H2FUTURE
Green Hydrogen

Deliverable 2.8

KPIs to monitor the Demonstrations and perform the Exploitation Tasks

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Disclaimer: This report contains a preliminary list of KPIs which is defined at the start of the project, but which may change throughout the course of the project given development in thinking related to the operation of the electrolyser plant. This may lead to adjustment of both the number and character of KPIs.

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1 Introduction

1.1 The H2FUTURE Project

As part of the H2FUTURE project a 6 MW polymer electrolyte membrane (PEM) electrolysis system will be installed at a steelworks in Linz, Austria. After the pilot plant has been commissioned, the electrolyser is operated for a 26-month demonstration period, which is split into five pilot tests and quasi-commercial operation.

The main expected impact of the demonstration is validating the electrolysis route for progressive, yet plausible, implementations of steel manufacturing processes with lower CO_2 footprints. In addition, this project will explore the opportunities for taking advantage of attractive renewable electricity pricing and of possibilities for the provision of balancing services by an electrolysis plant.

Subsequently, replicability of the experimental results on a larger scale in EU28 for the steel industry and other hydrogen-intensive industries is studied during the project. Finally, policy and regulatory recommendations are made in order to facilitate deployment in the steel and fertilizer industry, with low CO_2 hydrogen streams also being provided by electrolysing units using renewable electricity.

1.2 Scope of the Document

In WP2, various use cases / pilot tests are defined including KPIs which may be derived from these tests. This document provides an overview of the defined system and/or plant KPIs for the use cases.

1.3 Notations, Abbreviations and Acronyms

Table 1-1: Acronyms list

AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserve
CO_2	Carbon dioxide
DC	Direct Current
ECFOH	Economic Feasible Operating Hours per year
ECOH	Economic Operating Hours per year
EU	European Union
FCH2JU	Fuel Cell and Hydrogen Joint Undertaking
FCR	Frequency Containment Response
GHG	Greenhouse Gases
H_2	Hydrogen
HHV	Higher Heating Value
KPI	Key Performance Indicator

mFRR	Manual Frequency Restoration Reserve
MV	Medium Voltage
PEM	Polymer Electrolyte Membrane / Proton Exchange Membrane
RES	Renewable Energy Sources
THD	Total Harmonic Distortions
TSO	Transmission System Operator
WP	Work Package

2 Key Performance Indicators (KPIs)

Key performance indicators (KPIs) can be defined as a set of quantifiable measures that can be used for a technology to gauge its performance over time. These metrics are used to determine the progress of development of the technology in achieving its strategic and operational goals, and also to compare its performances against other technologies that deliver similar services. [1] Furthermore, KPIs should provide insight in the causes ('which conditions changed?') and impacts of improvements over time.

The strategic and operational goals of the H2FUTURE project relate to the expected technological progress of the PEM electrolysis technology as well as to the economic and environmental impacts of using the technology in relation to steel production and provision of services for electricity system balancing.

The main expected impact of the demonstration is validating the electrolysis route for progressive, yet plausible, implementations of steel manufacturing processes with lower CO_2 footprints. To that aim, future hydrogen streams should be produced reliably and affordably. This can be achieved in general through technology improvement, system optimization, realisation of economics of scale, and fostering competition. In addition, this project will explore the potential of increasing the affordability, or reducing the cost by taking advantage in real time of attractive renewable electricity pricing and of possible remuneration of electrolysis as a contributor to balancing services.

Apart from that, this project aims to increase the innovation capacity of three key industrial players across Europe, to reduce the CO_2 footprint of the steel production of voestalpine and potentially of other steel producers within Europe, and to safeguard profitability and therefore employment with European steel manufacturers.

All in all, this can be translated in three concrete goals; achieving

1. Technological learning effects as reflected in system efficiency increases, and
2. Viable economic business cases of the electrolysis route for the steel value chain, while
3. Decrease of environmental footprint of steel production given EU sustainability goals (decrease of GHG emissions by 80-95% by 2050, with the European Commission stating that European industry would have to cut back its emissions below 1990 levels by 34-40% by 2030 and by 83-87% by 2050).

These three goals give rise to three categories of performance indicators i.e. sets of technological, economic, and health, safety and environmental performance parameters. In addition, given the FCH2JU data collection requirements we distinguish between performance indicators related to electrolysis-based hydrogen production, and project-specific performance indicators. The latter are subdivided into steel plant site specific KPIs and KPIs for provision of grid services.

Next, although administrative data are strictly speaking no KPIs, given the FCH2JU requirement for data provision they are included as a separate category and combined with general

[1] KPI definition adapted from www.investopedia.com which states: Key performance indicators can be defined as a set of quantifiable measures that a company uses to gauge its performance over time. These metrics are used to determine a company's progress in achieving its strategic and operational goals, and also to compare a company's performance against other businesses within the industry.

performance parameters. Finally, following FCH2JU the hydrogen related parameters are split in descriptive parameters which do not change during project lifetime (e.g. 'nameplate' capacities) and operational parameters which are the result of actual operational performance, and which may differ from year to year. The approach is summarized schematically in the table below.

