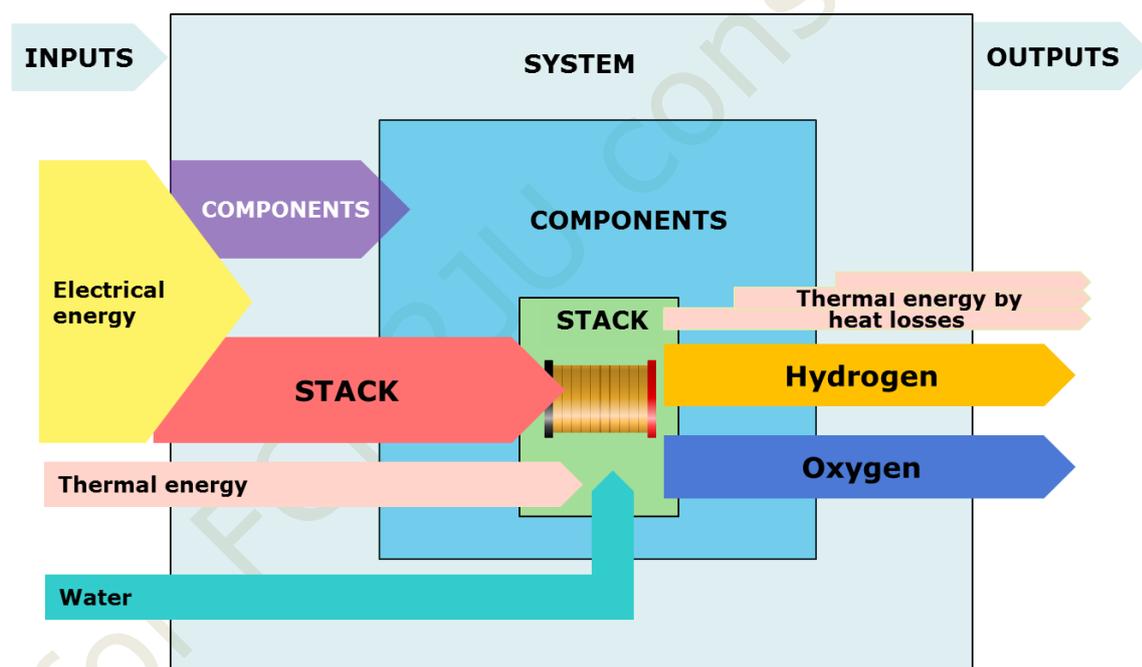


Figure 5

Schematic diagram of typical inputs/outputs mass flows and energy of an electrolyser system

The approach used in this document is to review the definitions, starting from fundamental thermodynamics of the electrolysis processes, and in turn apply them at single cell, stack, component and finally at system level. To facilitate the comparison of water electrolysis technologies (at cell, stack or system levels), there is a need to use quantitative descriptors. In this account, the term "energy efficiency coefficient" (symbol

is ε) will be the descriptor used for this purpose. ε is a real number such as: $0 \leq \varepsilon \leq 1$. To express the energy efficiency coefficient in percentage, it is necessary to multiply ε by 100. It should be noted here that in literature sometimes the term “efficiency” is used instead of “energy efficiency coefficient”. In some cases, this might lead to confusion (e.g. it is necessary to differentiate between energy, current and overall efficiencies) that needs to be avoided by using appropriate terms (in this document, the descriptor used for current and overall efficiency is labelled by η). It should also be noted here that there are several methods to define the “energy efficiency coefficient” of water electrolysis. The objective of this document is to review the various definitions and explain their differences and the corresponding simplifying assumptions.

There are basically **THREE main approaches** to define and calculate water electrolysis efficiency coefficient to facilitate comparison of results.

The **FIRST approach** is mostly used by the research academic/scientific community. It is based on thermodynamic considerations. The focus is on the water electrolysis reaction only, at constant temperature and pressure (T,p) conditions. The electrolysis cell is placed in a thermostat (this could be air when the electrolysis takes place at ambient temperature, but in most laboratory experiments, it could be a thermostatic device which is used to perform electrolysis at temperatures different from ambient temperature). The energy efficiency coefficient is defined as the ratio of the minimum amount of energy required to split one mole of water at T,p (current is zero) to the real amount of energy required to split one mole of water at T,p (current is non-zero). The difference is due to the second principle of thermodynamics: transport of electric charges across the cell induces irreversible energy degradation (dissipation). Therefore the denominator is larger than the numerator and $\varepsilon \leq 1$, except at equilibrium where $\varepsilon = 1$.

$$\varepsilon_{cell} = \frac{\text{energy requirement in reversible conditions}}{\text{energy requirement in irreversible conditions}} = \frac{W_t \text{ (J.mol}^{-1}\text{)}}{W_r \text{ (J.mol}^{-1}\text{)}} \quad [A]$$

It should be noted here that despite the simplicity of this definition, **three different cases (quantitative expressions)** of ε could be found in literature for this FIRST approach. The difference arises from the different thermodynamic simplifying assumptions that are applied in the evaluation of the energy flows between the electrolysis cell and the environment. These assumptions impact both the numerator and the denominator of Eq. [A].

In **Case 1**, the enthalpy change of the reaction (reversible electrical work + reversible heat) is taken as reference at the numerator and the total electrical work plus a constant additional reversible heat input is provided at the denominator.

In **Case 2**, the Gibbs free energy of the reaction (reversible electrical work) is taken as reference at the numerator and only the total electrical work is provided at the denominator.

In **Case 3**, the enthalpy change of the reaction (reversible electrical work + reversible heat) is taken as reference at the numerator (as for case 1) and the total electrical work plus a variable additional heat input (depending on U_{Cell} to make a difference between endo and exothermal mode of operation) is provided at the denominator.

Case 4 is a more general approach of case 3 where it is assumed that the heat input into the cell is totally provided by an external source.

These four cases will be presented and discussed in detail in section 3.7.3.

The **SECOND approach** is a more practical one, and it is mainly used by the industry sector. Compared to the definitions of the FIRST case, there are two main differences:

(i) all parasitic losses (those of the electrolysis unit such as energy and current losses, heat losses, etc. but also those of auxiliary subsystems such as heaters, pumps, etc.) are taken into account at the denominator of the definition of η , in order to define the overall performance of the complete electrolyser system; (ii) the energy of reference (the numerator in the definition of ε) is different.

This is the ratio of the energy content of the products obtained at the exhaust of the device (cell, stack, system plant) to the total energy that is provided to the system.

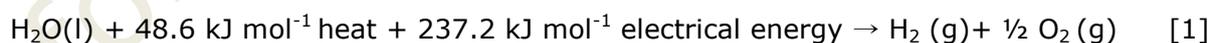
$$\eta_{cell} = \frac{\text{energy content of products}}{\text{total energy requirements}} = \frac{W_t \text{ (J.mol}^{-1}\text{)}}{W_r \text{ (J.mol}^{-1}\text{)}} \quad [B]$$

The **THIRD approach** acknowledges the fact that the efficiency definitions of the FIRST and SECOND approaches provide insights on the conservation of energy only (first principle of thermodynamic). Environmental conditions and energy degradation are not quantitatively considered. However, to ensuring meaningful comparisons between different technologies (e.g. electrolysis plant, photovoltaic system, wind turbine generator), and eventually ranking them is not a straightforward task. In order to do that, there is a need to define the best theoretical performance of a device. The best approach is to performing a detailed **exergy** analysis, i.e. to take into account the exergy (energy quality) of various input/output energy flows to calculate the efficiency. The analysis of the exergy losses (magnitude and location within the device), will provide a more detailed picture of the strengths and weaknesses of any energy conversion device and it will help in identifying improvements in various components of the device. However this approach will not be followed in this document.

3.7.2 ELECTROLYSIS THERMODYNAMICS FUNDAMENTALS

3.7.2.1 THERMODYNAMICS OF THE WATER DISSOCIATION REACTION

The energetics of the water electrolysis reaction performed under reversible conditions (current intensity $I = 0$) under **Standard Ambient Temperature and Pressure conditions (IUPAC SATP) $T^\circ = 25^\circ\text{C}$ (298.15 K) and $p^\circ = 10^5 \text{ Pa} = 1 \text{ bar(a)}$** is summarized in Eq. [1]:



The total energy required by the electrolysis process $\Delta H_{cell}(T^\circ, p^\circ) = 285.8 \text{ kJ mol}^{-1}$ is the sum of the thermal energy needs $\Delta Q_{rev}(T^\circ, p^\circ)$, and the electrical energy needs $\Delta G_{cell}(T^\circ, p^\circ)$ also known as the Gibbs free energy change of the reaction. All these quantities are related via the Gibbs-Helmholtz equation:

$$\Delta H_{cell}(T, p) = \Delta Q_{rev}(T, p) + \Delta G_{cell}(T, p) \quad [2]$$

where T is the absolute temperature (in K) of the electrolysis cell.

Under standard conditions eq [2] values are: $285.8 \text{ kJ mol}^{-1} = 48.6 \text{ kJ mol}^{-1} + 237.2 \text{ kJ mol}^{-1}$.

Under reversible conditions ($I = 0$) the thermal energy change is related to the entropy change $\Delta S(T)$ of the water splitting reaction, i.e. $\Delta Q_{\text{rev}}(T,p) = T \Delta S(T,p)$.

The entropy change $\Delta S(T^\circ, p^\circ)$ for one mole of water at standard conditions, based on:

$S_{\text{H}_2}^0 = 130.7 \text{ J (mol} \cdot \text{K)}^{-1}$, $S_{\text{O}_2}^0 = 205.1 \text{ J (mol} \cdot \text{K)}^{-1}$ and $S_{\text{H}_2\text{O}}^0 = 69.9 \text{ J (mol} \cdot \text{K)}^{-1}$ is:

$$\Delta S(298) = 130.7 + 0.5 \times 205.1 - 69.9 = 163.3 \text{ J (mol} \cdot \text{K)}^{-1},$$

leading to $\Delta Q_{\text{rev}}(298) = 298 \times 163.3 = 48.6 \text{ kJ mol}^{-1}$

3.7.2.2 CELL VOLTAGE OF THE WATER ELECTROLYSIS REACTION

From the thermodynamic viewpoint, the minimum but necessary cell voltage required for the onset of the water electrolysis reaction under reversible conditions, U_{rev}^0 at **SATP conditions**, is defined as¹:

$$U_{\text{rev}}^0 = \Delta G^0 / (n F) \quad [3]$$

where n is the number of electron transferred ($n = 2$ in the case of water electrolysis), and F is the Faraday constant (i.e. the product of the elementary electric charge by the Avogadro number, $F = 96485.3329 \approx 96485 \text{ C mol}^{-1}$).

Hence, at standard conditions $\Delta G^0 = 237.22 \text{ kJ mol}^{-1}$, then $U_{\text{rev}}^0 = \mathbf{1.2293 \text{ Volts}}$.

Remarks

- This is only valid when the heat corresponding to $T\Delta S$ (48.6 kJ mol^{-1}) can be entirely transferred from the surrounding ambient to the process e.g. by supplying pre-heated water to the cell when the process is at endothermic state.
- Hydrogen generation cannot take place when the cell voltage $U_{\text{cell}} < U_{\text{rev}}^0$.
- The electrolysis cell can operate adiabatically (with a zero heat balance between thermal energy transferred to the cell and produced by the cell) at the so called **thermo-neutral potential**, E_{tn} , or **thermo-neutral voltage** U_{tn} , which is defined, at SATP conditions, by:

$$U_{\text{tn}}^0 = \Delta H^0 / (n F) \quad [4]$$

In equation [4], at SATP conditions, $\Delta H^0 = \text{HHV} = \mathbf{285.84 \text{ kJ mol}^{-1}}$ ($U_{\text{tn}} = \mathbf{1.4813 \text{ V}}$). At different physical conditions and namely when water is in the gaseous state $\Delta H^0 = \mathbf{LHV} = \mathbf{241.8 \text{ kJ mol}^{-1}}$ ($U_{\text{tn}} = \mathbf{1.253 \text{ V}}$). It should be noted that U_{tn}^0 , eq. [4], is larger than U_{rev}^0 eq. [3], as it contains the heat associated with the entropy change ΔQ_{rev} .

¹ IUPAC notation should be used here. E or E^{emf} is used for automotive cells ($\Delta G < 0$). Voltage = U is used for electrolysis cells ($\Delta G > 0$).

- **Higher Heating Value (HHV in $\text{J}\cdot\text{mol}^{-1}$)**, which includes the heat of vaporization of water, is used as reference for **liquid water electrolysis**
- **Lower Heating Value (LHV)** is used for steam electrolysis, e.g. Solid Oxide Electrolysis (SOEC), which is not discussed in this document.
- Under strictly adiabatic conditions (a case of limited interest), the cell is cooling down when $U_{\text{rev}} < U_{\text{cell}} < U_{\text{tn}}$ because the necessary heat required for the entropy change is taken only from the heat stored inside the cell. In such case it is not possible thermal exchange between the cell and the surroundings.
- When the operating cell voltage $U_{\text{cell}} > U_{\text{tn}}$, the heat required by the reaction is provided in-situ by internal dissipation (overvoltages and ohmic dissipations). In the case when the dissipated heat is higher than the required heat, this results in an increase of the cell temperature.

3.7.2.3 HEAT BALANCE (Q_{CELL}) OF THE WATER ELECTROLYSIS REACTION

Under specific operating conditions (at constant T and p operating conditions), the heat balance Q_{cell} can be defined as the difference between **the reversible heat ΔQ_{rev}** associated with the entropy change of the reaction, $\Delta Q_{\text{rev}} = T\Delta S$, which is spontaneously transferred from the surroundings to the cell when the temperature gradient $T_{\text{cell}} < T_{\text{out}}$, and the energy loss due to internal dissipation via charge transfer overvoltages ($\Sigma|\eta_i|$) and ohmic dissipation ($R_e I$) associated with the **irreversible heat Q_{irrev}** which is spontaneously transferred from the cell to the surroundings when $T_{\text{cell}} > T_{\text{out}}$:

$$Q_{\text{irrev}} (\text{J}\cdot\text{mol}^{-1}) = n\cdot F\cdot(U_{\text{cell}} - U_{\text{rev}}) = n\cdot F\cdot\eta_{\text{loss}} = n\cdot F\cdot(\Sigma|\eta_i| + R_e I) \quad [5]$$

$$\Leftrightarrow nFQ_{\text{irrev}} \sim (U_{\text{cell}} - U_{\text{rev}}) = \eta_{\text{loss}}$$

$$\Rightarrow Q_{\text{cell}} = \Delta Q_{\text{rev}} - Q_{\text{irrev}} = T\Delta S - n\cdot F\cdot(U_{\text{cell}} - U_{\text{rev}})$$

$$\text{With } \Delta Q_{\text{rev}} = T\Delta S = \Delta H_{\text{rev}} - \Delta G_{\text{rev}} = n\cdot F\cdot(U_{\text{tn}} - U_{\text{rev}}) \quad [6]$$

This leads to the expression of **heat balance Q_{cell}** as follows:

$$Q_{\text{cell}} = n\cdot F\cdot(U_{\text{tn}} - U_{\text{rev}}) - n\cdot F\cdot(U_{\text{cell}} - U_{\text{rev}}) = n\cdot F\cdot(U_{\text{tn}} - U_{\text{cell}}) \quad [7]$$

In SATP conditions: $\Delta Q_{\text{rev}}^{\circ} = nF(1.48 - 1.23) = 285.8 - 237.2 = 48.6 \text{ kJ mol}^{-1}$
and $\Delta Q_{\text{rev}}/2F \sim 0.25 \text{ Volt}$.

This expression describes the total heat exchange between the surrounding and the electrolysis cell according to the value of U_{cell} against that of U_{tn} . The heat balance, Q_{cell} , for all the operating conditions depends by the reversible heat ($\Delta Q_{\text{rev}} = T\Delta S$) exchanged with the outside and the irreversible heat ($n\cdot F\cdot\eta_{\text{loss}}$) resulting from the overvoltages and of the Joule effect. It is not possible to distinguish between these two sources of heat but if $U_{\text{cell}} < U_{\text{tn}}$ then the system needs an external heat input (via the thermostat) and if $U_{\text{cell}} > U_{\text{tn}}$ then the excess heat is released to the environment (via the thermostat or by radiation, conduction, convection). However, the direction of the heat flow can be known: to the system or to the surroundings.

In the scientific community there are two opposing points of view for cell level:

- one suggesting that it is *possible* to distinguish between reversible (i.e. provided by the surrounding or the thermostat (called Q_{input})) and irreversible sources (i.e. heat released to the surrounding)
- one suggesting that it is *not possible* to distinguish between the two

The consequence of this disagreement explains (at least partly) the different definitions of the efficiency cases described below.

