TECHNOLOGY DEMONSTRATION OF LARGE-SCALE PHOTO-ELECTROCHEMICAL SYSTEM FOR SOLAR HYDROGEN PRODUCTION

Project Deliverable Report – D7.2

Title:	**Field and balance of plant ready for use**
Work Package	**WP 7**
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FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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EXECUTIVE SUMMARY

Several system concepts have been developed within the PECSYS project. Up to now two cassette-based concepts are tested in the laboratories. Now the systems are further developed so that they can be tested in a technical scale. In the first case, a PEM based electrolyser was coupled with a 0.75 m² $Cu(In,Ga)Se_2$ photovoltaic PV panel from Solibro and tested in the sun simulator at IEK-5 Forschungszentrum Jülich. In the second concept, an alkaline electrolysis cassette design was developed by CNR and was tested outdoors in combination with a 260 cm² silicon heterojunction PV panel from HZB.

The amount of hydrogen produced for each set-up was measured and the efficiency of solar to hydrogen conversion was calculated, using the lower heating value of hydrogen, in relation to the incident solar energy. Both the PEM based and the alkaline based system achieved values of solar to hydrogen conversion efficiency above 6 % under all operating conditions considered.

An electrolysis configuration given in the project proposal was not developed further, because of the relatively high Ohmic resistance due to the long distance the ions have to pass in the electrolyte. In comparison, the PEM cassette design shows a higher technical maturity than the alkaline type, but in principle both systems are suitable to integrate in the 10 m² demonstration plant.

TABLE OF CONTENTS

ABBREVIATIONS and ACRONYMS

DoA	Description of Action
EC	Electrolyser
FZJ	Forschungszentrum Jülich
MFM	Mass Flow Meter
PEM	Proton Exchange (Polymer Electrolyte) Membrane
PTFE	Polytetrafluoroethylene
PV	Photovoltaic
STH	Solar to Hydrogen conversion
TRL	Technology Readiness Level
WP	Work Package

1 INTRODUCTION

The setup of a large scale electrolysis system is planned in Jülich where the project can take advantage of the existing test infrastructure. To build up the test system specific to this project, it is necessary to manufacture suitable boxes for the electrolysis. This will be done in the workshops of FZJ and by external manufacturers. The framework where the PV modules will be mounted will be erected in south orientation.

Till now we have no decision on which type of PV-EC will be used in the project demonstrator. Because of this, we have focused the systems configuration on the innovative new cassette design we have developed within the WP 4, which is more favourable in our opinion, as can be found in the previous deliverable reports. The systems setup chosen at present is based on a single pipe circulation which simplifies the whole system and improves the reliability of the demonstration plant. We have also developed a process control strategy for this concept. The system provides the possibility to measure the amount of hydrogen produced. When the consortium decides which concept will be installed the systems configurations have to be adapted to the technique.

2 DELIVERABLE OBJECTIVE AND RELATED TASKS

Deliverable objective: Field and balance of plant ready for use.

2.1 Description of the task

No.	Task description	Start date	End date
T 7.2	Procure necessary hardware and select test	01.04.2018	30.04.2019

Several system approaches have been developed within the PECSYS project. Up to now two cassette-based approaches have been tested in the laboratory. The systems have been further developed so that they can be tested in a technical scale.

The systems components for one submodule based on a Solibro PV cell (0.75 m²), have been procured and tested. The system components for the whole 10 m² demonstration plant will be procured when the PV-EC demonstrator setup is defined by the project consortium. The amount of hydrogen produced for each set-up was measured and the efficiency solar to hydrogen was calculated, using the lower heating value of hydrogen, in relation to the incident solar energy. Both the PEM based- and the alkaline based system achieved values of solar to hydrogen conversion efficiency above 6 % under all operating conditions considered.

In the 10 m² demonstration system the hydrogen production rate will be measured for the whole system in sum. Additionally temperatures of cells and cell voltages will be monitored.