Table 2-1: Schematic overview of categories of (key performance) indicators

KPI theme	Type of performance	Descriptive indicators	Operational indicators
KPIs related to electrolysis-based hydrogen production	Admin data & general	Table 2-2	Table 2-6
	Technical	Table 2-3	Table 2-7
	Economic	Table 2-4	Table 2-8
	Health, Safety and Environmental	Table 2-5	Table 2-9
Project-specific KPIs	Integration in steelworks		Table 2-10
	Provision of grid services		Table 2-11

Many of the KPIs, which are defined and described in the tables below, distinguish three technology levels i.e. the electrolyser stack level, the electrolyser system level and the electrolyser plant level. These levels comprise the following elements (see Figure 1 below):

- Stack: the stack section of the electrolyser where actual hydrogen production takes places
- System: this is the stack section and the power conversion section (transformer and rectifier) where AC power at mid-voltage level is converted into DC power
- Plant: This includes the electrolyser system and the auxiliary systems such as the water demineralization unit, water pumps, uninterruptable power supply for safety and automation, building ventilation, and system and gas cooling units.

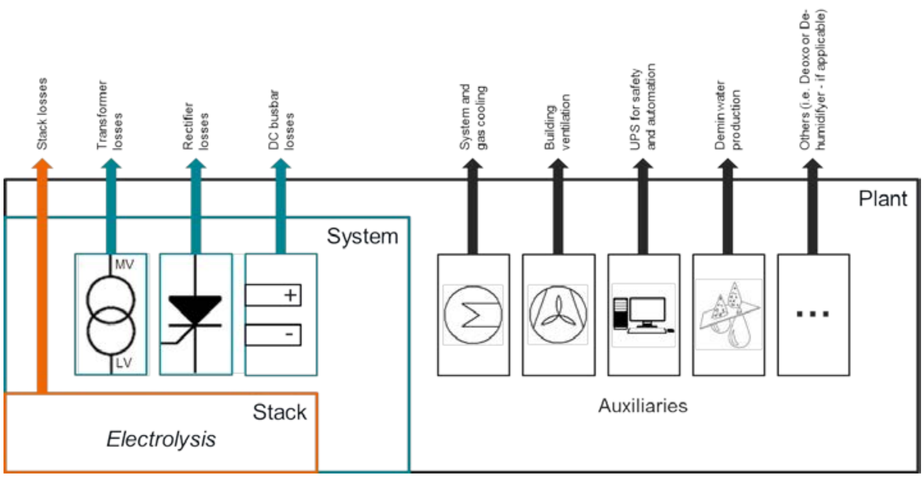

Figure 1: Electrolysis stack-, system- and plant levels

2.1 Descriptive indicators

This section provides an overview of the descriptive parameters i.e. those parameters that do not change during project lifetime (e.g. 'nameplate' capacities) and which only have to be filled in once at the start of the project. Subsequently, Tables are shown with descriptive parameters for the following groups of performance parameters;

- Administrative data and general (Table 2-2)
- Technical (Table 2-3)
- Economic (Table 2-4)
- Health, Safety and Environmental (Table 2-5).

Table 2-2: Administrative data and general performance parameters – descriptive

ID-AGD	Parameter	Description and additional info	FCH2JU indicator
1	Country	Country in which the electrolyser demonstration takes place.	Y
2	Town	Name of the town in which the electrolysis demo plant is located.	Y
3	Postcode	Postcode (Zip code) of the location of the electrolysis demo plant.	Y
4	Deployment date	Date at which the electrolyser was first put in operation	Y
5	Electrolyser manufacturer	Name of the manufacturer of the electrolysis demo plant.	Y
6	Stack manufacturer	Name of the manufacturer of the electrolysis stack(s) of the demo plant.	Y
7	Technology	Type of electrolysis technology used in the electrolysis demo plant. [AE - Alkaline electrolysis, PEME - Proton exchange membrane electrolysis, SOEC - Solid oxide electrolysis cell, PCEC - Proton ceramic membrane cell, AME - alkaline membrane cell, Other (specify in the comment field)]	Y

Table 2-3: Technological performance parameters – descriptive

ID-TD	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Nominal H_2 weight capacity	The average mass-based rate of hydrogen production during the lifetime of the stack(s) at operation of the electrolyser on nominal operating conditions, i.e. nominal stack current.	kg/day	Y	
2	Nominal H_2 volume capacity	The average volume-based rate of hydrogen production in normal cubic meters per hour during the lifetime of the stack at operation of the electrolyser on nominal power. This value is calculated by dividing the mass-based rate of hydrogen production per hour by the density of a cubic meter of hydrogen under normal conditions (0.0899 kg/Nm^3 @ 273,15K / 1013,25 mBar).	Nm^3/h	Y	
3	Nominal power	The AC power input on system level that is used as target value for design of the electrolyser. (calculated based on lifetime averaged stack efficiency)	kW	Y	
4	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.	%	Y	
5	System minimum power	Minimum power for which the system is designed, as a percentage of nominal power.	%	Y	
6	Stack nominal power	Individual stack power, as rated by the manufacturer (kW direct current) (calculated based on lifetime averaged stack efficiency)	kW	Y	
7	Electrolyser footprint	Surface area taken up by the electrolyser system (stacks with piping and power converter) excluding auxiliary equipment.	m^2	Y	