The algebraic sign of Q_{cell} shows the direction of the net heat flow:

- $Q_{cell} = 0$ (when $U_{cell} = U_{tn}$), i.e. the cell operates isothermally without a net exchange of heat between the cell and the surroundings;
- $Q_{cell} > 0$ (when $U_{cell} < U_{tn}$), heat is absorbed by the cell at low current intensity to maintain T constant;
- $Q_{cell} < 0$ (when $U_{cell} > U_{tn}$), the excess heat produced at high current intensity is released from the cell and some external cooling may be needed to maintain T constant.

3.7.3 ENERGY EFFICIENCY DEFINITION : FIRST APPROACH

As introduced above, in the simplest case of a single electrolysis cell, the energy efficiency ϵ_{cell} of the electrolysis cell can be defined as the ratio between the theoretical amount of total energy W_t (J/mol) required to split one mole of water (i.e. the opposite of its enthalpy of formation ΔH_f) and the real amount of energy W_r (J/mol) used in the process. When liquid water is electrolyzed (this is the case of PEM, alkaline and anionic membrane technologies), the reference energy consumption is that of liquid water (absolute value of the HHV of hydrogen combustion in oxygen).

$$\epsilon_{cell} = \frac{\text{energy requirement in reversible conditions}}{\text{energy requirement in irreversible conditions}} = \frac{W_t \text{ (J.mol}^{-1}\text{)}}{W_r \text{ (J.mol}^{-1}\text{)}} \quad [8]$$

Hereafter **four different cases** are presented **as the state of the art** for the definition of energy efficiency, performed on the basis of different thermodynamic assumptions.

3.7.3.1 ENERGY EFFICIENCY – CASE 1 (CONSTANT REVERSIBLE HEAT INPUT BASED)

Definition

In this first case, which take into account all the energies (electrical and thermal) involved, the numerator of Eq. [8] (the energy requirement in reversible conditions), is defined as the necessary electrical work + the necessary heat flow ($\Delta Q_{rev} = T \cdot \Delta S \text{ J.mol}^{-1}$) associated with for the entropy change. Therefore:

$$W_t = \Delta G_{rev} + \Delta Q_{rev} = \Delta H_{rev} \Leftrightarrow W_t = n \cdot F \cdot U_{rev} \text{ (electrical work)} + n \cdot F \cdot (U_{tn} - U_{rev}) \text{ (reversible } Q)$$

$$W_t = n \cdot F \cdot U_{tn} \text{ (J/mole) (total energy)}$$

The denominator of Eq. [8], the energy requirement in irreversible conditions, is defined as the real electrical energy consumption (the necessary electrical work + the extra amount of electrical work which is dissipated internally into heat) + the necessary heat associated with for the entropy increase. Therefore:

$$W_r = \Delta G_{rev} + \Delta Q_{rev} + nF\eta_{loss}$$

$$W_r = n \cdot F \cdot U_{rev} \text{ (electrical work)} + n \cdot F \cdot (U_{tn} - U_{rev}) \text{ (reversible Q)} + n \cdot F \cdot (U_{cell} - U_{rev}) \text{ (irreversible Q)}$$

$$W_r = n \cdot F \cdot (U_{tn} + U_{cell} - U_{rev}) \text{ (J/mole) (total energy).}$$

Therefore, the "energy efficiency coefficient" in case 1 is given by:

$$\varepsilon_{cell,case1} = \frac{\Delta H_{rev}}{\Delta H_{rev} + nF\eta_{loss}} = \frac{\Delta G_{rev} + \Delta Q_{rev}}{nFU_{cell} + \Delta Q_{rev}} = \frac{U_{tn}}{U_{tn} + U_{cell} - U_{rev}} \quad [9]$$

In SATP conditions:

$$\varepsilon_{cell,case1}^0 = \frac{U_{tn}^0}{U_{tn}^0 + U_{cell}(SATP) - U_{rev}^0} = 1 \quad [10]$$

since $U_{cell}(SATP) = U_{rev}^0$.

In any T,p conditions :

$$\varepsilon_{cell,case1} = \frac{U_{tn}(T,p)}{U_{tn}(T,p) + U_{cell}(T,p) - U_{rev}(T,p)} < 1 \quad [11]$$

Graphical analysis

Figure 6 shows the plot of Eq. [9], the energy efficiency coefficient ε_{cell} against U_{cell} up to 2.0 Volt in SATP conditions ($U_{tn}^0 = 1.48$ V and $U_{rev}^0 = 1.23$ Volt). Starting at $U_{cell} = U_{rev}^0$, this is a continuous decreasing function of U_{cell} . The plot is similar to the plot obtained for Case 2 but the rate at which ε_{cell} decreases with U_{cell} is slower (see the quantitative comparison of case 1,2 and 3 in Figure 12 below).

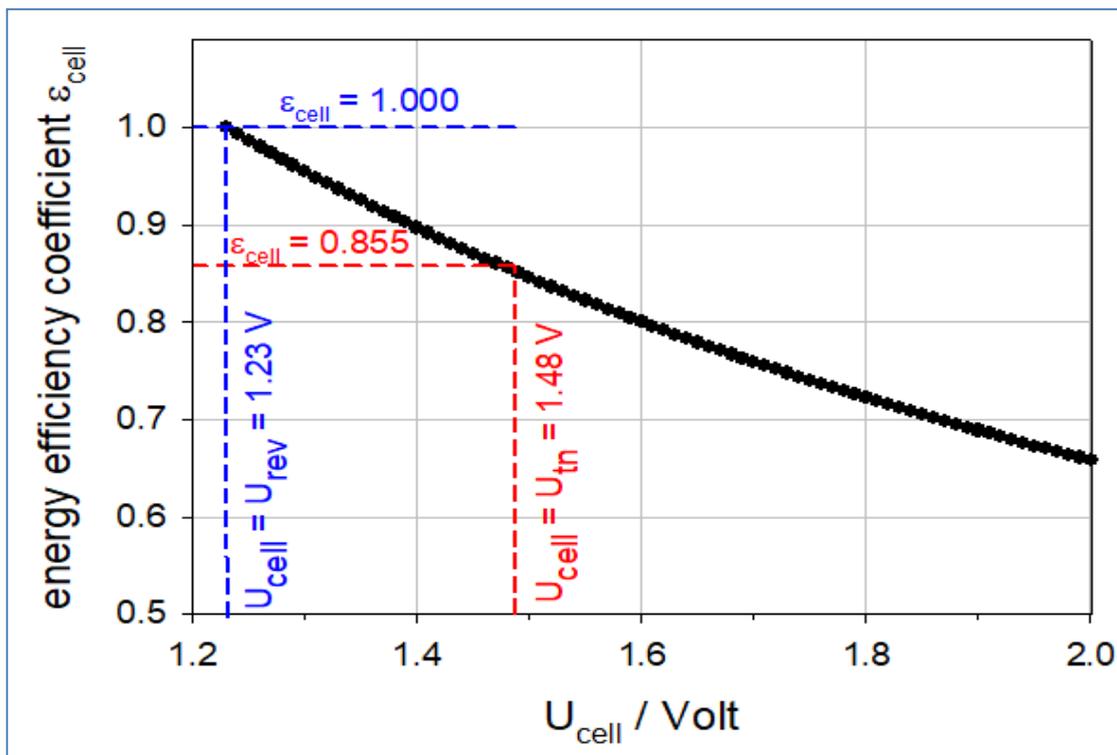


Figure 6: Thermodynamic efficiency plot (Case 1)

Discussion

Arguments in favour

- The necessary fixed thermodynamic quantity ΔQ_{rev} (the reversible heat needed by the entropy increase of the water dissociation reaction) is provided ONLY by an external heat source (air or thermostat) and NOT by internal dissipation of electrical work. The possibility that heat can be partly (when $U_{\text{rev}} < U_{\text{cell}} < U_{\text{tn}}$) or totally (when $U_{\text{cell}} \geq U_{\text{tn}}$) produced in-situ by internal dissipation and thus can vary with U_{cell} (according to the operating conditions exothermic or endothermic) is disregarded. There is a constant external input of reversible heat to the cell under all operating conditions (exothermic and endothermic) and this is the only heat that is provided by the surroundings to the cell.

Arguments against

- W_r contains a constant heat input from an external source equal to ΔQ_{rev} under all operating conditions (any U_{cell}) including operation under strong exothermic conditions ($U_{\text{cell}} > U_{\text{tn}}$) where excess heat is produced by the cell and not absorbed by an external source.
- The heat balance in Case 1 is NOT fully consistent with the temperature gradient between the cell and the surroundings and therefore NOT consistent with non-equilibrium thermodynamics.
- It is not possible to differentiate between the heat arising from the thermostat and the heat arising from internal dissipation. Only the temperature gradient

(non-equilibrium thermodynamics) determines the direction of ΔQ_{rev} (from where ΔQ_{rev} heat comes from).

- All the dissipated heat generated by additional electrical work inside the cell due to the irreversible process is reverted to the external temperature control device and NOT used inside the cell for the entropy increase. Therefore, none of the heat produced inside the cell by dissipation of electrical work is used for the entropy increase of the reaction.
- The energy input for a system is equivalent to the electricity input for the stack plus electricity input for the auxiliaries (denominator). Thus, if ΔQ_{rev} is added at the denominator of the stack efficiency calculation and compare stack and system efficiencies are compared, the power consumption of the auxiliaries will result lower than what can be effectively measured.
This because the stack efficiency during exothermic operation is lower than the actual one (higher energy consumption) and to fulfil the system efficiency the power consumption from the auxiliaries must be smaller than the actual one.
- In addition, in case 1, the energy input is in part calculated instead of being simply measured as it usually occurs with the conversion efficiency of any process.

3.7.3.2 ENERGY EFFICIENCY - CASE 2 (FREE ENERGY VARIATION BASED)

Definition

In this second case, the numerator of Eq. [8] (the energy requirement in reversible conditions), is defined as the necessary electrical work ONLY. The necessary heat flow ($\Delta Q_{rev} = T \cdot \Delta S \text{ J} \cdot \text{mol}^{-1}$) associated with the entropy change (and that is transferred from the thermostat to the cell) is not taken into account. Therefore:

$$W_t = \Delta G_{rev} = n \cdot F \cdot U_{rev} \text{ (electrical work)}$$

The denominator of Eq. [8], the energy requirement in irreversible conditions, is defined as the real electrical energy consumption. This is the necessary electrical work + the extra amount of electrical work which is dissipated internally into heat. Therefore:

$$W_r = \Delta G_{rev} + nF\eta_{loss}$$

$$W_r = n \cdot F \cdot U_{rev} \text{ (reversible electrical work)} + n \cdot F \cdot (U_{cell} - U_{rev}) \text{ (irreversible } Q)$$

$$W_r = n \cdot F \cdot (U_{cell}) \text{ (J/mole) (total energy = total electrical work)}$$

Therefore, the "energy efficiency coefficient" in case 2 (in the literature, in case 2 the ϵ_{cell} definition is sometimes called the **thermodynamic voltage efficiency**) is given by:

$$\epsilon_{cell, case2} = \frac{\Delta G_{rev}}{nFU_{cell}} = \frac{nFU_{rev}}{nFU_{cell}} = \frac{U_{rev}}{U_{cell}} \quad [12]$$

In SATP conditions:

$$\epsilon_{cell, case2}^0 = \frac{U_{rev}^0}{U_{cell}(SATP)} = 1 \quad [13]$$

since $U_{cell}(SATP) = U_{rev}^0$

In any T,p conditions :

$$\varepsilon_{cell,case2}(T, p) = \frac{U_{rev}(T, p)}{U_{cell}(T, p)} \quad [14]$$

Graphical analysis

Figure 7 shows the plot of Eq. [12], the thermodynamic voltage efficiency as a function of U_{cell} **in SATP conditions**. Starting at $U_{cell} = U_{rev}$, this is a continuous decreasing function of U_{cell} . It can be seen that ε_{cell} is **100%** when U_{cell} is equal to $U_{rev} = 1.23V$. When the cell voltage is equal to the thermoneutral voltage ($U_{cell} = U_{tn} = 1.48V$ in SATP conditions), the energy efficiency coefficient expressed in percentage is equal to 83.1%. Regarding the heat balance, it should be noted here that when $U_{rev} < U_{cell} < U_{tn}$ (*i.e.* the cell voltage is less than the thermoneutral voltage) there is a heat flux from the thermostat to the cell: this range of U_{cell} is called endothermal mode of operation. When $U_{cell} = U_{tn}$ (*i.e.* the cell voltage is equal to the thermo-neutral voltage), the heat flow between the thermostat and the cell is zero because all the necessary heat is produced in-situ, inside the cell, by degradation of electrical work (second principle, dissipation associated to transport of charged species). When $U_{cell} > U_{tn}$ (*i.e.* the cell voltage is higher than the thermo-neutral voltage) there is a heat flux in the opposite direction, from the cell to the thermostat, because the amount of heat produced in-situ by dissipation exceeds the cell requirements: this is the exothermal mode of operation. The sign of the temperature gradient ($T_{in}-T_{out}$) is negative in the endothermal domain, equal to zero at the thermo-neutral point and positive in the exothermal domain.

Under endothermic operations, $U_{rev} < U_{cell} < U_{tn}$, of relatively large thermally isolated cells where the water flow rate is relatively low the water temperature outlet, T_{out} , is lower than the inlet water temperature T_{in} . Under exothermic conditions $U_{cell} > U_{tn}$ T_{out} will be higher than T_{in} .

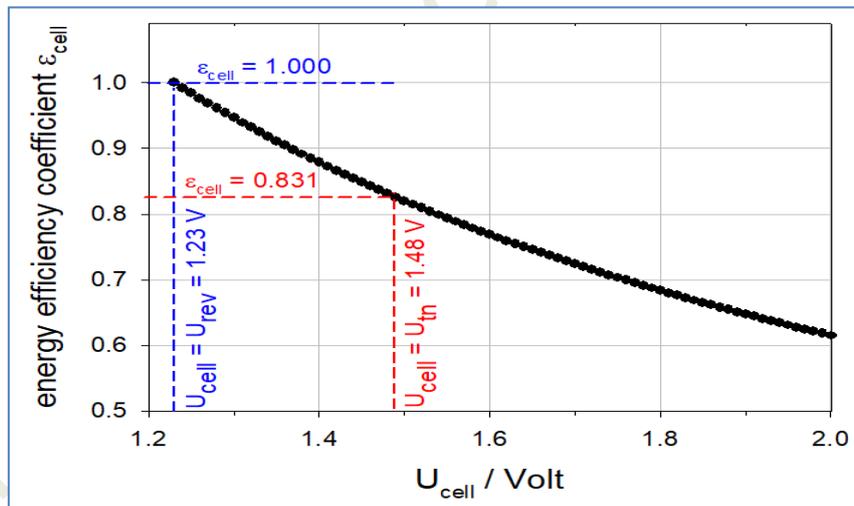


Figure 7: Thermodynamic efficiency plot (Case 2)

Discussion

Arguments in favour

- Equation [12] is homogeneous because only the electrical work is taken into account at the numerator and denominator.
- Heat flows are disregarded: this is acceptable for near-ambient temperature electrolysis (PEM and alkaline) because the lack of reversibility at the anode makes the endothermal range very narrow (the thermo-neutral point is reached at very low current densities like $10-20 \text{ mAcm}^{-2}$ only).

- Corrections for operating conditions different to SATP conditions can be easily implemented.

Arguments against

- Equation [12] does not reflect the real conditions and is not rigorous because it considers only the electrical work as useful energy output and not the total energy output.
- In transient operation, with periodical cycles, the time spent in the endothermal domain may increase and in such case the heat flow should be taken into account.