3 CONTRIBUTION TO PROJECT OBJECTIVES

This deliverable contributes directly and indirectly to the achievement of main and specific objectives indicated in section 1.1 of the Description of the Action (GA -735218):

Project Objectives	*Contribution of this deliverable*	
	Yes	*No*
Main objective		
To demonstrate an operational PV-EC system measuring at least 10 m² with a solar to hydrogen (STH) efficiency of at least 6 % supporting a hydrogen production of at least 16 g/h at a levelised cost of 5€/kg	X	
Specific objectives		
To study and develop devices for integrated PV-EC concepts and scale viable concepts to prototype size > 100 cm²		X
To use socio-techno-economic analysis to predict and select concepts with levelised cost of hydrogen production below € 5/kg		X
To scale the prototypes of the less mature but promising technologies to a demonstrator with active area > 10 m²	X	
To achieve a hydrogen production of 16 gH_2/h from the demonstrator resulting in a STH efficiency of at least 6 %	X	
To ensure that the initial demonstrator STH efficiency does not reduce by more than 10 % after six months of continuous operation	X	

4 DESCRIPTION OF COMPLETED ACTIONS

The setup of the planned test bed for the PV-EC demonstrator is divided into two main parts. This is due to the fact that the PV-EC demonstrator needs sunlight for operating, so this part has to be installed outside. For the demonstrator, the expected efficiency needs to be evaluated and some measurement equipment needs to be installed additionally. This will be done in a lab environment as shown in **Figure 2** inside the laboratory hall of the IEK-3. The main parts of the process engineering will be also installed inside the lab hall.

Further advantages of the divided demonstrator in an inside and outside part are:

- Rain protection of sensitive system parts
- Division from prototype parts (danger of gas leakage)/ outside from well-established process engineering parts / inside

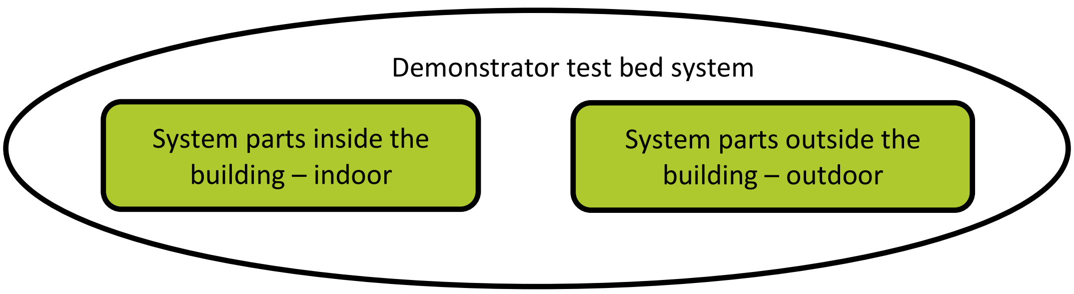


Figure 1: *Principle scheme of the test bed for the demonstrator setup*

Table 1: *Overview of indoor and outdoor parts of the demonstrator test bed*

Indoor	Outdoors
PC, data acquisition and system control	PV Panel with EC- Demonstrator
Gas separator	Frame
Measurement instrumentation	Attachments for frame mounting
Actuators, valves, tubes	Protection of roof planking
	Tubes and cables for sensors

Figure 2*:View of inside building (lab)*

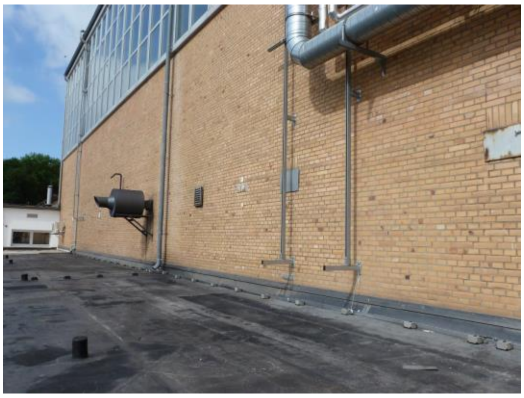


Figure 3:*View of outside part of the lab*

4.1 Description of outdoor part of the test bed system

The setup of the outdoor demonstrator part will be located on a part of the rooftop, shown on **Figure 3**. Here we plan the mounting of a framework like **Figure 4** displays.

Figure 4: *Picture of the framework expected to house the demonstrator*

The rooftop is located next to the experiment hall where the indoor part of the demonstrator will be mounted. Through the independent orientation of the framework the solar panels could be orientated directly towards south. The pillars will fix the solar panels in the most suitable angle adjusted to the latitude of Jülich (50°,54',23" North) and considering the inclination of the roof. To protect the roof's surface, it is planned to buffer the framework with rubber mats. To secure the framework with the solar panels from powerful wind, paving slabs will load the framework. The weather and climate data of Jülich recorded from another institute located inside the FZJ campus shall be used to calculate the STH efficiency.