ID-TD	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
8	Electrolyser volume	Volume taken up by the electrolyser system (stacks with piping and power converter) excluding auxiliary equipment.	m^3	Y	
9	Rated system lifetime	Expected system lifetime as rated by the manufacturer - specify the criterion used for "end of life". For H2FUTURE, Siemens defines the lifetime as the design lifetime considering long-term availability of spare parts as well as lifetime of components which cannot be replaced economically.	h	Y	
10	Rated stack lifetime	Expected stack lifetime based on full load operating hours as rated by the manufacturer - specify the criterion used for "end of life". For H2FUTURE, Siemens defines the end of stack lifetime by the point of time, when cell voltage (averaged over the stack) increased by 250 mV. However, the operator may decide to continue operation even at lower efficiency based on own economic considerations.	h	Y	
11	Hydrogen purity	Purity of the hydrogen produced in the electrolyser (after drying, oxygen removal and/or other purification step, if applicable) - please specify in the comment field the nature and concentration of the impurities, if known.	%	Y	
12	Power converter	Converter type for the electricity fed to the electrolyser.	List values: [AC/DC, DC/DC, No converter, Other]	Y	

ID-TD	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
13	Operating pressure	The output pressure of the electrolyser stack(s).	Bar(g)	Y	
14	Operating temperature	Operating temperature of the electrolyser stacks at which hydrogen production takes place.	°C	Y	
15	Input voltage on system level	Inlet voltage of the electricity fed into the electrolyser system	V	Y	
16	Power usage (energy consumption) of the electrolysis plant in cold standby	Total power usage (energy consumption) of the electrolyser plant from medium voltage grid connection (no-load losses of the transformer) down to auxiliaries consumption on low voltage level, measured when the electrolyser is in cold standby mode.	kWh/h	N	1
17	Power usage (energy consumption) of the electrolysis plant in hot standby	Total power usage (energy consumption) of the electrolyser plant from medium voltage grid connection (no-load losses of the transformer) down to auxiliaries consumption on low voltage level, measured when the electrolyser is in hot standby mode.	kWh/h	Y	1
18	Power usage (energy consumption) of auxiliary equipment in hot standby	Total power usage (energy consumption) of the auxiliary equipment on low voltage level, measured when the electrolyser is in hot standby mode.	kWh/h	N	
19	Power usage of the auxiliary equipment at nominal capacity	Power usage of the demi-water unit, the water pump(s), the cooling system(s), and the system(s) for hydrogen cleaning/-purification at operation on nominal capacity	kWh/h	Y	

ID-TD	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
20	Rated stack electrical efficiency (HHV, DC current)	The expected efficiency on stack level, at nominal load operation, of the use of DC electric energy to split liquid water into gaseous hydrogen and oxygen relative to the HHV hydrogen energy content (e.g. 39.4 kWh/kg at 25°C). This is calculated using the thermoneutral voltage and the rated stack voltage at begin of lifetime – considering 1% losses from recombination. For example, at 25°C it would be calculated using the following formula: $= \frac{1{,}48\,V \times number\ of\ cells}{Stack\ voltage} - 1\%$	%	Y	
21	Rated system electrical efficiency (HHV, AC current)	The expected efficiency on system level, at nominal load operation, of the use of AC electric energy to split liquid water into gaseous hydrogen and oxygen relative to the HHV hydrogen energy content (e.g. 39.4 kWh/kg at 25°C). The efficiency is determined using rated stack efficiency (ID-TD 20) multiplied with the expected efficiency of the AC/DC conversion including losses on medium voltage transformer.	%	Y	

Table 2-4: Economic performance parameters – descriptive

ID-ED	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	CAPEX - electrolyser	Actual cost of plant manufacturing per kW of rated nominal power (labour, materials, utilities), or purchase price – including ancillary equipment and commissioning, excluding land costs, overheads, VAT and other taxes	€/kW	Y	
2	Electrolyser price	Price of the transaction between the electrolyser manufacturer and the electrolyser buyer. Any grant amount should not be accounted for here (price before any rebates, grants etc.)	€	Y	
3	CAPEX to deliver grid services	Additional investment costs for electrolyser system necessary to enable provision of grid services	€/kW	N	

An additional KPI could be included about additional CAPEX required to enable electrolyser operation in overload. However, because overload operation is not part of the system for the H2FUTURE project the parameter is not further considered here.