3.7.3.3 ENERGY EFFICIENCY - CASE 3 (ENTHALPY BASED)

Definition

In this third case, the numerator of Eq. [8] (the energy requirement in reversible conditions) is defined as ΔH_{rev} , as for case 1. Therefore:

$$W_t = \Delta G_{rev} + \Delta Q_{rev} = \Delta H_{rev} \Leftrightarrow W_t = n \cdot F \cdot U_{rev} \text{ (electrical work)} + n \cdot F \cdot (U_{tn} - U_{rev}) \text{ (reversible } Q)$$

$$W_t = n \cdot F \cdot U_{tn} \text{ (J/mole) (total energy)}$$

The denominator of Eq. [8], the energy requirement in irreversible conditions, takes into account the detailed heat balance. Therefore, the expression of the denominator depends on the value of U_{cell} . There are three situations: (i) $U_{rev} < U_{cell} < U_{tn}$; (ii) $U_{cell} = U_{tn}$; (iii) $U_{cell} > U_{tn}$. Therefore:

When $U_{rev} < U_{cell} < U_{tn}$: endothermal range of operation

W_r = electrical work from DC source + heat from DC source resulting from electricity dissipation + complementary heat from thermostat to maintain cell temperature constant. Therefore:

$$W_r = n \cdot F \cdot U_{rev} \text{ (electrical work)} + n \cdot F \cdot (U_{cell} - U_{rev}) \text{ (heat internal dissipation)} + n \cdot F \cdot (U_{tn} - U_{cell})$$

where $n \cdot F \cdot (U_{tn} - U_{cell}) = Q_{cell}$. This is the net heat input (Q_{input}) since part of the heat is already supplied via the irreversible reaction (heat internal dissipation)

The following equation:

$$W_r = n \cdot F \cdot U_{rev} + n \cdot F \cdot \eta_{loss} + (\Delta Q_{rev} - n \cdot F \cdot \eta_{loss})$$

can be modified as::

$$W_r = n \cdot F \cdot U_{rev} + \Delta Q_{rev} = n \cdot F \cdot U_{rev} + nF (U_{tn} - U_{rev})$$

$$W_r = n \cdot F \cdot U_{tn}$$

Therefore, if the heat input is exactly matching $n \cdot F \cdot (U_{tn} - U_{cell}) = Q_{cell}$, the "energy efficiency coefficient" in case 3 when $U_{rev} < U_{cell} < U_{tn}$ is given by:

$$\varepsilon_{cell, case3} = \frac{W_t}{W_r} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{tn}} = 1 \text{ for } U_{rev} < U_{cell} < U_{tn} \quad [15]$$

When $U_{cell} = U_{tn}$: thermoneutral point of operation

W_r = electrical work from DC source only. Therefore:

$$W_r = n \cdot F \cdot U_{rev} + n \cdot F \cdot (U_{tn} - U_{rev}) = n \cdot F \cdot U_{tn}$$

Then, the “energy efficiency coefficient” in case 3 when $U_{cell} = U_{tn}$ is given by:

$$\varepsilon_{cell,case3} = \frac{W_t}{W_r} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{tn}} = 1 \text{ for } U_{cell} = U_{tn} \quad [16]$$

This is valid if there is no external heat input to the cell. Using a thermostat means that there is an external heat input hence case 4 for the condition of $U_{cell} = U_{tn}$ must be used.

When $U_{cell} > U_{tn}$: exothermal range of operation

This is the usual mode of operation of PEM and alkaline technology. In this field the process is exothermic, thus no heat is supplied from the surroundings to the cell. As a result, $Q_{input} \sim 0$; and based on these other assumptions:

- the cell is thermally insulated
- the energy needed for cooling the water in order to keep the temperature constant (balance of plant) is disregarded.

W_r = electrical work from power source only (zero heat from thermostat).

$$W_r = n \cdot F \cdot U_{rev} + n \cdot F \cdot \eta_{loss} = n \cdot F \cdot U_{cell}$$

with $n \cdot F \cdot \eta_{loss} > \Delta Q_{rev}$

which means the heat internally produced in the exothermic process is **larger** than the required reversible heat associated to the entropy variation of the process and thus no external heat is absorbed by the cell (therefore cooling is possibly needed).

With $W_t = n \cdot F \cdot U_{tn}$

the “energy efficiency coefficient” in case 3 when $U_{cell} > U_{tn}$ (sometimes called the enthalpy efficiency in the literature) is given by:

$$\varepsilon_{cell,case3} = \frac{W_t}{W_r} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{cell}} = \frac{U_{tn}}{U_{cell}} < 1 \quad [17]$$

Summary

The “energy efficiency coefficient” in case 3 is given by the two set of equations:

$$\begin{cases} \text{when } U_{rev} < U_{cell} \leq U_{tn} : \varepsilon_{cell,case3} = 1 \\ \text{when } U_{cell} > U_{tn} : \varepsilon_{cell,case3} = \frac{U_{tn}}{U_{cell}} < 1 \end{cases} \quad [18]$$

In SATP conditions:

$$\begin{cases} \text{when } U_{rev}^0 < U_{cell}(SATP) \leq U_{tn}^0 : \varepsilon_{cell,case3} = 1 \\ \text{when } U_{cell}(SATP) > U_{tn}^0 : \varepsilon_{cell,case3} = \frac{U_{tn}^0}{U_{cell}} < 1 \end{cases} \quad [19]$$

In any T,p conditions :

$$\begin{cases} \text{when } U_{rev}(T,p) < U_{cell}(T,p) \leq U_{tn}(T,p) : \varepsilon_{cell,case3} = 1 \\ \text{when } U_{cell}(T,p) > U_{tn}(T,p) : \varepsilon_{cell,case3} = \frac{U_{tn}(T,p)}{U_{cell}(T,p)} < 1 \end{cases} \quad [20]$$

Graphical analysis

Figure 8 shows the plot of the energy efficiency ϵ_{cell} versus U_{cell} calculated up to 2.0 Volt in case 3 (using equations 15, 16 and 17).

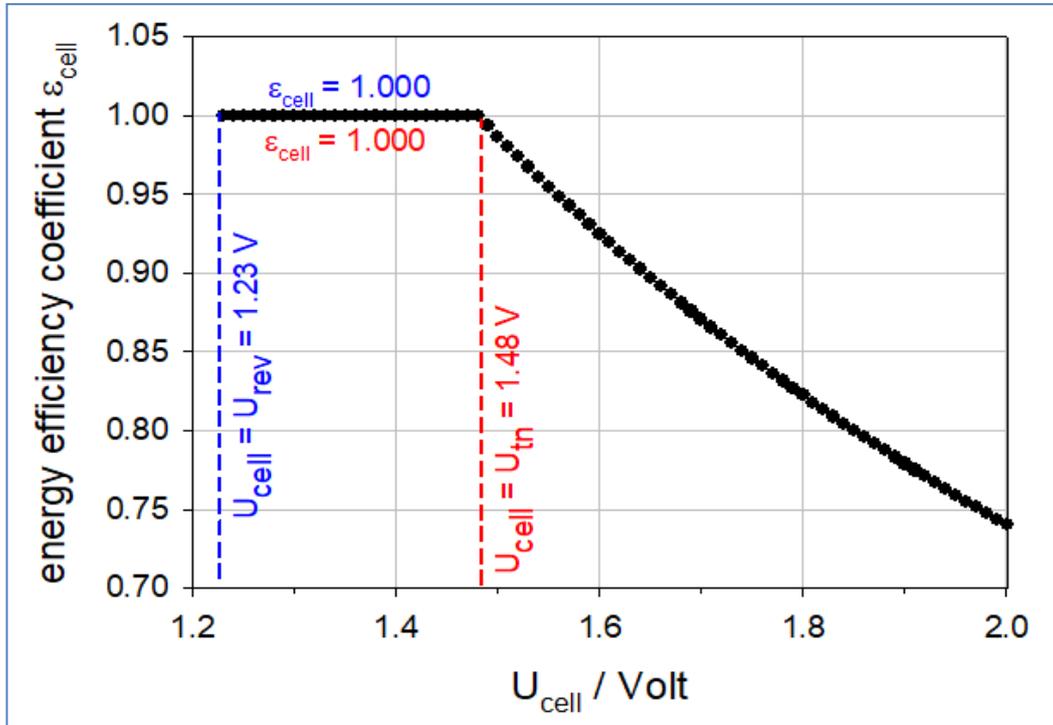


Figure 8: Thermodynamic efficiency plot (Case 3)

Discussion

Arguments in favour

- Case 3 is close to physical reality: when $U_{\text{cell}} < U_{\text{tn}}$, the heat associated with the entropy increase is provided by the temperature control external device AND from internal dissipation. This is the reason why the efficiency is conventionally assumed constant for $U_{\text{rev}} < U_{\text{cell}} < U_{\text{tn}}$ since only the exact amount of heat needed is provided by external + internal sources. When $U_{\text{cell}} > U_{\text{tn}}$, the cell does not receive any heat from the thermostat ($Q_{\text{input}} = 0$); Q_{cell} becomes < 0 because the excess heat produced by internal irreversibility is released outside the cell. Each mole of water inside the cell receives from outside exactly the amount of heat needed (from internal dissipation + a fraction from the thermostat).
- The heat balance in Case 3 is consistent with the temperature gradient between the cell and the surroundings and therefore consistent with non-equilibrium thermodynamics.
- Case 3 definition of cell and stack efficiency is perfectly homogeneous with system efficiency definition. This is the equation reported in almost all publications.

Arguments against

- Eq. [17] is not valid when $U_{\text{cell}} < U_{\text{tn}}$, because it gives $\epsilon_{\text{cell}} > 1$. However, assuming that the correct definition is given by the sum of Eq. [15], [16 and [17], then $\epsilon_{\text{cell}} \leq 1$ whatever U_{cell} .

- The definition of $\Delta Q_{rev} = 0$, implies that either $T = 0$ or $\Delta S = 0$, which is impossible above zero Kelvin. A differentiation has to be made between ΔQ_{rev} which is the necessary heat required by the reaction and the origin of that heat. In case 3, the origin of the necessary heat ΔQ_{rev} depends on the temperature gradient (non-equilibrium thermodynamics): it can be originated partly from the thermostat and partly from internal dissipation when $(T_{cell} - T_{out}) < 0$ (in the endothermal mode $\cong U_{cell} < U_{tn}$) or only from internal dissipation (in the exothermal mode $\cong U_{cell} > U_{tn}$).
- With this definition it is not possible to distinguish between the part of the heat arising from the reversible heat (i.e. from the surrounding or the thermostat) and that coming from the irreversible losses (i.e. heat released to the surrounding) in the total balance

3.7.3.4 CASE 4 (ELECTRICITY AND HEAT INPUT BASED)

In a more general approach when the **heat supplied by an external source**, this heat source should be taken into account in the efficiency equation.

in this case, $Q_{cell} = Q_{input} > 0$. Consequently Q_{input} must be measured and reported in the efficiency equation:

$$\varepsilon_{cell,case4,general} = \frac{\Delta H_{rev}}{nFU_{cell} + Q_{input}} = \frac{n \cdot F \cdot U_{tn}}{nFU_{cell} + Q_{input}} \quad [21]$$

This equation is largely applicable in cases where ΔT is measurable with an adequate accuracy such as in large single cell of a, short stacks and stacks.

If the external heat is supplied by heating the water at the inlet, e.g. to bring the temperature of the water at the desired operating temperature, Q_{input} can be determined as follows:

$$Q_{input} = \text{thermal power} \cdot \text{time} = P_{thermal} \text{ (J/s)} \cdot t \text{ (s)}$$

$$P_{thermal} = \text{water flow} \cdot \text{water thermal capacity} \cdot \Delta T$$

$$P_{thermal} = \dot{m}_{H_2O} \cdot C_p \cdot \Delta t$$

\dot{m}_{H_2O} is provided in (g/s)

Water heat capacity under standard conditions $C_p = 4,18 \text{ J/(g}\cdot\text{K)}$

$$\Delta T = T_{out, cell} - T_{in, cell} \text{ (K)}$$

T_{in} = water temperature at the inlet of the cell

T_{out} = water temperature at the outlet of the cell

This approach can give information on the effective heat exchange between the cell and the surroundings. If $\Delta T < 0$ the reaction inside the cell is endothermic and the heat provided to the cell must be considered in the efficiency equation. Thus, when the effective heat supplied to the process is properly taken into account for $U_{rev} < U_{cell} < U_{tn}$ the resulting efficiency is below 100%.

Graphical analysis

Two different conditions

Endothermic operation
 $I \neq 0$ for $U_{rev} < U_{cell} \leq U_{tn} \rightarrow$
 $Q_{input} + Q_{irreversible} \geq T\Delta S$
 $nFU_{cell} \geq \Delta G$

$$\epsilon_{cell} = \frac{W_t}{W_r} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{cell} + Q_{input}}$$

$$\epsilon_{cell, case3} \leq 1 \text{ for } U_{cell} \geq U_{rev}$$

Exothermic operation
 $I \neq 0$ for $U_{cell} > U_{tn} \rightarrow$
 $Q_{input} = 0$

$$\epsilon_{cell} = \frac{W_t}{W_r} = \frac{U_{tn}}{U_{cell}}$$

$$\epsilon_{cell, case3} < 1 \text{ for } U_{cell} > U_{tn}$$

$$\epsilon_{cell, case3} = 1 \text{ for } U_{cell} = U_{tn} \text{ if } \rightarrow Q_{input} = 0 \text{ and } I = 0$$

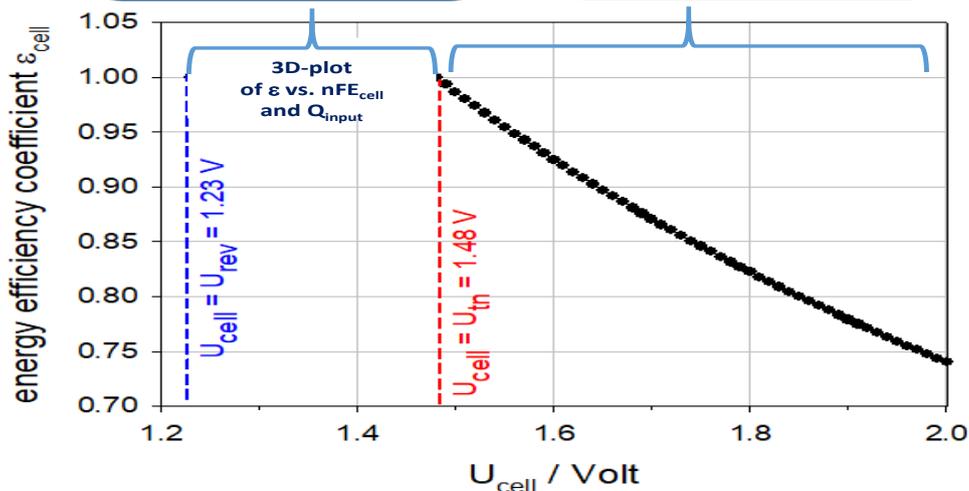


Figure 9: Thermodynamic efficiency plot (Case 4)

Reaction can only occur if $n \cdot F \cdot U_{cell} \geq \Delta G$ and $Q_{input} + Q_{irr} \geq T\Delta S$ and the efficiency is function of both Electrical and thermal energy input as per eq [21]:

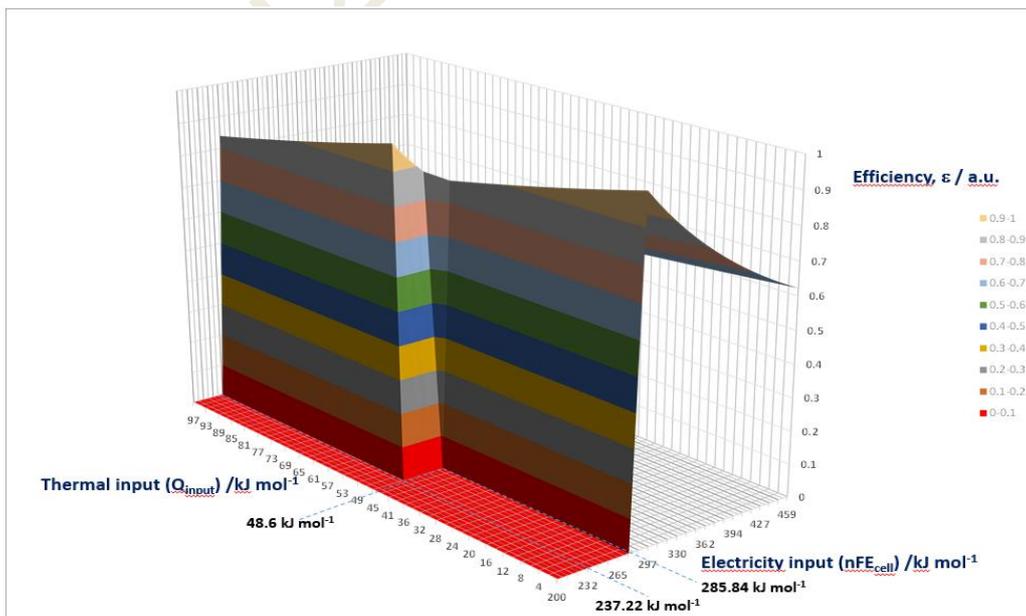


Figure 10: Thermodynamic efficiency plot (Case 4)

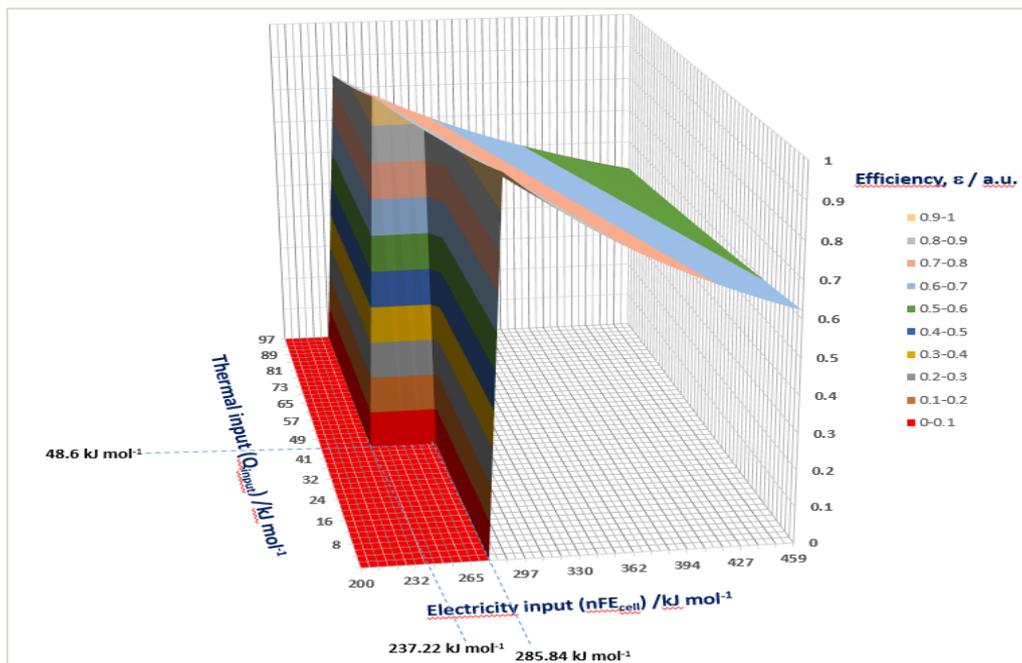


Figure 11: Thermodynamic efficiency plot (Case 4)

When Q_{input} is zero, the bi-dimensional plot is equal to that above reported for case 3, see figure 8

Efficiency is 1 when total energy input (heat and electricity) is 285.84 kJ mol^{-1} . This minimum energy requirement can be supplies as electricity + heat or electricity only.