Previously we have shown results from outdoor measurements performed with a PV module combined with the PEM electrolysis systems. To remind you of them, **Figure 5** illustrates the setup. You can see the PV module placed on our rooftop with the given orientation.

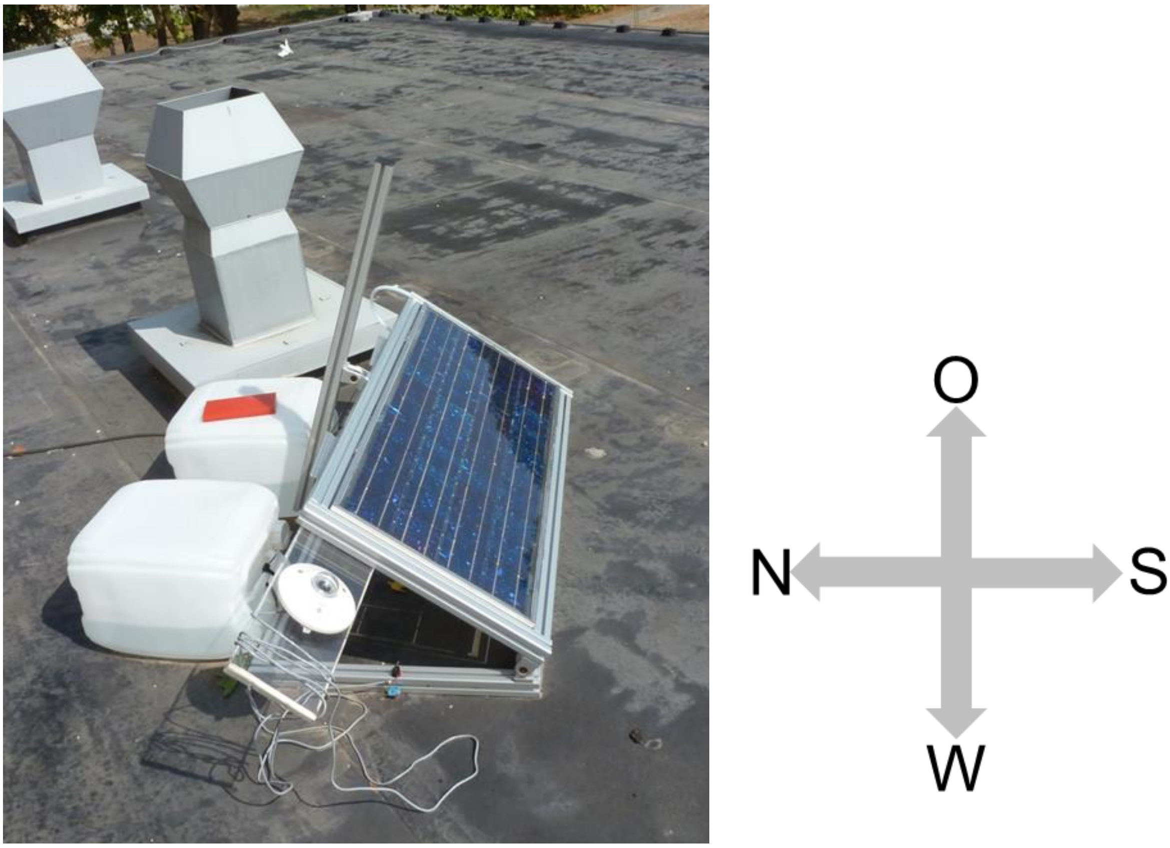


***Figure 5**: PV panel and pyranometer combined with PEM electrolysis on the rooftop of IEK-3 at Forschungszentrum Jülich.*

With this system we performed several outdoor tests. The difference to the most recent configuration is, that we have a serial connection of only two electrolysis cells (instead of twelve) and we have a coupling via a DCDC (now without) converter. An example of data obtained by tracking the irradiance and PV module output power, the electrolyser power and the heating value of the produced hydrogen, is shown in Figure 6.