Table 2-5: HSE performance parameters – descriptive

ID-HD	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Electricity origin	Origin of the electricity used in the electrolyser	No unit, select list value [Solar, Wind, Hydro-electric, Grid, Other]	Y	

2.2 Operational indicators

This section provides an overview of the operational parameters i.e. parameters which are the result of actual operational performance, and which may differ from year-to-year during project lifetime. Subsequently, Tables are shown with operational parameters for the following sets of performance parameters;

- Administrative data and general (Table 2-6)
- Technical (Table 2-7)
- Economic (Table 2-8)
- Health, Safety and Environmental (Table 2-9)
- Integration in steelworks (Table 2-10)
- Provision of grid services (Table 2-11).

Table 2-6: Administrative data and general performance parameters – operational

ID-AGO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Start date for reporting	Start date of the period for which the data you provide here are relevant: typically Jan. 1 of reference year (i.e. for 2016 if you are reporting in 2017) or start date of operations if this is subsequent to Jan. 1 in the year	dd-mm-yyyy	Y	
2	End date for reporting	End date of the period for which the data you provide here are relevant: typically Dec. 31 of reference year (i.e. for 2016 if you are reporting in 2017) or start date of operations if this is subsequent to Jan. 1 in the year	dd-mm-yyyy	Y	
3	Hours of operation	Numbers of hours in which the electrolyser produced hydrogen in the reporting period.	h	Y	
4	Hours of operation - cumulative	Number of hours in which the electrolyser produced hydrogen in the current and previous reporting periods.	h	Y	
5	Days of operation	Numbers of days on which the electrolyser produced hydrogen in the reporting period.	Days	Y	

ID-AGO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
6	Days of operation - cumulative	Number of days on which the electrolyser produced hydrogen in the current and previous reporting periods.	Days	Y	
7	Quantity of hydrogen produced	Quantity of hydrogen produced in the reporting period.	t	Y	6
8	Quantity of hydrogen produced cumulative	Quantity of hydrogen produced in the current and previous reporting periods	t	N	
9	Electricity consumed	Quantity of AC electricity consumed on electrolyser system level in the reporting period, which includes the consumption related to power conversion and stack operation.	kWh	Y	
10	Electricity volume turnover on the day ahead market	Electric energy volume turnover in the reporting period on the day ahead market in MWh (gross and net)	MWh	N	6
11	Electricity volume turnover on the intraday market	Energy volume turnover in the reporting period on the intraday market in MWh (gross and net)	MWh	N	6
12	Electricity consumed - cumulative	Quantity of AC electricity consumed on electrolyser system level in the current and previous reporting periods.	MWh	N	

Table 2-7: Technological performance parameters – operational

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Time from cold start to nominal power	The time from receipt of the start command by the electrolysis plant that is at ambient temperature and has not been operated for at least 24 hours, to start the auxiliaries (pumps, vents etc.), activate the transformer-rectifier system, and ramp up the electrical load from 0% to 100% of nominal power.	s	Y	
2	Time from cold start to nominal capacity [Start-up time from cold standby to nominal capacity]	The time from receipt of the start command by the electrolysis plant that is at ambient temperature and has not been operated for at least 24 hours, to start the auxiliaries (pumps, vents etc.), activate the transformer-rectifier system, and ramp up the hydrogen production from 0% to 100% of the nominal hydrogen production capacity.	s	Y	1
3	Start-up time from hot standby to minimum partial load	The time from receipt of the start command by the electrolysis plant that is at a temperature close to the normal operating temperature but has not been operated for at least 1 hour, to start the auxiliaries, activate the transformer-rectifier system, and ramp up the electrical load from 0% to the minimum partial load level.	s	N	1
4	Time from hot standby to nominal power	The time from receipt of the start command by the electrolysis plant that is at a temperature close to the normal operating temperature but has not been operated for at least 1 hour, to start the auxiliaries, activate the transformer-rectifier system, and ramp up the electrical load from 0% to 100% of nominal power.	s	Y	

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
5	Time from hot standby to nominal capacity [Start-up time from hot standby to nominal capacity]	The time from receipt of the start command by the electrolysis plant that is at a temperature close to the normal operating temperature but has not been operated for at least 1 hour, to start the auxiliaries, activate the transformer-rectifier system, and ramp up the electrical load from 0% to 100% of nominal hydrogen production capacity.	s	Y	1
6	Transient response time (ramping up)	Average time to ramp up from 30% to 100% load at nominal power and operating temperature over the timeframe of this data collection exercise	s	Y	1
7	Transient response time (ramping down)	Averaged time to ramp down from 100% to 30% load at nominal power and operating temperature over the timeframe of this data collection exercise	s	N	1
8	Maximum overload operation	Minimum % power (vs nominal power) allowing to operate the device while maintaining minimum of 98% of the maximum efficiency	%	Y	
9	Maximum % power for 98% efficiency	Maximum % power attained (vs nominal power) allowing to operate the device while maintaining minimum of 98% of the maximum efficiency (preliminary definition based on FCH JU – more information concerning this parameter is needed)	%	Y	
10	Minimum part-load operation	Minimum part-load operation achieved in the timeframe of this data collection exercise, as a percentage of nominal capacity, in terms of power input	%	Y	
11	Duration of planned maintenance	Total duration of planned maintenance leading to system downtime during the timeframe of this data collection exercise	h/y	Y	