3.7.3.5 WATER ELECTROLYSIS EFFICIENCY CASES COMPARISON

A comparison of the energy efficiencies for cases 1,2 and 3 presented above is shown in figure 12. For any given U_{cell} , it is evident that case 3 provides a higher efficiency values compared to cases 1 and 2 with a difference of around 15-17%, while between case 1 and case 2 the difference of efficiency goes from 0% at U_{rev} up to 5% at 2.0 V.

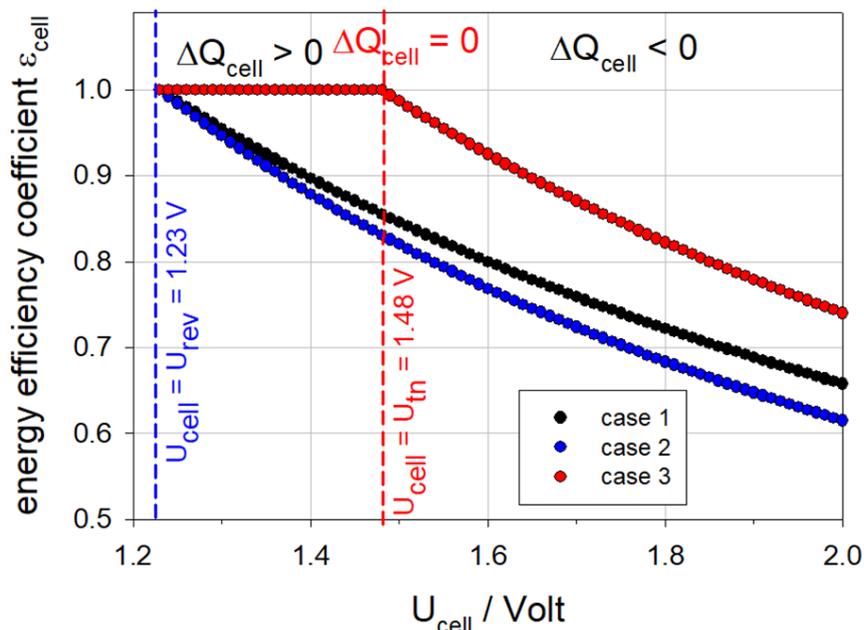


Figure 12: Plots of the energy efficiency Vs. U_{cell} for cases 1, 2 and 3

3.7.4 ENERGY EFFICIENCY AS FUNCTION OF OPERATING TEMPERATURE

Absolute temperature (T) and pressure (p) are the two main physical variables used to define the state of the electrolysis cell. All thermodynamic functions of interest used to define the energy efficiency coefficient are functions of (T, p). Therefore, it is necessary to provide an expression of these thermodynamic functions at any (T, p) operating conditions of interest in order to be able to calculate the efficiency of the electrolyser (cell, stack or system level) at such conditions.

Simplified expression of the efficiency versus T at $p = 1 \text{ bar } (10^5 \text{ Pa})$

For PEM and alkaline electrolysis, in a first approximation, the enthalpy change of the water splitting reaction $\Delta H(T, p)$ can be considered as constant over the limited temperature range of interest (0 – 100°C). This is shown in Figure 13. $\Delta H(T, p)$ is equal to the standard enthalpy change $\Delta H^0 = nF U_{\text{tn}}^0$. Hence, the energy efficiency coefficient $\varepsilon_{\text{cell}}$ of a water electrolysis cell or stack can be approximated over this temperature range by using the SATP reference values for U :

$$U_{\text{rev}}^0 = 1.23 \text{ V and } U_{\text{tn}}^0 = 1.48 \text{ V}$$

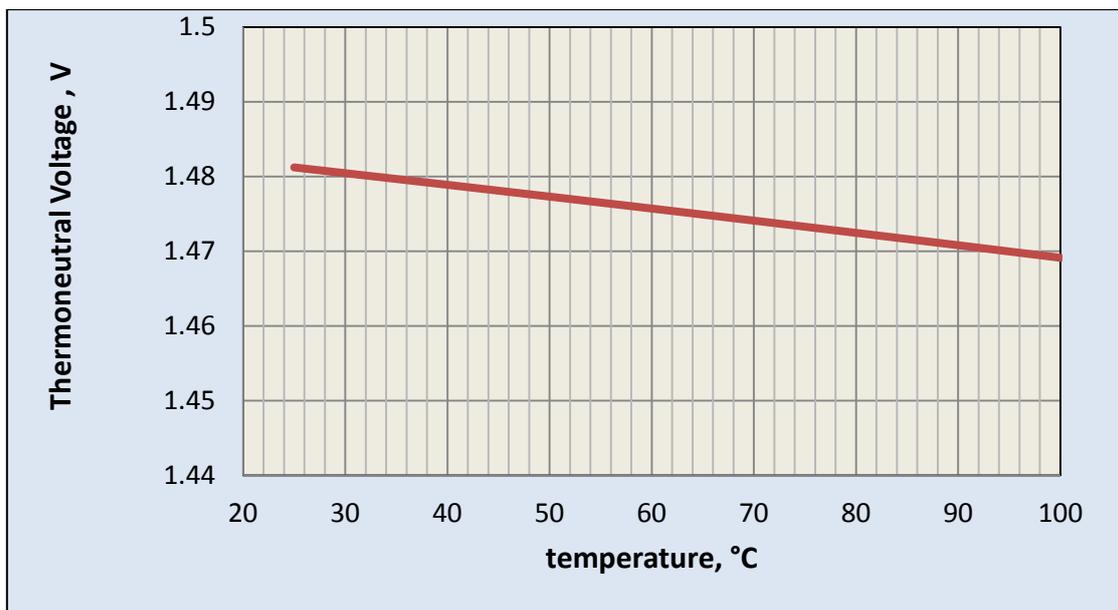


Figure 13

Thermo-neutral voltage evolution vs. temperature liquid water

Expression of the efficiency versus T at $p = 1$ bar without simplifying assumption

For a more accurate energy efficiency calculation, it is necessary to take into account the effect of operating temperature. Empirical polynomial expressions for calculation of the thermodynamic voltage $U_{rev}(T,p)$ based on Gibbs free energy change, and the thermo-neutral voltage U_{tn} have been reported in the literature^[9]. For liquid water conditions, in the range 0 to 100°C and $p = 1.013 \cdot 10^5$ Pa = 1.013 10^5 bar and up to 200°C with $p = 1.824 \cdot 10^5$ Pa = 1.824 bar, the expressions are:

$$U_{rev}(T, 1atm) = 2F \Delta G(T) = 1.5184 - 1.5421 \cdot 10^{-3} \cdot T + 9.523 \cdot 10^{-5} \cdot T \cdot \ln(T) + 9.84 \cdot 10^{-8} T^2 \quad [22]$$

$$U_{tn}(T, 1atm) = 2F \Delta H(T) = 1.485 - 1.49 \cdot 10^{-4} \cdot (T - T^0) - 9.84 \cdot 10^{-8} \cdot (T - T^0)^2 \quad [23]$$

where T is expressed in Kelvin in both cases and $T^0 = 273.15$ K. It should be noted here that these two equations are valid for $p = 1$ atm, and not $p = 1$ bar. The difference in pressure is 1 %. Therefore, Eq. [22] and [23] can be used when the pressure is 1 bar.

The example of the corrected thermo-neutral voltage value, U_{tn} , as a function of the reaction temperature, at atmospheric pressure, is described in Fig 13 (water in the liquid state). Its value changes from 1.481 V at 25°C to 1.469 V at 100°C (a variation of only 0.82% that confirms the above assumption that temperature effect can be neglected in a first approximation). A similar linear behavior applies to the variation of the cell voltage at reversible conditions, U_{rev} but with a relatively larger change of around 5 % being U_{rev} 1.229 V at 25°C and 1.167 V at 100°C.

3.7.5 ENERGY EFFICIENCY AS FUNCTION OF OPERATING PRESSURE

Dry and ideal gases conditions

It should be first noted that only the Gibbs free energy change of the water dissociation reaction (ΔG) changes with pressure. The enthalpy change (ΔH) is constant because the

effect of pressure on the free-energy and the entropy changes cancel each other out. Therefore, there is a need to provide a definition of the role of pressure on the reference case (the numerator of Eq. [8]) only for case 2 (ΔH is used at the numerator for Cases 1 and 3).

Assuming that the product streams (H_2 and O_2) at the exhaust of the electrolyser are dry and ideal gases, then the minimal electric energy required to evolve one mole of hydrogen $W_t = \Delta G_{rev}(T, p, I=0)$ (in J/mol_{H_2}) can be determined by introducing the variation ΔU_{cell} of the cell voltage with the pressures of reacting species (p_{H_2O}) and products (p_{H_2} and p_{O_2}), as follows:

$$nF U_{rev}(T, p) = \Delta G_{rev}(T, p^\theta) + RT \ln \left[\left(\frac{p_{O_2}}{p^\theta} \right)^{\frac{1}{2}} \left(\frac{p_{H_2}}{p^\theta} \right) / \left(\frac{p_{H_2O}}{p^\theta} \right) \right] = nF (U_{rev}(T, p^\theta) + \Delta U_{cell}) \quad [24]$$

with:

$$\Delta U_{cell} = U_{rev}(T, p) - U_{rev}(T, p^\theta) = \frac{RT}{2F} \ln \left[\left(\frac{p_{O_2}}{p^\theta} \right)^{\frac{1}{2}} \left(\frac{p_{H_2}}{p^\theta} \right) / \left(\frac{p_{H_2O}}{p^\theta} \right) \right] \quad [25]$$

The different pressures (expressed in bar) in Eqs. [24] and [25] have the following meaning:

- I p_{O_2} = oxygen partial pressure,
- I $p_{H_2O}/p^\theta = a_{H_2O} = 1$ for PEM and alkaline water electrolysis (where a_{H_2O} is the activity of water),
- I p_{H_2} = hydrogen partial pressure,
- I p^θ = reference pressure at the working temperature.

In each cell compartment, the total pressure p is the sum of partial pressures:

- I $p = \sum p_i = p_{O_2} + p_{H_2} + p_{H_2O}$,
- I p^A = pressure of the anodic compartment = p , including the presence of some H_2 (hydrogen leakage through the separator) and of water vapour,
- I p^C = pressure of the cathodic compartment = $p + \Delta p$, assuming a differential pressure Δp between the two compartments.

Water saturated and ideal gases

Since gases produced during electrolysis are usually saturated with water vapor, equations [24] and [25] need corrections.

For ideal wet gases:

$$nF U_{rev}(T, p^\theta) = \Delta G_{rev}(T, p^\theta) + RT \ln \left[\left(\frac{p^A - p_{H_2O}^{sat}}{p^\theta} \right)^{\frac{1}{2}} \left(\frac{p^C - p_{H_2O}^{sat}}{p^\theta} \right) / \left(\frac{p_{H_2O}^{sat}}{p^\theta} \right) \right] = 2F (U_{rev}(T, p^\theta) + \Delta U_{cell}) \quad [26]$$

$$\Delta U_{cell} = \frac{RT}{2F} \ln \left[\left(\frac{p^A - p_{H_2O}^{sat}}{p^\theta} \right)^{\frac{1}{2}} \left(\frac{p^C - p_{H_2O}^{sat}}{p^\theta} \right) / \left(\frac{p_{H_2O}^{sat}}{p^\theta} \right) \right] \quad [27]$$

where $U_{rev}(T, p^\theta)$ is the cell voltage at reference pressure p^θ and temperature T , and $p_{H_2O}^{sat}(T)$ = water saturation pressure at an operating temperature T .

Equi-pressure operation

For pressure values identical at both electrodes ($p^A = p^C = p = p^\theta$) and assuming no gas leakages through the separator, it is possible to use a **simplified expression of**

equation [27] to take into account the effect of pressure on the cell voltage U_{rev} derived from the Nernst equation. This simplified expression is given by eq.[28].

$$\Delta U_{cell} = U_{rev}(T, p) - U_{rev}(T, p^\theta) = \frac{RT}{2F} \ln \left[\left(\frac{p - p_{H_2O}^{sat}}{p^\theta} \right)^{\frac{1}{2}} \right] \quad [28]$$

Real and wet gases

Finally, to take into account the fact that real gases are produced instead of ideal gases (large operating pressures above 100 bars), it is necessary to use appropriate state equations that pertain to real gases (not considered here).

3.7.6 ENERGY EFFICIENCY STACK

The energy efficiency of a liquid water electrolysis stack operating at temperature T and pressure p is equal to the mean energy efficiency of the individual cells, multiplied by the number N of cells in the stack. The energy consumption of auxiliaries (W_{aux}) is NOT taken into account. In other words, a stack is equivalent to a single cell having a mean cell voltage value of $U_{cell} = U_{stack}/N$. Therefore, all the previous equations used to define the energy efficiency coefficient prevail; the only thing to do is to replace U_{cell} by U_{stack}/N , whenever necessary, in these equations.

Remark : it is also possible to calculate the energy efficiency coefficient of the j^{th} cell in a stack of N cells by setting :

$$U_{cell} = U_{cell}^{j^{th}} \quad [29]$$

For the case where U_{stack} is used the corresponding efficiency equations are as follows:

Case 1:

$$\mathcal{E}_{stack,case1} = \frac{N \cdot U_{tn}(T, p)}{N \cdot U_{tn}(T, p) + U_{stack}(T, p) - N \cdot U_{rev}(T, p)} \quad [30]$$

Case 2:

$$\mathcal{E}_{stack,case2} = \frac{N \cdot U_{rev}(T, p)}{U_{stack}(T, p)} \quad [31]$$

Case 3:

When $U_{cell} > U_{tn}$

$$\mathcal{E}_{stack,case3} = \frac{N \cdot U_{tn}}{U_{stack}} \quad [32]$$

$$\text{When } U_{\text{rev}} < U_{\text{cell}} \leq U_{\text{tn}} \quad \varepsilon_{\text{stack,case 3}} = \frac{N \cdot n \cdot F \cdot U_{\text{tn}}}{N \cdot n \cdot F \cdot U_{\text{tn}}} = 1 \quad [33]$$

Case 4:

$$\varepsilon_{\text{stack,case 4}} = \frac{N \cdot n \cdot F \cdot U_{\text{tn}}}{N \cdot n \cdot F \cdot U_{\text{tn}} + Q_{\text{input}}} = 1 \quad [34]$$

With $U_{\text{stack}} = N \cdot [U_{\text{cell}}(T, p^{\theta}, I) + \Delta U_{\text{cell}}]$ and Q_{stack} the heat balance at the stack level as derived from [7], i.e.:

$$Q_{\text{stack}} = N \cdot n \cdot F \cdot (U_{\text{tn}} - U_{\text{cell}}) = n \cdot F \cdot (N \cdot U_{\text{tn}} - U_{\text{stack}}) \quad [35]$$

3.7.7 ENERGY EFFICIENCY –SYSTEM

At system level, the energy consumption of ALL the necessary ancillary equipment (e.g. AC/DC conversion, water purification, water pre-heating, pumps for water circulation, hydrogen purification, hydrogen drying, process monitoring, etc.) used to operate the electrolyzer are added to the denominator of the equations used for the definition of the energy efficiency coefficient. This terms (W_{aux} for auxiliary equipment in $\text{J} \cdot \text{mol}^{-1}$) is added to the energy requirement in irreversible ($I \neq 0$) conditions.