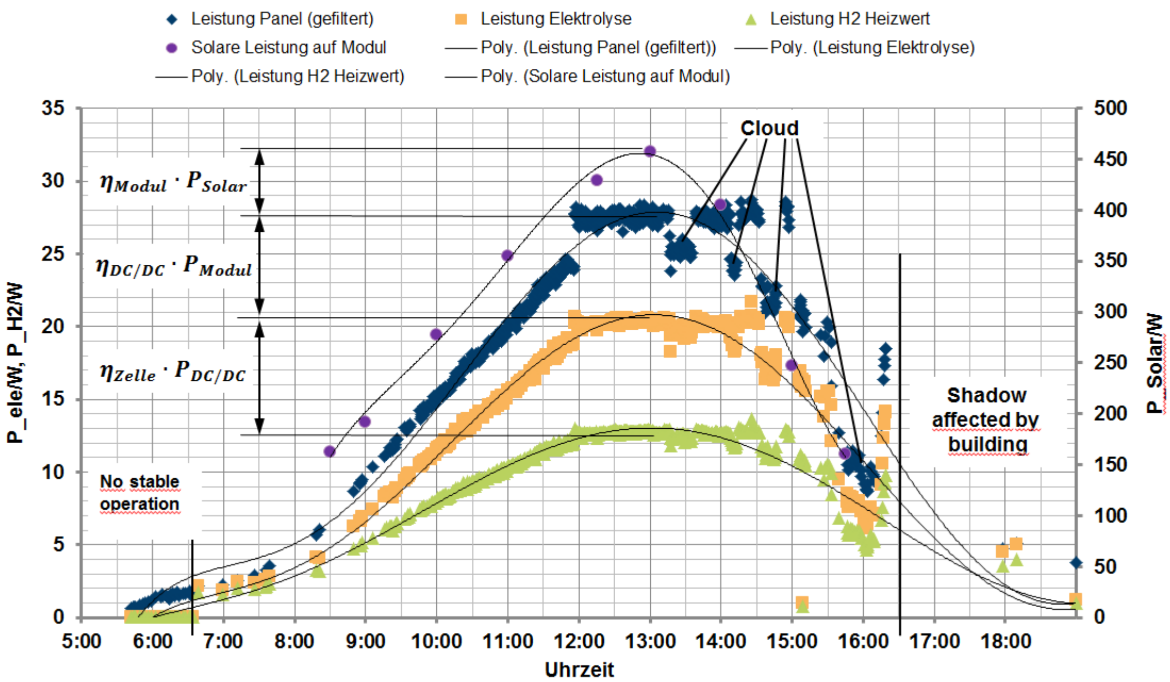


Figure 6*: Daily course of the power output. The different losses affected by energy conversion within the system are given. The equivalent values of power are shown for the incident solar irradiation (circles), PV panel (diamonds), electrolyser input (squares) and the heating value of the generated hydrogen (triangles).*

4.2 Description of indoor system part

The process engineering for separating hydrogen from the recycled media is located inside the lab. Also the necessary actuators, sensors and the data acquiring system with a PC and the control software are installed here.

4.2.1 Description of process engineering

In Task 7.1 – Concept for test field balance of plant, gas handling and safety- the strategy of the demonstrator plant was described. As a reminder a schematic of the main components is shown in Fig. 7. A list of the main components and their functions is also provided in Table 2. In this report, we explain in more detail than in Deliverable 7.1, how the process engineering supports the demonstrator – in this case the PEM cassette system is chosen as a reference. All data that are recorded, receive a time stamp, which allows a clear temporal allocation of the measured values. The time recording runs based on Central European Time (CET), used in most parts of Europe, which is 1 hour ahead of Coordinated Universal Time (UTC).