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
12	Number of failures	Number of failures in the reporting period leading to unplanned downtime of the electrolysis plant	#	N	
13	Time-based availability of the electrolysis plant	Availability of the electrolyser plant in the considered operating period relative to the planned operating time, excluding the duration of planned maintenance = ($t_{OT\_planned}$ - $t_{D\_plant)}$ / $t_{OT\_planned}$ *100%, with $t_{OT\_planned}$ is the planned operating time and t_{D_plant} is the unplanned downtime of the electrolyser plant in the operating period due to any failure of the stacks, power conversion or auxiliaries systems	%	Y	2, 6
14	Time-based availability of the stack modules	Availability of the stacks in the considered operating period relative to the planned operating time excluding the duration of planned maintenance = ($t_{OT\_planned}$ -t_{D_stack}) / $t_{OT\_planned}$ * 100 [%] with t_{D_stack} is the downtime due to failure of a stack module, and $t_{OT\_planned}$ is the planned operating time in the considered operating period	%	N	2, 6
15	Time-based availability of the system	Availability of the electrolyser system in the considered operating period relative to the planned operating time, excluding the duration of planned maintenance = ($t_{OT\_planned}$ - t_D) / $t_{OT\_planned}$ * 100 [%] with t_{D_system} is the unplanned downtime due to any failure of the electrolyser system, and $t_{OT\_planned}$ is the planned operating time in the considered operating period	%	N	2, 6

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
16	Availability unplanned and planned	Availability of the electrolyser plant in the considered operating period relative to the total operating period = (t_{OT_total} - $t_{D\_plant\ u\&p}$) / t_{OT_total} *100 [%], with t_{OT_total} is the total operating period and $t_{D\_plant\ u\&p}$ is the planned and unplanned downtime of the electrolyser plant in the operating period due to any failure of the stacks, power conversion or auxiliaries systems and maintenance	%	N	2, 6
17	Production-based availability	Availability based on the lost H_2 production = m_{actual} / $m_{planned}$ * 100 [%] with m_{actual} … actual hydrogen production in the operating period [kg], $m_{planned}$ … planned hydrogen production in the operating period [kg]	%	N	2, 6
18	Plant power limitation (time)	The electrolyser plant's power consumption is limited due to electrolyser plant events = t_L / t_{OP} * 100 [%] with t_L … time of electrolyser limitation, t_{OP} … operating period	%	N	2, 6
19	Plant power limitation (power)	The electrolyser plant's power consumption is limited due to electrolyser plant events = (P_L * t_L) / (P_R * t_{OP}) * 100 [%] with P_L … power limitation, P_R … rated power, t_L … time period of electrolyser power limitation, t_{OP} … operating period	%	N	2, 6
20	Efficiency degradation or Voltage degradation rate	The efficiency degradation of the stack(s) determined as increase in cell voltage averaged over the cells of the stacks(s) divided by the number of operating hours in a specified period. Nominal hydrogen production level will be used as a reference point for calculating the voltage degradation rate.	µV/h	Y	2, 6

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
21	Efficiency degradation per 1000h or Voltage degradation rate per 1000h	Increase in cell voltage averaged over the cells of the stack(s) after every thousand hours the electrolyser system has been in operation = (1.48 * (1 / $V_{t=0}$ – 1 / V_t) *100%) / (t / 1000), where $V_{t=0}$ is the initial cell voltage, V_t is the cell voltage after an operating time t measured in hours. The efficiency degradation is the absolute decrease of the stack efficiency; i.e. the decrease in efficiency in percent point. Nominal hydrogen production level will be used as a reference point for calculating the voltage degradation rate.	%/1000h	Y	2, 6
22	System efficiency degradation per 1000h	System efficiency degradation in percentage per 1000 h of operation within the timeframe of this data collection exercise. If the system has operated for less than 1000 h, please extrapolate and indicate the extrapolation methodology used in the comment field	%/1000h	Y	
23	Stack electrical efficiency with maximised hydrogen production	The efficiency on stack level, at nominal load operation, of the use of DC electric energy to split liquid water into gaseous hydrogen and oxygen relative to the HHV hydrogen energy content (e.g. 39.4 kWh/kg at 25°C). This is calculated using the thermoneutral voltage and the actual stack voltage – considering 1% losses from recombination. For example, at 25°C it would be calculated using the following formula: $= \frac{1{,}48\,V \times number\ of\ cells}{Stack\ voltage} - 1\%.$	%	Y	2, 6