The efficiency equations for the system is the following:

$$\frac{N \cdot U_{\text{tn}}(T, p)}{U_{\text{stack}} + W_{\text{aux}} / (nF)} \quad [36]$$

The heat balance equations for the system is the following:

$$Q_{\text{system}} = n \cdot F \cdot (N \cdot U_{\text{tn}} - U_{\text{stack}}) + W_{\text{aux}} \quad [37]$$

3.7.8 CURRENT EFFICIENCY

3.7.8.1 CURRENT EFFICIENCY LOSSES

In an ideal water electrolysis cell where membranes/separators are assumed to be impermeable to gases, the current efficiency ε_I is equal to 100%. However, materials (polymer electrolyte of PEM or diaphragm of alkaline) are not fully impermeable. Mass transport of hydrogen and/or oxygen across the cell separator, especially when the cell is operated under pressure, is an issue that raises both safety and current efficiency problems. Depending on the characteristics of the materials used in the cells, a fraction of the gases transported across the cell separator can react chemically or electrochemically. In conclusion, in a water electrolysis cell, the current efficiency is less than 100%, due to gas cross-over or permeation effects.

It is usually difficult to measure accurately the gas flow rates (in moles per second) for gases permeated through the membrane separator, $\dot{n}_{H_2,loss}$ and $\dot{n}_{O_2,loss}$, because the hydrogen flow rates could be relatively small (at single cell and short stack laboratory tests), containing water vapour residues and as already mentioned due to the cross-over and permeation effects some hydrogen and oxygen can react together and produce water before the measurement procedure.

3.7.8.2 CURRENT EFFICIENCY – SINGLE CELL

This is the fraction of the electric current passing through an electrochemical cell which accomplishes the desired chemical reaction. For a set of cell components and for a given cell design, the current efficiency η_I is mainly a function of operating temperature T , operating pressure p and operating current density.

$$\eta_I(T, p, I) = 1 - \frac{2 \cdot F}{I_{DC}} \cdot [\dot{n}_{H_2,loss}(T, p, I) + 2\dot{n}_{O_2,loss}(T, p, I)] \quad [38]$$

where \dot{n}_i is the molar flow of component (i) permeated through the membrane separator in mole per second, 2 is the number of Faraday per mole of H_2 and 4 per mole of O_2 , and I_{DC} the direct current provided, expressed in Ampere.

In an ideal water electrolysis cell, $\dot{n}_{H_2,loss} = \dot{n}_{O_2,loss} = 0$ and $\eta_I(T, p, I) = 1$, independently of the operating conditions (T, p, I).

In a real water electrolysis cell, $\dot{n}_{H_2,loss} \neq \dot{n}_{O_2,loss} \neq 0$ and $\eta_I(T, p, I) < 1$.

In practical conditions, it is easier and more accurate to measure the hydrogen or the oxygen flow rates at the exhaust of the electrolyser instead of measuring H_2 and O_2 cross-permeating flows which are in many cases extremely small. Then, equation [39] (for hydrogen production) or [40] (for oxygen production) apply:

$$\eta_I^{H_2} = \frac{\text{measured } H_2 \text{ flow rate}}{\text{theoretical } H_2 \text{ flow rate}} = \frac{2 \cdot F \cdot \dot{n}_{H_2 \text{ measured}}}{I_{DC}} \quad [39]$$

$$\eta_I^{O_2} = \frac{\text{measured } O_2 \text{ flow rate}}{\text{theoretical } O_2 \text{ flow rate}} = \frac{4 \cdot F \cdot \dot{n}_{O_2 \text{ measured}}}{I_{DC}} \quad [40]$$

The measurement of the relevant outlet gas, hydrogen or oxygen shall be performed using a properly dimensioned and highly accurate mass flow meter placed after the water removal steps that shall be designed to remove more than 99.9% of gas water content. Concentration of hydrogen in oxygen should be measured by gas chromatographic analysis or via other analytical techniques with similar detection limit after a gas drying step. The molar fraction of the components in the outlet gases should be also measured, but in normal conditions it is assumed that traces of oxygen and water vapour in hydrogen or hydrogen and water vapour in oxygen are minor and thus usually negligible. In case of high differential pressures and thin membranes (50 to 90 μm), instead current efficiency of about 98% or even lower can be observed. Nevertheless safety sensors to monitor oxygen level in hydrogen outlet or hydrogen level in oxygen outlet are strongly recommended to detect dangerous situations due to gas cross-over of the separator.

3.7.8.3 CURRENT EFFICIENCY - STACK

The stack current efficiency at the operation temperature and pressure is defined as the ratio between the flow rate of the produced hydrogen, \dot{n}_{H_2} expressed in mole per second multiplied by the Faraday constant and the provided direct current, I_{DC} expressed in Ampere multiplied by the number of cells, N . It is expressed as follows:

$$\eta_{I\ stack}^{H_2} = \frac{\text{measured } H_2 \text{ flow rate}}{\text{theoretical } H_2 \text{ flow rate}} = \frac{2 \cdot F \cdot \dot{n}_{H_2 \text{ measured}}}{N I_{DC}} \quad [41]$$

$$\eta_{I\ stack}^{O_2} = \frac{\text{measured } O_2 \text{ flow rate}}{\text{theoretical } O_2 \text{ flow rate}} = \frac{4 \cdot F \cdot \dot{n}_{O_2 \text{ measured}}}{N I_{DC}} \quad [42]$$

3.7.8.4 COULOMBIC AND FARADIC EFFICIENCIES

These expressions have the same meaning as current efficiency.

3.7.9 TOTAL EFFICIENCY – SINGLE CELL AND STACK

The total efficiency η_{ω} is defined as the product of energy efficiency and current efficiency values. It can be applied at single cell or stack level

$$\eta_{\omega}^{cell} = \varepsilon_{cell} \cdot \eta_I^{cell} \quad [43]$$

$$\eta_{\omega}^{stack} = \varepsilon_{stack} \cdot \eta_I^{stack} \quad [44]$$

3.7.10 ENERGY EFFICIENCY DEFINITION: INDUSTRY'S VIEWPOINT

3.7.10.1 ENERGY EFFICIENCY COEFFICIENT

As already discussed at the beginning of this document (section 3.7.1), the reference energy state used by the industry sector to define the energy efficiency coefficient of a water electrolysis cell, stack or system is different from the reference case used by the academic community. The general definition is:

$$\eta_{cell} = \frac{\text{energy content of products}}{\text{total energy requirements}} = \frac{W_t (J \cdot \text{mol}^{-1})}{W_r (J \cdot \text{mol}^{-1})} \quad [B]$$

The energy content of products used at the numerator of the equation is usually the hydrogen heating value in oxygen (not in air), which is by definition the opposite of the standard enthalpy of formation of a water molecule $\text{HHV} = \Delta H^0 = 285.8 \text{ kJ mol}^{-1}$. There are potentially different practices that will inevitably lead to different values of the energy efficiency coefficient. In order to facilitate comparison, it is necessary to list these different practices:

- Some authors use the heating value of hydrogen combustion in air instead of oxygen
- Some authors use the High Heating Value of hydrogen combustion in oxygen/air (leading to the formation of liquid water) and some other use the Low Heating Value (LHV) of hydrogen combustion in oxygen/air (leading to the formation of gaseous water).
- Authors use different (T,p) conditions to calculate the energy content of their product.
- The usual practice in industry is not to calculate the efficiency coefficient in percent (as in the academic community) but instead to calculate the specific energy consumption of a system (e.g. in kWh/kg_{H2} or in kWh/Nm³_{H2}).

The reason for such discrepancies is clear: the reference state is not unique but dictated by the applications. Therefore, the same electrolyser when used for different applications can have different efficiencies. Hence, there is a need to provide clear specifications to allowing comparisons.

The main issue is to specify the (T,p) conditions at which the reference energy content of hydrogen is calculated. These (T,p) conditions could be considered at the exhaust of the electrolysis cell stack or the (T,p) conditions at the exhaust of the plant, after gas treatment (oxygen removal, drying and eventually compression).

Specifically, the **instantaneous** hydrogen production efficiency (based on the **HHV**) is defined as the ratio between the flow rate of the produced hydrogen, \dot{n}_{H_2} expressed in mole per second multiplied by the HHV expressed in Joule per mole of hydrogen and **the total thermal and electric power** provided to the system expressed in Watt, i.e.:

$$\eta^{HHV} = \frac{HHV \cdot \dot{n}_{H_2}}{P_{thermal} + P_{electrical}} \quad [45]$$

Equation [45] provides a practical and general (energy + current) value of the efficiency. An integral form of Eq. [45] is needed to determine the specific energy consumption in kWh/kg_{H2}. When the system is operated under stationary conditions, the expression (over a given time interval Δt) is simply:

$$\eta^{HHV} = \frac{HHV \cdot \dot{n}_{H_2} \cdot \Delta t}{W_e + Q_{cell} + Q_{H_2O}} = \frac{HHV \cdot N_{H_2}}{W_e + Q_{cell} + Q_{H_2O}} \quad [46]$$

where:

- \dot{n}_{H_2} is the number of moles of hydrogen produced over time (molar flow rate)
- N_{H_2} is the number of moles of hydrogen produced over the time period Δt considered,
- $W_e = nF U_{cell}$ is the electric energy input,
- Q_{cell} is the difference between the entropy change ($T\Delta S$) and the heat Q_{irrev} associated with irreversible losses due to overvoltages of the electrochemical reactions and Joule effect in the internal resistance.
- Q_{H_2O} is the thermal energy input of additional heat exchanger (external to the system) for further water heat up.

3.7.10.2 OVERALL COMPONENT EFFICIENCY

Component efficiency for the HHV is defined as the ratio between the flow rate of the produced hydrogen, \dot{n}_{H_2} expressed in mole per second multiplied by the HHV expressed in Joule per mole and the **total thermal and electric power** provided to the component expressed in Watt as follows:

$$\eta_{component}^{HHV} = \frac{HHV}{P_{component\ extern}} \cdot \dot{n}_{H_2} \quad [47]$$

3.7.10.3 OVERALL SYSTEM EFFICIENCY

At system level (Stack + BoP), it is necessary to take into account the energy consumption of all the necessary ancillary equipment. System efficiency for the HHV is defined as the ratio between the flow rate of the produced hydrogen, \dot{n}_{H_2} expressed in mole per second multiplied by the HHV expressed in $J \cdot mol^{-1}$, and the **total thermal and electric power** supplied to the system, for the operation of all ancillary equipment, expressed in Watt. It is expressed in percentage as

$$\eta_{system}^{HHV} = \frac{HHV}{P_{system\ extern}} \cdot \dot{n}_{H_2} \quad [48]$$

3.7.10.4 OTHER EXPRESSIONS OF PRACTICAL INTEREST

Some authors also calculate the energy efficiency coefficient of the system by multiplying the stack efficiency (assuming a current efficiency of 1) by the AC/DC conversion efficiency (in this case, the reference case is the enthalpy change of the reaction = case 3 of the definition used in the academic community and the efficiency of gas conditioning is not taken into account) :

$$\varepsilon_{system} = \frac{N \cdot U_{tn}(T, p)}{U_{stack}}$$

This definition contains the same **eq[32] in case 3** under exothermal operation multiplied by the AC/DC conversion efficiency

$$\varepsilon_{system} = \frac{N \cdot U_{tn}(T, p)}{U_{stack}} \left(\frac{\eta_{AC/DC}}{1 + \xi} \right) \quad [49]$$

In Eq. [49], ξ is the ratio between parasitic power and net power consumed by the electrolyser due to the energy consumption by the auxiliaries.

$\eta_{AC/DC}$ = efficiency of the AC/DC converter, DC/DC voltage regulator or power conditioner.

Another equation of practical interest is obtained from Eq. [49] by taking into account the hydrogen current efficiency⁽¹⁰⁾:

$$\varepsilon_{system} = \frac{N \cdot U_{tn}(T, p)}{U_{stack}} \cdot \frac{2 \cdot F \cdot \dot{n}_{H_2}}{I_{DC} \cdot N} \cdot \left(\frac{\eta_{AC/DC}}{1 + \xi} \right) \quad [50]$$

for FCH2JU consultation

3.7.11 EXERGY ANALYSIS

3.7.11.1 EXERGY DEFINITION

In general terms Exergy can be defined as the maximum work that can be extracted when a system is brought into equilibrium with its surroundings without incurring any losses (Wall 1977). The efficiency of a process is defined as the used exergy outflow divided by the used exergy inflow. The term **Yield** is brought together with the **Exergy** to replace the term Efficiency to avoid confusion between Energy and Exergy efficiency descriptors.

Field of application

- The water splitting reaction (chemical reaction) is analysed at constant (T,p,I) conditions only; the transformation takes place in a thermostatic reactor; the heat needed to bring tap water up to the operating temperature of interest is not taken into account in the efficiency calculation and the reaction products (H₂ and O₂) are considered at the same (T,p) conditions.
- The water electrolysis cell (device) is also analysed at constant (T,p,I) conditions but the heat needed to bring tap water up to the operating temperature of interest is taken into account in the efficiency calculation and the (T,p) of product gases may differ from those of the reaction.

The water electrolysis cell, stack and plant are thermodynamically open systems operating in either stationary or non-stationary conditions. The exergy balance can be established in integral form (J) or in power (J·s⁻¹) or in specific power (J·s⁻¹·m⁻²). The exergy yield relates the exergy output to the exergy input. Due to internal irreversible degradations (mainly dissipation at cell and stack levels), the exergy output is less than the exergy input and the exergy yield is less than unity. To calculate the exergy yield, it is necessary to take into account the different exergy contributions:

- The work or work-power received from the DC power source (the exergy content of 1 Joule of electricity is equal to 1 Joule).
- The heat-exergy (the heat-exergy power or flow rate) associated with heat transfers (the exergy content of 1 Joule of heat is modulated by the associated Carnot factor).
- The transformation-exergy (the transformation-exergy power or flow rate) associated with the chemical reaction. This is the co-enthalpy balance of the water splitting reaction:

$$\Delta k = \sum_i v_i [(h - h_i^0) - T_{env}(s_i - s_i^0)] \quad [46]$$

Where

v_i = generalized stoichiometric reaction number.

h = enthalpy at operating condition

h_i^0 = enthalpy at reference condition

T_{env} = ambient temperature

s_i = entropy at operating condition

s_i^0 = entropy at reference condition

The exergy yield can be defined starting from the overall efficiency formula used in the industry, Eq [45], that takes into account the energy content of the hydrogen production and the electrical and thermal energy inputs as⁽⁷⁾:

$$\zeta^{HHV} = \frac{E^{HHV} \cdot \dot{n}_{H_2}}{\dot{E}_e + \dot{E}_{q,cell} \left(1 - \frac{T_{env}}{T_{cell}}\right) + \dot{E}_{q,H_2O} \left(1 - \frac{T_{env}}{T_{cell}}\right)} \quad [52]$$

where:

ζ^{HHV} is the exergy yield of the water splitting reaction.

E^{HHV} in J/mole is the molar exergy value associated with the hydrogen production at (T_{cell}, P_{cell}) conditions (based on the HHV reaction because liquid water is electrolysed in a PEM water electrolysis cell). The value is very close to the energy content.

\dot{n}_{H_2} in mol/s is the molar hydrogen flow.

\dot{E}_e in J/s is the electricity exergy input from the DC power source.

$\dot{E}_{q,cell}$ in J/s is the exergy input to the PEM cell for the reaction.

T_{env} in K is the temperature of the environment (ambient).

T_{cell} in K is the operating temperature of the electrolysis cell.

\dot{E}_{q,H_2O} in J/s is the exergy content of input water that is heated up from ambient to the operating temperature.

3.7.11.2 RELATION BETWEEN ENERGY EFFICIENCY AND EXERGY YIELD

Since PEM, AEM and alkaline water electrolysis cells operate in near-ambient operating conditions, the exergy content of the heat flows ($\dot{E}_{q,cell}$ and \dot{E}_{q,H_2O}) is small because $T_{cell} \approx T_{env}$. In this condition, when an electrolyser operates in exothermic mode, the only thermal energy needed is for the heating of water added to the system to replace the one converted into hydrogen and oxygen. Therefore the main type of energy supplied to the system is the electrical one and as electricity has 100% exergy content the energy efficiency and exergy yield are close.