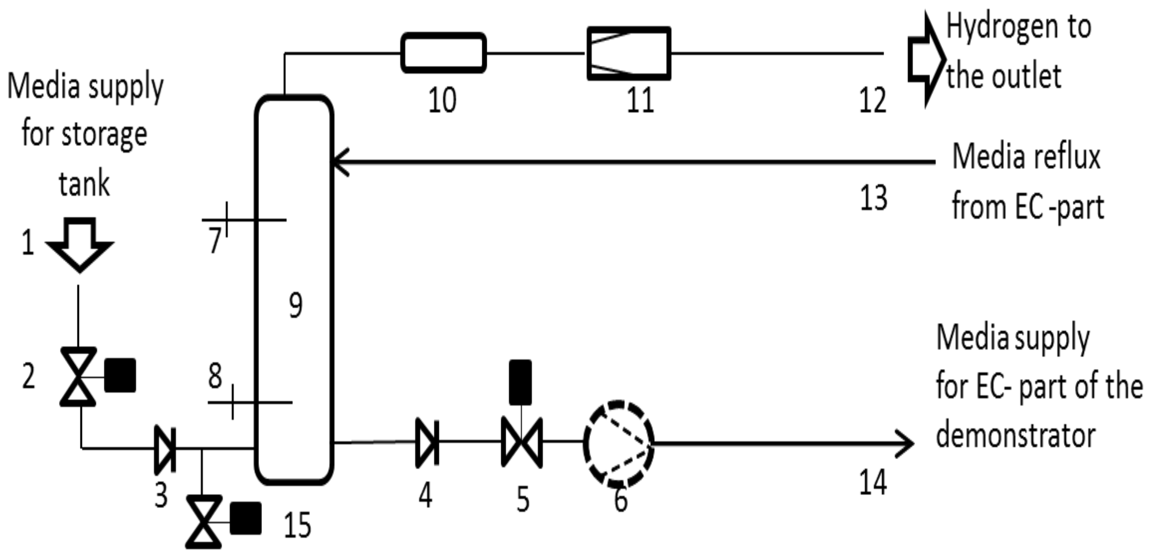


Figure 7: *Scheme of process engineering part of the demonstrator testbed associated with the parts list in Table 2.*

Table 2 *Function and specifications of the used actuators and sensors*

Nr:	Part	Function	Specification
1	water supply	Supplies water from the lab	6 mm water tube, connected from lab environment
2	magnetic valve	Valve actuator, for keeping the water level in the water reservoir on a constant level	24 V valve, with 6 mm connectors
3	non-return valve	hinders media from the circulation loop entering into the water supply side	spring loaded 6 mm valve
4	non-return valve	hinders gas from the EC- loop to flow back into the water supply side	spring loaded 6 mm valve
5	magnetic valve	Valve actuator for close and opening the water loop to the EC- part	24 V valve, with 6 mm connectors
6	circulation pump	not necessary in case of the PEM cassette system, might be an option for other concepts	to be defined in dependence of which system would be chosen to be compared with the reference
7	level sensor	fluid sensor registers maximum fluid level	capacitive coupled level sensor, 24 V
8	level sensor	fluid sensor registers minimum fluid level	capacitive coupled level sensor, 24 V

Nr:	Part	Function	Specification
9	water reservoir	tank composed of stainless steel to buffer the water for the EC device and to separate the hydrogen from the water	atmospheric open tank volume of around 1 liter and several 6 mm connectors
10	drying agent	solvent in order to reduce humidification of the produced hydrogen before measurement	200 ml cartridge of silica gel
11	mass flow meter	measurement of the produced hydrogen, connected with a data acquisition system for energy balancing	ethernet controlled 6mm MFM, for hydrogen measurement
12	pipe	leads hydrogen out of the lab into the environment	6 mm PTFE tube
13	pipe	leads the water hydrogen mixture back to the water reservoir	6 mm PTFE tube
14	pipe	leads the water to the EC device	6 mm PTFE tube
15	magnetic valve	purging valve	24 V valve, with 6 mm connectors

In case of the PEM-system no additional safety sensors are necessary. The reason is we don't collect the oxygen and this is why we have no risk of the formation of explosive oxygen-hydrogen mixtures at the anode and so the hydrogen in oxygen sensor is not needed. The hydrogen will be collected and measured inside our building and we will use the already existing hydrogen sensors to ensure are a reliable and safe operation.

4.2.2 Description of control strategy

The PV-EC system runs almost automatically. The PEM-cassette, which is chosen as a reference system, even needs no control of a pump, because it's hydraulically operated. This means that for controlling; only the water level in the water tank [9] needs to be directly monitored. In the planned system the PC used for the data acquiring can be used with common software – for example LabVIEW- to realize this. **Figure 8:** Process flow chart for the control strategy shows the process flow for controlling the sensors and actuators. For a small system based on the cassette design these setup has successfully tested.

If the start switch is pressed and no emergency case exists, the level check routine starts its procedure. Depending on the state of the level sensors max [7] and min [8] different procedures can take part:

- If the min sensor is "on" and the max sensor is also "on" there is too much water in the system. In this case the water drain valve [15] is opened until the max sensor changes its state to "off". Then the program shifts in the step "Level O.k."
- If the min sensor is "off" and the max sensor is "off" too, there is to less water in the system. In this case the water supply valve [2] opens until the min sensors changes its state to "on". Then the water supply valve closes again, and the program shifts in the step "Level O.K."