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
24	Specific stack electrical input	The specific stack electrical input equals the hydrogen specific energy content in HHV (e.g. 39.4 kWh/kg at 25°C) divided by the stack efficiency at nominal hydrogen production.	kWh/kg	N	2, 6
25	System electrical efficiency with maximised hydrogen production	The efficiency on system level, at nominal load operation, of the use of AC electric energy to split liquid water into gaseous hydrogen and oxygen relative to the HHV hydrogen energy content (e.g. 39.4 kWh/kg at 25°C). The efficiency is determined using stack efficiency (ID-TO 23) multiplied with the measured efficiency of the AC/DC conversion including losses on medium voltage transformer.	%	Y	2, 6
26	Energy consumption for H_2 production [Specific system electrical input]	The 'energy consumption for H_2 production' or 'specific system electrical input' equals the hydrogen specific energy content in HHV (e.g. 39.4 kWh/kg at 25°C) divided by the electrolyser system efficiency	kWh/kg	Y	2, 6
27	Plant electrical efficiency with maximised hydrogen production	The efficiency on electrolyser plant level, at nominal load operation, is determined under consideration of additional losses caused by auxiliary systems (i.e. system cooling, gas treatment, building ventilation, demin water production, provision of uninterruptible power for safety, control & automation systems)	%	N	2, 6
28	Energy consumption for H_2 production @ plant level [Specific plant electrical input]	The energy consumption for H_2 production equals the hydrogen specific energy content in HHV (e.g. 39.4 kWh/kg at 25°C) divided by the electrolyser plant efficiency.	kWh/kg	N	2, 6

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
29	Energy consumption for H_2 compression	Energy consumption of compression of hydrogen from the output pressure of the electrolyser to the desired pressure level for the hydrogen application.	kWh/kg	Y	
30	Average hydrogen production	Average hydrogen output of the system in a specified operating period = total power consumption on DC level multiplied by the stack electrical efficiency, and divided by the specific energy content of hydrogen in HHV and the total number of operating hours in the specified operating period. Alternatively, the average hydrogen output of the system in a specified operating period can be calculated from the stack current hours and related operating hours, considering production losses of 1% due to recombination: $average\ production\ rate = number\ of\ cells \times stack\ current\ hours\ [Ah] \div operating\ hours \times 0{,}03761\ \left[\frac{g}{Ah}\right] \times 99\%$	kg/h	N	2, 6
31	Average oxygen production	Average oxygen production of the system will be determined by directly measuring the flow of oxygen after cooling. This oxygen measurement can be used as a cross check for the hydrogen production rate.	kg/h	N	2, 6
32	Power factor	Minimum of observed power factor (cos phi, averaged over a 60s measuring period) at the MV feeder to the transformer-rectifier system when operating the electrolyser system at partial load and 100% of nominal production	./.	N	1

ID-TO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
33	Harmonic distortions	Max. of observed harmonic current distortions (THD_I, averaged over a 60s measuring period) at the MV feeder to the transformer-rectifier system when operating the electrolyser system at partial load and 100% of nominal production	./.	N	1
34	Stability	Number of required manual interventions during a 100h stability test when operating the electrolyser system at random loads between minimum partial load and 100% of the nominal load with load changes every 15 minutes.	1/h	N	1

Table 2-8: Economic performance parameters – operational

ID-EO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Price/cost of electricity	Average price paid for the consumed electricity - or electricity cost (for electrolysers coupled to their own renewable energy installation), over the timeframe of this data collection exercise.	€c/kWh	Y	
2	Average price of electricity consumption	Average price of consumed electricity after deduction of ancillary services market returns	€/MWh/y	Y	6
3	Electricity cost	Cost of electricity from RES as input for the electrolysis plant	€/kg H_2	Y	
4	O&M costs	Operational and maintenance costs per unit hydrogen output, including electricity, insurances, running costs, maintenance, repairs. Taxes excluded.	€/kg H_2	Y	
5	Cost of hydrogen produced	Average cost of the hydrogen produced, including OPEX and CAPEX *), over the timeframe of this data collection exercise.	€/kg H_2	Y	6
6	End of life stack replacement	Specific costs for end of life stack replacement	€/kW	N	

*) Besides the number of full load hours, the CAPEX contribution depends on many parameters such as project lifetime or depreciation period, financing structure and financial parameters. These need to be standardized in order to be able to compare various projects

Table 2-9: HSE performance parameters – operational

ID-HO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Fraction of renewable energy input	Fraction of electricity sourced from renewables in the total electricity feed over the timeframe of this data collection exercise. (This could be certified electricity from renewable sources based upon TÜV SÜD CMS Standard 83.)	%	Y	
2	Number of safety incidents	Total number of safety incidents or accidents - including near misses - over the timeframe of this data collection exercise	#	Y	
3	Carbon footprint of produced hydrogen	CO_2 intensity of produced H_2 stream, depending on use case (and hydrogen end-user market).	kg CO_2/ MJ H_2	N	all
4	Number of emergency stops	Number of emergency stops at plant level	Stops/ 100 hrs operation	N	all