Also, the heat produced by a water electrolysis plant operating in near-ambient conditions has a low exergy value and cannot be used for work production. It is considered as a loss and can be used only for heating purposes.

This is why an energy analysis is considered as sufficient to determine the characteristics of a water electrolysis cell or stack operating in such near-ambient conditions. The situation is different for a high temperature water electrolysis cell, but this analysis it is not considered in this account. At system level, it is important to evaluate the exergy yield contribution by the different BoP components in order to obtain the total exergy yield of the system.

3.7.12 SUMMARY TABLES OF EQUATIONS

The following Tables provide a summary of the various efficiency equations presented in this document.

Table 2
ENERGY EFFICIENCY

ENERGY EFFICIENCY - ϵ		
SINGLE CELL	NOTE	Eq. No
$U_{rev}^0 = \Delta G^0 / (n F)$	1.229V at SATP	[3]
$U_{rev}(T, 1atm) = 1.5184 - 1.5421 \cdot 10^{-3} \cdot T + 9.523 \cdot 10^{-5} \cdot T \cdot \ln(T) + 9.84 \cdot 10^{-8} T^2$	U_{rev} in the temperature range 0-100°C	[22]
$U_{tn}^0 = \Delta H^0 / (n F)$	1.481V at SATP	[4]
$U_{tn}(T, 1atm) = 1.485 - 1.49 \cdot 10^{-4} \cdot (T - T^0) - 9.84 \cdot 10^{-8} \cdot (T - T^0)^2$	U_{tn} in the temperature range 0-100°C	[23]
$\epsilon_{cell,case1} = \frac{U_{tn}}{U_{tn} + U_{cell} - U_{rev}}$	Case 1 Constant heat input-based definition	[9]
$\epsilon_{cell,case1} = \frac{U_{tn}(T, p)}{U_{tn}(T, p) + U_{cell}(T, p) - U_{rev}(T, p)}$	Case 1 For any T,p condition	[11]
$\epsilon_{cell,case2} = \frac{U_{rev}}{U_{cell}}$	Case 2 Free energy-based definition	[12]
$\epsilon_{cell,case2}(T, p) = \frac{U_{rev}(T, p)}{U_{cell}(T, p)}$	Case 2 For any T,p condition	[14]
$\epsilon_{cell,case3} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{tn}}$	Case 3 $\epsilon = 1$ When $U_{rev} < U_{cell} \leq U_{tn}$	[15] [16]
$\epsilon_{cell,case3} = \frac{U_{tn}}{U_{cell}}$	Case 3 Enthalpy-based definition when	[17]

	$U_{cell} > U_{tn}$	
$\varepsilon_{cell,case3} = \frac{U_{tn}(T, p)}{U_{cell}(T, p)}$	Case 3 when $U_{cell} > U_{tn}$ For any T, p condition	[18]
$\varepsilon_{cell,case4} = \frac{n \cdot F \cdot U_{tn}}{n \cdot F \cdot U_{cell} + Q_{input}}$	Case 4	[21]
$\Delta U_{cell} = \frac{RT}{2F} \ln \left[\left(\frac{p^A - p_{H_2O}^{sat}}{p^\theta} \right)^{\frac{1}{2}} \left(\frac{p^C - p_{H_2O}^{sat}}{p^\theta} \right) / \left(\frac{p^{H_2O}}{p^\theta} \right) \right]$	Water saturated and ideal gases pressure correction voltage	[27]
$Q_{cell} = n \cdot F \cdot (U_{tn} - U_{cell})$	Cell heat balance $Q_{cell} < 0$ rejected $Q_{cell} > 0$ absorbed	[7]
STACK		
$\varepsilon_{stack,case1} = \frac{N \cdot U_{tn}(T, p)}{N \cdot U_{tn}(T, p) + U_{stack}(T, p) - N \cdot U_{rev}(T, p)}$	Case 1	[30]
$\varepsilon_{stack,case2} = \frac{N \cdot U_{rev}(T, p)}{U_{stack}(T, p)}$	Case 2	[31]
$\varepsilon_{stack,case3} = \frac{N \cdot U_{tn}}{U_{stack}}$	Case 3 when $U_{cell} > U_{tn}$	[32]
$\varepsilon_{stack,case3} = \frac{N \cdot n \cdot F \cdot U_{tn}}{N \cdot n \cdot F \cdot U_{tn}} = 1$	Case 3 when: $U_{rev} < U_{cell} \leq U_{tn}$	[33]
$\varepsilon_{cell,case4} = \frac{n \cdot F \cdot U_{tn}}{N \cdot n \cdot F \cdot U_{cell} + Q_{input\ stack}}$	Case 4 when: $U_{rev} < U_{cell} < U_{tn}$	[34]
$Q_{stack} = n \cdot F \cdot (N \cdot U_{tn} - U_{stack})$	Stack heat balance $Q_{stack} < 0$ rejected $Q_{stack} > 0$ absorbed	[35]
SYSTEM		
$N \frac{U_{tn}(T, p)}{U_{stack} + W_{aux}/(nF)}$	System efficiency	[36]

$$Q_{system} = n \cdot F \cdot (N \cdot U_{tm} - U_{stack}) + W_{aux} \quad \text{Heat balance} \quad [37]$$

Table 3
CURRENT EFFICIENCY

CURRENT EFFICIENCY - η_I		
SINGLE CELL	NOTE	Eq. No
$\eta_I(T, P, I) = 1 - \frac{2 \cdot F}{I_{DC}} \cdot [\dot{n}_{H_2,loss}(T, p, I) + 2\dot{n}_{O_2,loss}(T, p, I)]$	General formula (academic viewpoint)	[38]
$\eta_I^{H_2} = \frac{2 F \dot{n}_{H_2 \text{ measured}}}{I_{DC}}$	Hydrogen production efficiency (industry viewpoint)	[39]
$\eta_I^{O_2} = \frac{4 F \dot{n}_{O_2 \text{ measured}}}{I_{DC}}$	Oxygen production efficiency (industry viewpoint)	[40]
STACK		
$\eta_{Istack}^{H_2} = \frac{2 \cdot F \cdot \dot{n}_{H_2}}{I_{DC} \cdot N}$	Hydrogen production efficiency (industry viewpoint)	[41]
$\eta_{Istack}^{O_2} = \frac{4 \cdot F \cdot \dot{n}_{O_2}}{I_{DC} N}$	Oxygen production efficiency (industry viewpoint)	[42]

Table 4
OVERALL EFFICIENCY

OVERALL EFFICIENCY - η_ω		
SINGLE CELL	NOTE	Eq. No

$\eta_{\omega}^{cell} = \varepsilon_{cell} \cdot \eta_I^{cell}$	Total efficiency (academic viewpoint)	[43]
$\eta^{HHV} = \frac{HHV \cdot \dot{n}_{H_2}}{P_{thermal} + P_{electrical}}$	Instantaneous cell efficiency (industry viewpoint)	[45]
$\eta^{HHV} = \frac{HHV \cdot \dot{n}_{H_2} \cdot \Delta t}{W_e + Q_{cell} + Q_{H_2O}}$	Integral form of cell efficiency (stationary operating conditions)	[46]
STACK		
$\eta_{\omega}^{stack} = \varepsilon_{stack} \cdot \eta_I^{stack}$	Total efficiency (academic viewpoint)	[44]
COMPONENT		
$\eta_{component}^{HHV} = \frac{HHV}{P_{component\ extern}} \dot{n}_{H_2}$	Component efficiency	[47]
SYSTEM		
$\eta_{system}^{HHV} = \frac{HHV}{P_{system\ extern}} \dot{n}_{H_2}$	System efficiency (industry viewpoint)	[48]
$\varepsilon_{system} = \frac{N \cdot U_{tn}(T, p)}{U_{stack}} \left(\frac{\eta_{AC/DC}}{1 + \xi} \right)$	System efficiency excluding faradaic efficiency (industry viewpoint)	[49]
$\varepsilon_{system} = \frac{N \cdot U_{tn}(T, p)}{U_{stack}} \cdot \frac{2 \cdot F \cdot \dot{n}_{H_2}}{I_{DC} \cdot N} \cdot \left(\frac{\eta_{AC/DC}}{1 + \xi} \right)$	System efficiency including faradaic efficiency (industry viewpoint)	[50]

Table 5
EXERGY YIELD¹

EXERGY YIELD - ζ^{HHV}		
SINGLE CELL	NOTE	Eq. No

$$\zeta^{HHV} = \frac{E^{HHV} \cdot \dot{n}_{H_2}}{\dot{E}_e + \dot{E}_{q,cell} \left(1 - \frac{T_{env}}{T_{cell}}\right) + \dot{E}_{q,H_2O} \left(1 - \frac{T_{env}}{T_{cell}}\right)} \quad [52]$$

¹Exergy Yield expressions for Components and Systems are not covered in this report.

3.7.13 REVERSIBLE POTENTIAL (E_{rev})

It is defined as the minimum necessary cell voltage needed to start the water electrolysis as in eq [3].

At SATP conditions it is expressed as E° and its value is 1.229 V

3.7.14 REVERSIBLE VOLTAGE (V_{rev})

See equivalent definition of reversible potential 3.7.13

3.7.15 THERMONEUTRAL POTENTIAL (E_{tn})

The thermoneutral potential at standard conditions (25°C and 1013 hPa) is 1.481 V. It is defined as the voltage at which an electrolysis cell operating at 25 °C can operate without producing excess heat, see eq [4]

3.7.16 THERMONEUTRAL VOLTAGE (v_{tn})

See equivalent definition of thermoneutral potential 3.7.15

3.8 ELECTRICAL POWER

3.8.1 CELL ELECTRICAL POWER DENSITY

Input power per cell cross section [Units: W/m²]

3.8.2 ELECTRICAL POWER –APPARENT

The square root of the sum of the squares of the active and the reactive powers.⁽⁴⁾

3.8.3 ELECTRICAL POWER –REACTIVE

For sinusoidal quantities in a two-wire circuit, the product of the voltage, the current, and the sine of the phase angle between them. In a multiphase circuit; the sum of the reactive powers of the phases.⁽⁴⁾

3.8.4 ELECTRICAL POWER –REAL

For sinusoidal quantities in a two-wire circuit, the product of the voltage, the current, and the cosine of the phase angle between them. In a multiphase circuit, the sum of the active powers of the individual phases.⁽⁴⁾

3.8.5 ELECTRICAL POWER FACTOR

The ratio of the total active power in Watts to the total apparent power in Volt-Amperes (the product of root-mean-square (rms.) voltage and rms. Current).

Leading. A designation of the relative instantaneous direction of the currents to the voltages (angle is 0 to -90°).

Lagging. A designation of the relative instantaneous direction of the currents to the voltages (angle is 0 to +90°).⁽⁴⁾

3.8.6 ELECTRICAL POWER INPUT RATED OR NOMINAL

Maximum continuous electric input power that a device is designed to achieve under normal operating conditions specified by the manufacturer [Units: W]

3.8.7 PARASITIC LOAD

Power consumed by auxiliary machines and equipment such as balance of plant (BOP) necessary to operate an electrolyser system [Units: W].⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.8.8 POWER SYSTEM CAPACITY – RATED

Maximum capacity of the system, in terms of power, as rated by the manufacturer [Units: kW or MW]

3.8.9 POWER STACK CAPACITY – RATED

Maximum stack capacity, in terms of electrical DC power as rated by the manufacturer (kW direct current) [Units: kW or MW]

3.8.10 POWER SUPPLY RANGE

It is the functional range of an electrolysis system between its minimum power operating value and 100% (full scale) rated power DC charge.

3.8.11 RATED POWER

The value stated on the device nameplate. It is the power to be provided at the input terminals of a component or piece of equipment that is operated in compliance with the manufacturer's performance specifications.⁽⁴⁾

3.9 GAS CROSSOVER

Gas permeation through the separation membrane leading to transport of hydrogen to oxygen side and vice versa, leading to safety and efficiency reduction issues.

The phenomenon is due to various transport mechanism: differential pressure, diffusion, electro-osmotic drag, ions flux densities.

3.10 GAS LEAKAGE

The sum of all gases leaving the electrolyser module except the intended exhaust gases.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.11 GAS TIGHTNESS

System characteristic, that ensures that no exchange of fluids and gases between two or more compartments of a device occurs, i.e. between anode and cathode or surrounding space.⁽⁴⁾

3.12 GRID OR ELECTRICITY NETWORK

It is a plant and apparatus connected together for transmitting or distributing electricity.⁽³⁾

3.12.1 BALANCE REGULATION

Balance regulation is the regulation actions done in order to maintain the frequency and time deviation of the electricity grid in accordance with the set quality requirements. Regulation is also carried out for network reasons.

3.12.2 CONNECTION POINT

It is the interface at which the power-generating module, demand facility, distribution system is connected to a transmission system, offshore network, distribution system, including closed distribution systems, as identified in the connection agreement between relevant system operator and either power-generating or demand facility owner.⁽³⁾

3.12.3 CONTROL AREA

A coherent part of the interconnected system, operated by a single system operator and shall include connected physical loads and/or generation units if any.⁽⁵⁾

[source: ENTSOE glossary]

3.12.4 CONTROL RESERVE

Energy stock to be used to control the frequency of the power supply network in case of unpredictable variations in energy injection and withdrawal.

The reserve can be either positive, in order to balance deficits of the network, or negative, in case of surplus balance.

3.12.5 DISTRIBUTION SYSTEM

The transport of electricity on high-voltage, medium-voltage and low-voltage distribution systems with a view to its delivery to customers, but does not include supply.⁽⁵⁾

[source: ENTSOE glossary]

3.12.6 DISTRIBUTION NETWORK

An electrical Network, including Closed Distribution Networks, for the distribution of electrical power from and to third party[s] connected to it, a Transmission or another Distribution Network.⁽⁵⁾

[source: ENTSOE glossary]

3.12.7 DISTRIBUTION NETWORK OPERATOR

Either a Distribution System Operator or a Closed Distribution System Operator.⁽⁵⁾

[source: ENTSOE glossary]

3.12.8 DISTURBANCE

An unplanned event that may cause the transmission system to divert from the normal state.⁽⁵⁾

[source: ENTSOE glossary]

3.12.9 ENERGY FROM RENEWABLE SOURCES

Energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.⁽⁵⁾

[source: ENTSOE glossary]

3.12.10 ENERGY STORAGE

A device being used for storage of electrical energy and that can be used to balance the system.⁽⁵⁾

[source: ENTSOE glossary]

3.12.11 ELECTRICAL TIME DEVIATION

The time discrepancy between synchronous time and coordinated universal time ('UTC').⁽⁵⁾

[source: ENTSOE glossary]

3.12.12 ELECTRICAL SYSTEM FREQUENCY

The electric frequency of the system expressed in hertz that can be measured in all parts of the synchronous area under the assumption of a consistent value for the system in the time frame of seconds, with only minor differences between different measurement locations. Its nominal european value is 50Hz.⁽⁵⁾

[source: ENTSOE glossary]

3.12.13 FREQUENCY CONTROL

The capability of a power generating module or HVDC system to adjust its active power output in response to a measured deviation of system frequency from a setpoint, in order to maintain stable system frequency.^(3,5)

3.12.14 LOAD-FREQUENCY CONTROL AREA

A part of a synchronous area or an entire synchronous area, physically demarcated by points of measurement at interconnectors to other LFC areas, operated by one or more TSOs fulfilling the obligations of load-frequency control.⁽⁵⁾

[source: ENTSOE glossary]

3.12.15 FREQUENCY CONTROLLED NORMAL OPERATION RESERVE

The frequency controlled normal operation reserve is the momentarily available active power for frequency regulation in the range of 49.9 – 50.1 Hz and which is activated automatically by the system frequency.