Table 2-10: Steel plant specific performance parameters

ID-SO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Load smoothing factor (steel making processes)	The quality of the total power (load and electrolyser) in terms of constant power consumption measured in different periods (30sec, 1 min, 5min, 15 min, 1h, ..) $DEV_{Sum\_30s} = \frac{1}{403200} * \sum_{1}^{403200} \left\| \frac{P_{mittel-electrolyser\_30s} - P_{mittel-x\_30s}}{P_{mittel-x\_30s}} \right\|$ $DEV_{Sum\_1min} = \frac{1}{20160} * \sum_{1}^{20160} \left\| \frac{P_{mittel-electrolyser\_1min} - P_{mittel-x\_1min}}{P_{mittel-x\_1min}} \right\|$ $DEV_{Sum\_5min} = \frac{1}{4032} * \sum_{1}^{4032} \left\| \frac{P_{mittel-electrolyser_{5min}} - P_{mittel-x\_5min}}{P_{mittel-x\_5min}} \right\|$ $DEV_{Sum\_15min} = \frac{1}{1344} * \sum_{1}^{1344} \left\| \frac{P_{mittel-electrolyser\_15min} - P_{mittel-x\_15min}}{P_{mittel-x\_15min}} \right\|$ $DEV_{Sum\_1h} = \frac{1}{336} * \sum_{1}^{336} \left\| \frac{P_{mittel-electrolyser\_1h} - P_{mittel-x\_1h}}{P_{mittel-x\_1h}} \right\|$ $MAX\_DEV_{Sum\_30s} = MAX\left(\frac{P_{mittel-electrolyser\_30s} - P_{mittel-x\_30s}}{P_{mittel-x\_30s}}\right)$ $95\%MAX_{DEV_{Sum_{30s}}} = 95\%\ value\_MAX\left(\frac{P_{mittel-electrolyser\_30s} - P_{mittel-x\_30s}}{P_{mittel-x\_30s}}\right)$ $MAX\_DEV_{Sum\_1min} = MAX\left(\frac{P_{mittel-electrolyser\_1min} - P_{mittel-x\_1min}}{P_{mittel-x\_1min}}\right)$ $95\%MAX_{DEV_{Sum_{1min}}} = 95\%\ valueMAX\left(\frac{P_{mittel-electrolyser\_1min} - P_{mittel-x\_1min}}{P_{mittel-x\_1min}}\right)$ $MAX\_DEV_{Sum\_5min} = MAX\left(\frac{P_{mittel-electrolyser\_5min} - P_{mittel-x\_5min}}{P_{mittel-x\_1min}}\right)$ $95\%MAX_{DEV_{Sum_{5min}}} = 95\%\ valueMAX\left(\frac{P_{mittel-electrolyser\_5min} - P_{mittel-x\_5min}}{P_{mittel-x\_5min}}\right)$		N	4, 5

ID-SO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
		$MAX\_DEV_{Sum\_15min} = MAX\left(\frac{P_{mittel-electrolyser\_15min} - P_{mittel-x\_15mins}}{P_{mittel-x\_15min}}\right)$ $95\%MAX_{DEV_{Sum_{15min}}} = 95\%\ valueMAX\left(\frac{P_{mittel-electrolyser\_15min} - P_{mittel-x\_15min}}{P_{mittel-x\_15min}}\right)$ $MAX\_DEV_{Sum\_1h} = MAX\left(\frac{P_{mittel-electrolyser\_1h} - P_{mittel-x\_1h}}{P_{mittel-x\_1h}}\right)$ $95\%MAX_{DEV_{Sum_{1h}}} = 95\%\ valueMAX\left(\frac{P_{mittel-electrolyser\_1h} - P_{mittel-x\_1h}}{P_{mittel-x\_1h}}\right)$ With *x* being steel making process routes i.e. electric arc furnace (EAF), ladle arc furnace (LAF), or basic oxygen furnace.			

Table 2-11: Grid services performance parameters

ID-GO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
1	Error margin of activation	The electrolyser adapts its power consumption according to the online set-point of the Network Operation Centre. In case of over- or under-activation of the electrolyser the following error margin can be calculated: $(P_{act} - P_{set}) / P_{act}$ [%] P_{act} … actual power consumption P_{set} … target power consumption according to set-point	%	N	3
2	Linear activation	Droop of the system: $\sigma = (\Delta f / fn)/(\Delta P/Pn)$ with Δf … frequency deviation f_n … nominal frequency (50 Hz) ΔP … power change P_n … nominal power		N	3
3	Activation speed	50% of dedicated/offered primary control power must be linearly activated within 15 s in case of a frequency deviation of +/- 100 mHz, and 100% of dedicated/offered primary control power must be linearly activated within 30 s in case of a frequency deviation of +/- 200 mHz		N	3
4	Actual economic operating hours per year (ECOH)	Number of hours in a year in which the electrolyser was running due to economical reason by contributing a margin	h	N	6
5	Economic feasible operating hours per year (ECFOH)	Theoretical maximum number of hours in a year in which the electrolyser could have contributed a margin (ex-post)	h	N	6
6	Utilization of economic feasible operating hours	ECOH / ECFOH in %	%	N	6

ID-GO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
7	Contracted hours of ancillary services	Number of hours in which ancillary services bids were accepted and to be provided by the electrolyser	h	N	6
8	Contracted hours of FCR	Number of hours in which FCR bids were accepted and to be provided by the electrolyser	h	N	6
9	Contracted hours of aFRR	Number of hours in which aFRR bids (secondary control) were accepted and to be provided by the electrolyser	h	N	6
10	Contracted hours of mFRR	Number of hours in which mFRR bids (tertiary reserve) were accepted and to be provided by the electrolyser	h	N	6
11	Average provision of FCR	Average power of provision of FCR per year in MW	MW	N	6
12	Average provision of aFRR	Average power of provision of aFRR per year in MW	MW	N	6
13	Average provision of mFRR	Average power of provision of mFRR per year in MW	MW	N	6
14	Overall margin in a year, after operating expenses	Overall margin in a year, after operating expenses, including all costs for operating the electrolyser (except initial recognition costs or equivalent depreciations)	M€	N	6
15	Ancillary services provision per year	Average provision of ancillary services per year in MW	MW	N	6
16	Hedged quantities per year	Hedged quantities per year for any future product in MWh (gross and net)	MWh/ y	N	6
17	External power limitation (time)	The electrolyser plant's power consumption is limited due to external events (e.g. in the electricity grid) = t_L / t_{OP} * 100 [%] with t_L … time of limitation, t_{OP} … operating period	%	N	2, 6

ID-GO	Parameter	Description and additional info	Unit	FCH2JU indicator	Use case number
18	External power limitation (power)	The electrolyser plant's power consumption is limited due to external events (e.g. in the electricity grid) = P_L * t_L / (P_R * t_{OP}) * 100 [%] with P_L … power limitation, P_R … rated power, t_L … time period of power limitation, t_{OP} … whole testing period	%	N	2, 6

3 Conclusions

As part of the H2FUTURE project a 6 MW PEM electrolysis power plant will be installed at a steelworks in Linz, Austria, and operated for a 26-month demonstration period, which is split into five pilot tests and quasi-commercial operation. The main expected impact of the demonstration is validating the electrolysis route for progressive, yet plausible, implementations of steel manufacturing processes with lower CO_2 footprints. In addition, the demonstration is to show that the PEM electrolyser is able to produce green hydrogen from renewable electricity while using timely power price opportunities and to provide balancing services in order to attract additional revenue.

In order to gauge the performance of the electrolyser plant and its constituents over time, four categories of key performance indicators (KPIs) are defined i.e. sets of administrative and general performance, technological, economic, and health, safety and environmental KPIs. When defining these KPIs, the FCH2JU template for data provision on electrolyser demos is taken as point of departure. Amongst others, this implies that hydrogen related parameters are split in descriptive parameters which do not change during project lifetime (e.g. ‘nameplate’ capacities) and operational parameters which are the result of actual operational performance, and which may differ from year to year. FCH2JU based performance indicators related to electrolysis-based hydrogen production are complemented with project-specific performance indicators. The latter category is subdivided into steel plant site specific KPIs and KPIs for provision of grid services. Finally, in defining KPIs we distinguish three technology levels i.e. the electrolyser stack level, the electrolyser system level and the electrolyser plant level. These levels comprise the following elements:

- Stack: the stack section of the electrolyser where actual hydrogen production takes places
- System: this is the stack section and the power conversion section (transformer and rectifier) where AC power at mid-voltage level is converted into DC power
- Plant: This includes the electrolyser system and the auxiliary systems such as the water demineralization unit, water pumps, uninterruptable power supply for safety and automation, building ventilation, and system and gas cooling units.

It should be noted that the resulting preliminary list of KPIs may change throughout the course of the project given development in thinking related to the operation of the electrolyser plant. This could lead to adjustment of both the number and character of KPIs.

4 References

4.1 Project Documents

D2.1 Specifications of Pilot Test 1 / Use Case 1

D2.2 Specifications of Pilot Test 2 / Use Case 2

D2.3 Specifications of Pilot Test 3 / Use Case 3

D2.4 Specifications of Pilot Test 4 / Use Case 4

D2.5 Specifications of Pilot Test 5 / Use Case 5

D2.6 Specifications of quasi-commercial Operation

D2.7 Specifications of Final Tests

Grant Agreement

H2F_WP3.1_AOP526_Efficiency at Stack-, System- and Plant Level (internal deliverable)

4.2 External Documents

FCH JU (2017). Fuel cells and Hydrogen Joint Undertaking (FCH JU) - TRUST data collection, 3rd draft, Claudia Marenco, March.