3.12.16 FREQUENCY CONTAINEMENT RESERVES (FCR)

The active power reserves available to contain system frequency after the occurrence of an imbalance.⁽⁵⁾

[source: ENTSOE glossary]

3.12.17 FREQUENCY CONTAINEMENT RESERVES FULL ACTIVATION FREQUENCY DEVIATION

The rated value of frequency deviation at which the FCR in a synchronous area is fully activated.⁽⁵⁾

[source: ENTSOE glossary]

3.12.18 FREQUENCY RESPONSE DEADBAND

An interval used intentionally to make the frequency control unresponsive.⁽⁵⁾

[source: ENTSOE glossary]

3.12.19 FREQUENCY DEVIATION

The difference between the actual and the nominal frequency of the synchronous area which can be negative or positive.⁽⁵⁾

[source: ENTSOE glossary]

3.12.19.1 INSTANTANEOUS FREQUENCY DEVIATION

A set of data measurements of the overall system frequency deviations for the synchronous area with a measurement period equal to or shorter than one second used for system frequency quality evaluation purposes.⁽⁵⁾

[source: ENTSOE glossary]

3.12.19.2 MAXIMUM INSTANTANEOUS FREQUENCY DEVIATION

The maximum expected absolute value of an instantaneous frequency deviation after the occurrence of an imbalance equal to or smaller than the reference incident, beyond which emergency measures are activated.⁽⁵⁾

[source: ENTSOE glossary]

3.12.19.3 MAXIMUM STEADY-STATE FREQUENCY DEVIATION

The maximum expected frequency deviation after the occurrence of an imbalance equal to or less than the reference incident at which the system frequency is designed to be stabilised.⁽⁵⁾

[source: ENTSOE glossary]

3.12.19.4 STEADY-STATE FREQUENCY DEVIATION

The absolute value of frequency deviation after occurrence of an imbalance, once the system frequency has been stabilised.⁽⁵⁾

[source: ENTSOE glossary]

3.12.20 FREQUENCY RESTORATION CONTROL ERROR

The control error for the FRP which is equal to the ACE of a LFC area or equal to the frequency deviation where the LFC area geographically corresponds to the synchronous area.⁽⁵⁾

[source: ENTSOE glossary]

3.12.21 FREQUENCY RESTORATION PROCESS

A process that aims at restoring frequency to the nominal frequency and, for synchronous areas consisting of more than one LFC area, a process that aims at restoring the power balance to the scheduled value.⁽⁵⁾

[source: ENTSOE glossary]

3.12.21.1 FREQUENCY RESTORATION RESERVES (FRR)

The Active Power Reserves available to restore System Frequency to the Nominal Frequency, and for Synchronous Area consisting of more than one Load Frequency Control (LFC) Area to restore power balance to the scheduled value.⁽⁵⁾

[source: ENTSOE glossary]

3.12.21.2 AUTOMATIC FREQUENCY RESTORATION RESERVES, A-FRR

FRR that can be activated by an automatic control device.⁽⁵⁾

[source: ENTSOE glossary]

3.12.21.3 AUTOMATIC FRR FULL ACTIVATION TIME

The time period between the setting of a new setpoint value by the frequency restoration controller and the corresponding activation or deactivation of automatic FRR.⁽⁵⁾

[source: ENTSOE glossary]

3.12.21.4 MANUAL FREQUENCY RESTORATION RESERVES, MFRR

FRR that can be activated manually

3.12.22 FREQUENCY RESTORATION RANGE

The system frequency range to which the system frequency is expected to return in the GB, IE/NI and Nordic synchronous areas, after the occurrence of an imbalance equal to or smaller than the reference incident within the time to restore frequency.⁽⁵⁾

[source: ENTSOE glossary]

3.12.23 FREQUENCY SETPOINT

The frequency target value used in the FRP, defined as the sum of the nominal system frequency and an offset value needed to reduce an electrical time deviation.⁽⁵⁾

[source: ENTSOE glossary]

3.12.24 FULL ACTIVATION TIME

The time period between the activation request by TSO and the corresponding full activation of the concerned product.⁽⁵⁾

[source: ENTSOE glossary]

3.12.25 GRID-CONNECTED OPERATION

Mode when the system is operated while connected to a utility grid.

3.12.26 GRID-CONTROL

In the event of a major load fluctuation such as a power station outage or other unpredictable variations in energy injection and withdrawal in the grid, a set of different control reserve, primary, secondary and tertiary, can be activated at different ramp rates and time steps, as described in the below figure 11.

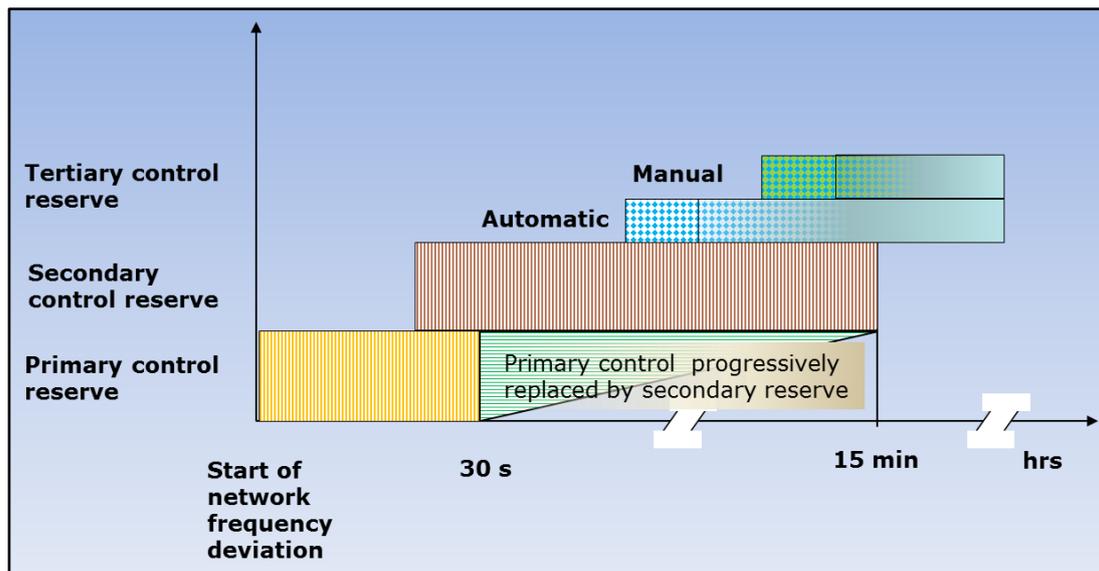


Figure 11

Grid control sequence of activation

3.12.26.1 REPLACEMENT RESERVES

The active power reserves available to restore or support the required level of FRR to be prepared for additional system imbalances, including operating reserves.⁽⁵⁾

[source: ENTSOE glossary]

3.12.26.1 RESERVES REPLACEMENT PROCESS

A process to restore the activated FRR and, additionally for GB and IE/NI, to restore the activated FCR.⁽⁵⁾

[source: ENTSOE glossary]

3.12.26.2 PRIMARY CONTROL RESERVE

It is the first and fastest control stock reserve to be used in case of grid frequency disturbance. It is deployed automatically with a proportional regulation for the reestablishment of the network frequency balance between energy production and consumption as fast as possible. Complete deployment time of PCR is depending by the country, usually is around 15-30 seconds.⁽⁶⁾

[source: ENTSOE - Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.26.3 PRIMARY RESERVE

The reserves performing primary control by automatic change of the working points regulated by the frequency.⁽⁶⁾

[source: ENTSOE Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.26.4 SECONDARY CONTROL RESERVE

It is the stock which is deployed automatically in a selective manner in those control areas where network imbalance occurs for the reestablishment of the frequency setting of 50 Hz between energy production and consumption.

It is started within 30 seconds from the imbalance and can last up to 15 minutes.⁽⁶⁾

[source: ENTSOE Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.26.5 SECONDARY CONTROL

Secondary control is a centralised automatic function to regulate the generation in a control area based on secondary control reserves in order: - to maintain its interchange power flow at the control program with all other control areas (and to correct the loss of capacity in a control area affected by a loss of production) and, at the same time, - (in case of a major frequency deviation originating from the control area, particularly after the loss of a large generation unit) to restore the frequency in case of a frequency deviation originating from the control area to its set value in order to free the capacity engaged by the primary control (and to restore the primary control reserves). In order to fulfil these functions, secondary control operates by the network characteristic method. Secondary control is applied to selected generator sets in the power plants comprising this control loop. Secondary control operates for periods of several minutes, and is therefore dissociated from primary control.⁽⁶⁾

[source: ENTSOE Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.26.6 TERTIARY CONTROL RESERVE

The power which can be connected (automatically or) manually under Tertiary control, in order to provide an adequate secondary control reserve, is known as the tertiary control reserve or minute reserve. This reserve must be used in such a way that it will contribute to the restoration of the secondary control range when required. The restoration of an adequate secondary control range may take, for example, up to 15 minutes, whereas tertiary control for the optimisation of the network and generating system will not necessarily be complete after this time.⁽⁶⁾

[source: ENTSOE Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.27 GRID CURRENT

The rate at which electric charge flows which is measured by the root-mean-square value of the positive sequence of the phase current at fundamental frequency.⁽⁵⁾

[source: ENTSOE glossary]

3.12.28 GRID STANDARD FREQUENCY RANGE

A defined symmetrical interval around the nominal frequency within which the system frequency of a synchronous area is supposed to be operated.⁽⁵⁾

[source: ENTSOE glossary]

3.12.29 GRID VOLTAGE

The difference in electrical potential between two points measured as the root-mean-square value of the positive sequence phase-to-phase voltages at fundamental frequency.⁽⁵⁾

[source: ENTSOE glossary]

3.12.30 GRID VOLTAGE CONTROL

The manual or automatic control actions at the generation node, at the end nodes of the AC lines or HVDC systems, on transformers, or other means, designed to maintain the set voltage level or the set value of reactive power.⁽⁵⁾

[source: ENTSOE glossary]

3.12.31 GRID VOLTAGE STABILITY

The ability of a transmission system to maintain acceptable voltages at all nodes in the transmission system in the N-situation and after being subjected to a disturbance.⁽⁵⁾

[source: ENTSOE glossary]

3.12.32 MANUAL FRR FULL ACTIVATION TIME

The time period between the set-point change and the corresponding activation or deactivation of manual FRR.⁽⁵⁾

[source: ENTSOE glossary]

3.12.33 GRID TIME TO RECOVER FREQUENCY

Maximum expected time after the occurrence of an imbalance smaller than or equal to the Reference Incident in which the System Frequency returns to the Maximum Steady State Frequency Deviation. This parameter is used in GB and IRE only (in larger SAs it is not necessary to require Power Generating Modules to operate continuously within higher System Frequency ranges).⁽⁵⁾

[source: ENTSOE glossary]

3.12.34 GRID FREQUENCY RECOVERY RANGE

The System Frequency range to which the System Frequency is expected to return after the occurrence of an imbalance equal to or less than the Reference Incident within the Time To Recover Frequency.⁽⁵⁾

[source: ENTSOE glossary]

3.12.35 TIME TO RESTORE FREQUENCY

The maximum expected time after the occurrence of an instantaneous power imbalance smaller than or equal to the reference incident in which the system frequency returns to the frequency restoration range for synchronous areas with only one LFC area and in the case of synchronous areas with more than one LFC area, the maximum expected time after the occurrence of an instantaneous power imbalance of an LFC area within which the imbalance is compensated.⁽⁵⁾

[source: ENTSOE glossary]

3.12.36 GRID FREQUENCY RESTORATION RANGE

Range to which the System Frequency should be restored after the Time to Restore Frequency has elapsed since a Reference Incident occurs.⁽⁵⁾

[source: ENTSOE glossary]

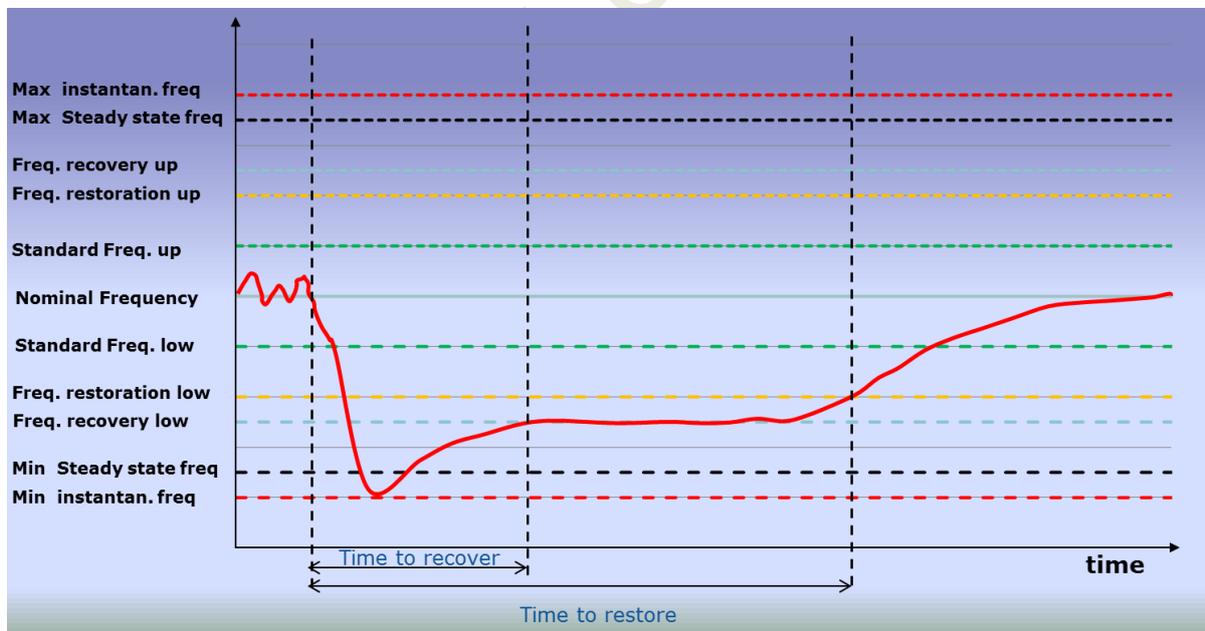


Figure 12

Frequency quality parameters

3.12.37 GRID-INDEPENDENT OR ISOLATED OPERATION

See equivalent definition of island operation 3.12.38

3.12.38 ISLAND OPERATION

The independent operation of a whole network or part of a network that is isolated after being disconnected from the interconnected system, having at least one power-generating module or HVDC system supplying power to this network and controlling the frequency and voltage.^(3,5)

3.12.39 METERING GRID AREA

A Metering Grid Area is a physical area where consumption, production and exchange can be metered. It is delimited by the placement of meters for period measurement for input to, and withdrawal from the area. It can be used to establish the sum of consumption and production with no period measurement and network losses.⁽⁵⁾

[source: ENTSOE glossary]

3.12.40 METERING POINT

An entity where energy products are measured or computed.⁽⁵⁾

[source: ENTSOE glossary]

3.12.41 NETWORK FREQUENCY

See 3.12.12

3.12.42 OFFSHORE GRID CONNECTION SYSTEM

The complete interconnection between an offshore connection point and the onshore system at the onshore grid interconnection point.⁽⁵⁾

[source: ENTSOE glossary]

3.12.43 OFFSHORE POWER PARK MODULE

A Power Park Module located offshore with an Offshore Connection Point.⁽⁵⁾

[source: ENTSOE glossary]

3.12.44 POWER GENERATING FACILITY

It is a facility that converts primary energy into electrical energy and which consists of one or more power-generating modules connected to a network at one or more connection points.⁽³⁾

3.12.45 POWER GENERATING MODULE

Means either a synchronous power-generating module or a power park module.⁽³⁾

3.12.46 RENEWABLE ENERGY SOURCES

Renewable non-fossil energy sources (wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases).⁽⁵⁾

[source: ENTSOE glossary]

3.12.47 TERTIARY CONTROL

Tertiary control is a change in the setpoints of generations or loads participating, in order to guarantee the provision of secondary control reserves at the right time and distribute the secondary control power to the various generations in the best possible way.⁽⁶⁾

[source: ENTSOE Supporting Document for the Network Code on Load-Frequency Control and Reserves 28.06.2013]

3.12.48 RESERVE PROVIDER

A legal entity with a legal or contractual obligation to supply FCR, FRR or RR from at least one reserve providing unit or reserve providing group.⁽⁵⁾

[source: ENTSOE glossary]

3.12.49 TRANSMISSION SYSTEM OPERATOR, TSO

A natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long term ability of the system to meet reasonable demands for the transmission of electricity.⁽⁵⁾

[source: ENTSOE glossary]

3.13 HEATING VALUE

The value of the heat of combustion of a fuel defined by the heat supplied to a thermal system by the entire reaction enthalpy of the exothermal combustion reaction at standard conditions (25°C, 10⁵Pa) [kJ mol⁻¹]

NOTE – The heating value is thus the negative reaction enthalpy of the combustion reaction.

Lower (LHV). The value of the heat of combustion of a fuel as measured by allowing all products of combustion to remain in the gaseous state. This method of measure does not take into account the heat energy put into the vaporisation of water (heat of vaporisation).

Higher Heating Value (HHV). The value of the heat of combustion of a fuel as measured by reducing all of the products of combustion back to their original temperature and condensing all water vapour formed by combustion. This value takes into account the heat of vaporisation of water.⁽⁴⁾

3.14 HYDROGEN

3.14.1 HYDROGEN PRODUCTION RATE

Amount of H₂ produced by an electrolysis cell/stack/system during a specified time interval at a rated power with a defined purity [Units: kg/h or, kg/day].

3.14.1.1 NOMINAL HYDROGEN WEIGHT CAPACITY

Nominal daily hydrogen production rate in weight, rated value in [Units: kg/day].

3.14.1.2 NOMINAL HYDROGEN VOLUME CAPACITY

Nominal Hourly hydrogen production rate in volume, rated value in [Units: Nm³/h].

3.15 KEY PERFORMANCE INDICATOR

Metric parameter used to quantify the relevant process parameters for a specific task/project.

3.16 OPERATING CONDITIONS

Test or standardized operating conditions that have been predetermined to be the basis of the test in order to have reproducible, comparable sets of test data.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.17 OPERATIONAL MODE

3.17.1 CONSTANT CURRENT OPERATION

Operational mode when the electrolyser is operated at a constant current (galvanostatic mode).⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.17.2 COLD STATE

Non operative state of a cell/stack/system when it is at ambient temperature with no power input or output.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.17.3 NOMINAL OPERATIONAL MODE

Operation of the device using the parameter setting defined to obtain the nominal performances as defined in the technical specification.

3.17.4 REGULATION MODE

A mode of operation where the device is working using a variable power i.e. provided by the network to compensate grid imbalances.

3.17.5 REGULATION PROFILE

It is a variable power profile like the grid power profile resulting from the energy injection and withdrawal. This can be affected by RES (renewable energy sources) energy fluctuations and network disturbances.

3.17.6 SHUTDOWN

Sequence of operations that occurs to stop the system and all its reactions in a controlled safe manner.

3.17.6.1 EMERGENCY SHUTDOWN

Control system actions, based on process parameters, or manually activated, taken to stop the system and all its reactions immediately to avoid equipment damage and/or personnel hazards. ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.17.7 STANDBY STATE

A state without hydrogen/oxygen output that allows fast re-starting of the system by keeping some parameters at or close to the nominal operating parameters.

3.17.7.1 COLD STANDBY STATE

Non-operating state of equipment turned off and ready for immediate start.

3.17.7.2 WARM STANDBY STATE

Operating state of equipment powered and warmed up at a temperature lower than the one needed for service operation.

3.17.7.3 HOT STANDBY STATE

Operating state of equipment powered and warmed up and ready for immediate service operation.

3.17.8 STEADY STATE

State of a physical system in which the relevant characteristics/operating parameters remain constant with time.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.18 OPERATIONAL PARAMETERS

3.18.1 INITIAL RESPONSE TIME

It is the time needed after a set-point change of a parameter to begin changing the output.

3.18.2 TOTAL RESPONSE TIME

It is the time needed after a set-point change of a parameter for reaching a new value.

3.18.3 OPERATING PROFILE

Description of system power profile versus operating time.

3.18.3.1 STEADY STATE PROFILE

Operation mode of the system when power is constant versus time.

3.18.3.2 INTERMITTENT PROFILE

Operation mode of the system when power is variable versus time.

3.18.4 OPERATING TEMPERATURE

Temperature at which the electrolyser (stack) operates.⁽⁸⁾

3.18.5 OVERLOAD CAPABILITY

The overload capability is the ability of electrolysis system to operate beyond the nominal operating and design point for a limited period of time, typically in the range of few minutes to less than one hour. Mostly the overload capability is used to provide a larger flexibility in different grid service applications (e.g. secondary control reserve).

3.18.5.1 MAXIMUM OVERLOAD CAPACITY

Maximum power, expressed in percent of nominal power, at which the electrolyser can operate for limited time periods in cases of peaks in operations.⁽⁸⁾

3.18.6 PARTIAL LOAD OPERATION – MINIMUM

Minimum partial load operation, as a percentage of rated nominal capacity, in terms of power input.

3.18.7 SYSTEM MINIMUM POWER

Minimum power for which the system is designed, as a percentage of nominal power (%).⁽⁸⁾

3.18.8 REACTIVITY

Reactivity is the time required for the electrolysis system to change from 0 to 100 % of the power (ramp-up) or from 100% of the power down to 0% (ramp-down).

3.18.9 SHUTDOWN TIME

Duration between the instant when the power supply is removed and the instant when the shutdown is completed as specified by the manufacturer.⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.18.10 STACK

3.18.10.1 STACK NOMINAL CAPACITY

Individual stack capacity, as rated by the manufacturer (kW direct current).⁽⁸⁾

3.18.10.2 STACK ARRAYS

Number of stack arrays within the system that can be operated independently.⁽⁸⁾

3.18.10.3 STACK CELL NUMBER

Average number of cells per stack.⁽⁸⁾

3.18.10.4 STACK NOMINAL POWER CAPACITY

Individual stack power capacity, as rated by the manufacturer

3.18.11 START-UP TIME

Time required for starting the device from cold state to nominal operating conditions.

3.18.11.1 COLD START TIME TO NOMINAL POWER

Time required to reach the nominal power when starting the device from cold standby mode.⁽⁸⁾

3.18.11.2 COLD START TIME TO NOMINAL CAPACITY

Time required to reach the nominal hydrogen output rate operating capacity when starting the device from cold standby mode.⁽⁸⁾

3.18.11.3 WARM START TIME TO NOMINAL POWER

Time required to reach nominal power when starting the device from warm standby mode.⁽⁸⁾

3.18.11.4 WARM START TIME TO NOMINAL CAPACITY

Time required to reach nominal capacity (in terms of H₂ production rate) when starting the device from warm standby mode (system already at operating temperature).

3.18.12 TRANSIENT RESPONSE TIME

Average time to ramp up from 30% to 100% load at nominal power and operating pressure and temperature. [Units: s]

3.19 PRESSURE

3.19.1 DIFFERENTIAL CELL PRESSURE

Difference in pressure across the electrolyte membrane as measured from one electrode to the other [Units: Pa].⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.19.2 HYDROGEN OUTPUT PRESSURE

Cell level: The hydrogen pressure (P_{H_2} out) is the gas pressure measured on the cathode side at the outlet of the electrolysis cell/stack. [Units: Pa]

3.19.3 MAXIMUM DIFFERENTIAL WORKING PRESSURE

Maximum differential pressure between the anode and cathode side, specified by the manufacturer, which the electrolyser cell can withstand without any damage or permanent loss of functional properties [Units: Pa]⁽²⁾.

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.19.4 MAXIMUM OPERATING PRESSURE

Maximum gauge pressure, specified in pressure by the manufacturer of a component or system, at which it is designed to operate continuously [Units: Pa].⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.19.5 OPERATING PRESSURE

Pressure at which the electrolyser (stack) operates⁽⁸⁾

3.20 PURITY OF GASES

The gas purity is a measure to indicate the amount of other gases in a particular gas. It is expressed as the molar or volumetric percentage of the gas which is equal to 100 percent minus the sum of the other gas impurities. There are different ways to express purity, as percentage e.g. 99.99 or with grade, e.g. N4.0 for 99.99%.

The first digit of the grade classification indicates the 'number of nines' purity, e.g. N4.0 = 99.99% purity.

The second digit is the number following the last nine, e.g. N4.6 oxygen has a guaranteed minimum purity level of 99.996%.

3.20.1 HYDROGEN PURITY

The allowable or tolerated amount of specific impurities (e.g. carbon monoxide) to define the hydrogen purity depends by the scope of use of the hydrogen produced. For fuel cell operation the hydrogen quality is defined in **ISO FUEL QUALITY 14687-2:2012a** ^[5]

3.20.2 OXYGEN PURITY

The allowable or tolerated amount of specific impurities in oxygen that depends by the scope of use of the oxygen produced.

3.21 RELIABILITY

The ability of an item to perform a required function under stated conditions for a stated period of time.⁽⁴⁾

3.21.1 STACK AVAILABILITY

Ratio of the time that the stack is operated compared with the time that it was required to operate.

3.21.2 SYSTEM AVAILABILITY

Ratio of the time that the system operated compared with the time that it was required to operate.

3.22 RESISTANCE (ELECTRICAL)

A material's opposition to the flow of electric current, resulting in the loss of cell voltage, the so called ohmic drop, due to charge carrier (electrons, ions) transport processes occurring in the components of the cell or stack.⁽⁴⁾

3.23 SAFEGUARDING

Procedure for actions of the controlling system based on monitoring of the technical process in order to avoid process conditions which would be hazardous to personnel, plant, product or environment.⁽⁴⁾

3.24 TESTING

3.24.1 ACCEPTANCE TEST

Contractual test to prove to the customer that the item meets certain conditions of its specification.⁽¹⁾

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1]

3.24.2 CONDITIONING TEST

Preliminary step that is required to properly operate an electrolyser cell or a stack and that is realized following a protocol specified by the manufacturer.

3.24.3 INITIAL RESPONSE TIME TEST

Test to measure the time necessary to begin changing load, following a set-point change.

3.24.4 PROCESS AND CONTROL TEST

Test of an electrolyser system that is carried out before operation to verify the integrity of component performance and control function⁽²⁾.

3.24.5 POLARIZATION CURVE TEST

Test used to verify the electrolyser performance that is carried out by applying to the electrolyzer a pre-defined set of current (galvanostatic test) or electric potential (potentiostatic test) and measuring respectively the voltage or current output as function of input parameter.

3.24.6 ROUTINE CONTROL TEST

Conformity test made on each individual item during or after manufacturing⁽²⁾.

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.24.7 SHORT STACK TEST

Test of electrolyser stack with number of cells significantly smaller than the designed stack with rated power, but with number of cells high enough to represent the scaled characteristics of the full stack.

3.24.8 SINGLE CELL TEST

Parametric tests for the assessment of the performances and degradation behaviour performed on one single cell.

3.24.9 STACK TEST

Parametric tests for the assessment of the performances and degradation behaviour performed on a stack.

3.24.10 TEST INPUT PARAMETER

Process parameter value that can be modified in a controlled manner during an experiment.

3.24.11 TEST OUTPUT PARAMETER

Measured value of parameter that can change as a function of the operating conditions modification.

3.25 THERMAL MANAGEMENT SYSTEM

Subsystem intended to provide cooling and heat rejection in order to maintain thermal equilibrium within the electrolyser cell system, and, if necessary, to affect the recovery of excess heat and to assist in heating during start-up⁽⁴⁾.

3.26 TIME

3.26.1 GENERATING TIME

Accumulative duration of the time intervals spent for hydrogen generation.

3.26.2 RATED SYSTEM LIFETIME

The period of time, expected or measured, for an equipment to be able to operate within specified process limit parameters as rated by the manufacturer.⁽⁸⁾

3.26.3 RESPONSE TIME

Time required for a power system to transfer from one defined state to another.⁽⁴⁾

3.27 VOLTAGE

3.27.1 CELL VOLTAGE

Potential difference between the positive and negative electrodes.

3.27.2 MAXIMUM VOLTAGE

Highest voltage at which an electrolyser module is able to produce hydrogen and oxygen continuously at its rated power or during maximum permissible overload conditions.^[2]

[Source: IEC TS 62282-1:2013, Fuel cell technologies - Part 1: Terminology, Edition 3.0 2013-11, with modification

3.27.3 MINIMUM VOLTAGE

Lowest voltage at which an electrolyser module is able to produce hydrogen and oxygen continuously at its rated power ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.27.4 OPEN CIRCUIT-VOLTAGE (OCV)

Voltage across the terminals of an electrolysis cell and in the absence of external current flow [Units: V] ⁽²⁾

[Source: modified from IEC TS 62282-1:2013, Fuel cell technologies - Part 1:]

3.28 WATER

3.28.1 WATER QUALITY

Required input water quality for the hydrogen production operations to fulfil the rated durability/lifetime.

3.28.2 WATER UTILIZATION FACTOR

It is the dimensionless ratio of the flow of water converted into hydrogen and oxygen versus the total water flow supplied to the stack.

3.28.3 WATER RECIRCULATION SYSTEM

Subsystem intended to provide treatment and purification of recovered or added water for use within the electrolyser unit.

3.28.4 WATER TRANSPORT LAYER

Porous transport layer to facilitate water diffusion at the anode compartment side.

4 SYMBOLS

Table 6

Definition of symbols used in the document

Symbol	Description
A	Active cell area of the cell (m^2 , cm^2)
C_p	Water heat capacity under standard conditions ($C_p = 4,18 \text{ Jg}^{-1}\text{K}^{-1}$)
E	Electrical potential (V)
F	Faraday's constant ($F = 96485.3 \text{ C/mol}$)
H	Molar enthalpy (J mol^{-1})
LHV	Low heating value (J mol^{-1})
HHV	High heating value (J mol^{-1})
I	Electrical current (A)
I_{max}	Maximum electrical current (A)
M	Molar mass
N	Number of objects in a series
n	Number of electrons exchanged in the reaction for one mole of gas
\dot{n}	Volumetric flow rate (mol s^{-1})
p	Pressure (Pa, bar)
p^θ	Reference pressure (Pa)
p^A	Anodic pressure (Pa)
p^C	Cathodic pressure (Pa)
P	Electrical power (W)
Q	Heat (J mol^{-1})
R	Universal gas constant ($R = 8.31446 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$)
t	Time
T	Temperature (K, °C)
$T_{x,y}$	Temperature of cell fluid x at cell location y (inlet=in or outlet=out)
T_{env}	Ambient temperature (K, °C)
T_{ehs}	Temperature of an external heat source (K, °C)
T_c	Cell temperature (K, °C)
U	Cell electrical potential (V)
V	Voltage measure (V)
V_{tn}	Thermo-neutral voltage (V)
j	Current density ($j = I / A$)
W	Work, electrical energy needed to transform 1 mole of reactant (J mol^{-1})
<i>Greek symbols</i>	
ε	Energy efficiency, dimensionless

Symbol	Description
ζ	Exergy yield, dimensionless
η	Current efficiency, dimensionless
ξ	ratio between parasitic power and net power consumed by the electrolyser due to the energy consumption by the auxiliaries, , dimensionless
ΔG	Gibb's free energy change (J mol^{-1})
ΔH	Enthalpy change in the overall liquid water electrolysis reaction (J mol^{-1})
ΔS	Entropy variation ($\text{J mol}^{-1}\text{K}^{-1}$)

5 REFERENCES

- (1) International Electrochemical Commission IEC TS 62282-1:2013, Fuel cell technologies - Part 1: Terminology, Edition 3.0 2013-11;
- (2) Modification of IEC TS 62282-1:2013, Fuel cell technologies - Part 1: Terminology Edition 3.0 2013-11;
- (3) COMMISSION REGULATION (EU) 2016/631 14-4-2016
- (4) EUR22295EN – DG JRC THE FUEL CELLS TESTING AND STANDARDISATION NETWORK – “FCTESTNET”: FUEL CELLS GLOSSARY (2006) -ISSN 1018-5593, ISBN 92-79-02747-6
- (5) European Network of Transmission System Operators for Electricity - ENTSOE glossary <https://www.entsoe.eu/data/data-portal/glossary/Pages/default.aspx> ; (last access: 05 Dec. 2017)
- (6) ENTSO-E, Network code on load-frequency control and reserves, 2013.
- (7) Meng Ni, Michael K.H. Leung, Dennis Y.C. Leung, Energy and exergy analysis of hydrogen production by a proton exchange membrane (PEM) electrolyzer plant, Energy Conversion and Management 49 (2008) 2748–2756.
- (8) FCH-JU Trust, parameter template (downloaded. 23/5/2017)
- (9) R.L LeRoy, C.T. V.Bowen, D.J. Leroy, The thermodynamics of aqueous water electrolysis, J. Electrochem. Soc. 127 (1980) 1954
- (10) F. Barbir, PEM electrolysis for production of hydrogen from renewable energy sources, Solar Energy 78 (2005) 661–669

***Europe Direct is a service to help you find answers
to your questions about the European Union.***

Freephone number (*):

00 800 6 7 8 9 10 11

(* The information given is free, as are most calls (though some operators, phone boxes or hotels may charge you).

More information on the European Union is available on the internet (<http://europa.eu>).

HOW TO OBTAIN EU PUBLICATIONS

Free publications:

- one copy:
via EU Bookshop (<http://bookshop.europa.eu>);
- more than one copy or posters/maps:
from the European Union's representations (http://ec.europa.eu/represent_en.htm);
from the delegations in non-EU countries (http://eeas.europa.eu/delegations/index_en.htm);
by contacting the Europe Direct service (http://europa.eu/europedirect/index_en.htm) or
calling 00 800 6 7 8 9 10 11 (freephone number from anywhere in the EU) (*).

(* The information given is free, as are most calls (though some operators, phone boxes or hotels may charge you).

Priced publications:

- via EU Bookshop (<http://bookshop.europa.eu>).

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.



EU Science Hub
ec.europa.eu/jrc



@EU_ScienceHub



EU Science Hub - Joint Research Centre



Joint Research Centre



EU Science Hub



Publications Office

doi:xx.xxxx/xxxx

ISBN xxx-xx-xx-xxxxx-x