If the min sensor is "on" and the max sensor is "off" the program steps directly in the step "level O.K."

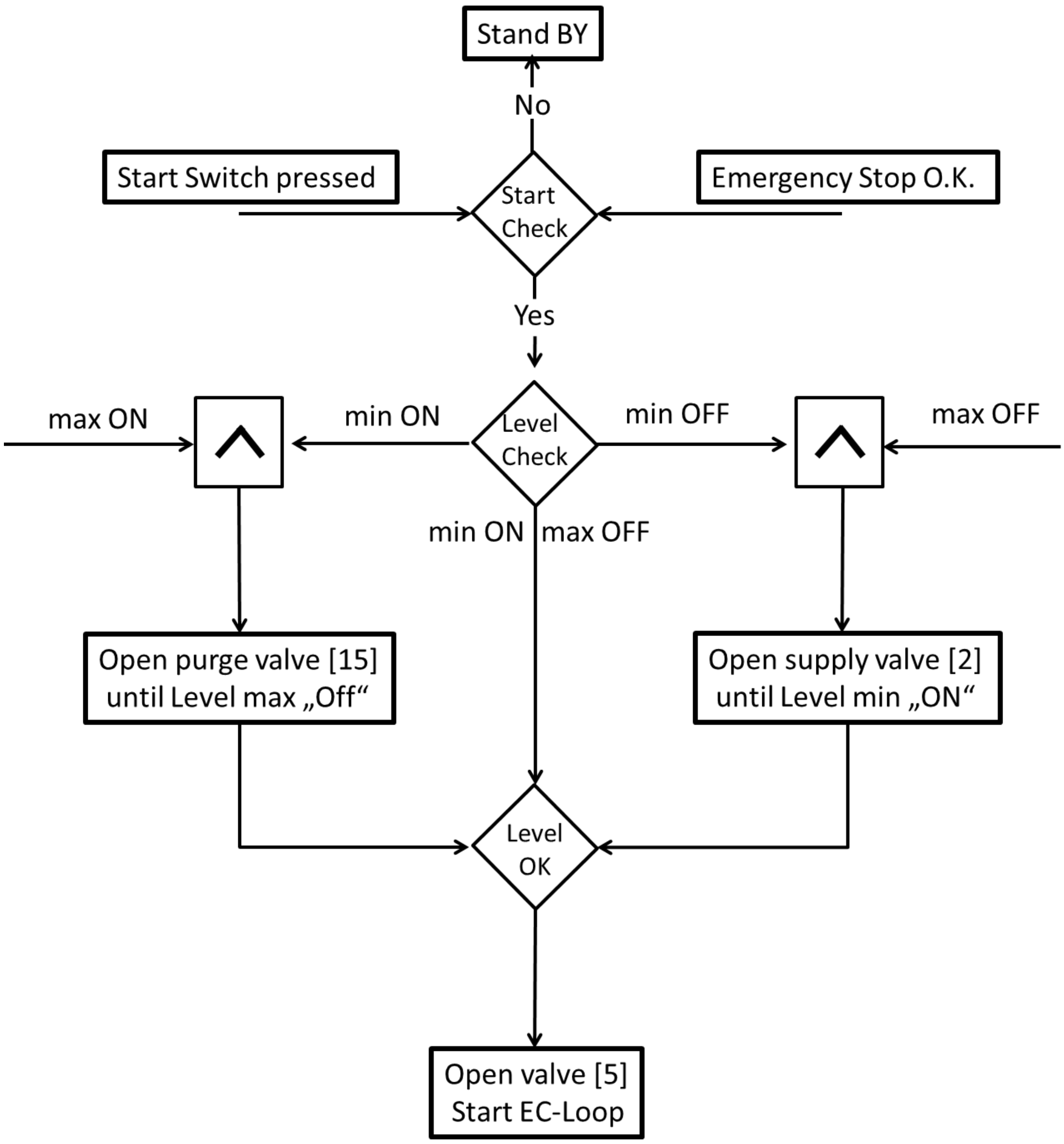


Figure 8: *Process flow chart for the control strategy of the test bed.*

When the step “level O.K.” reached, the magnetic valve [5] for starting the EC loop opens and the electrolyser is supplied with water. In this state, the operation is in a continuous mode until the stop button or an emergency button is pressed.

Furthermore, there are some sensors required to get some more detailed information on the demonstrator system performance. The most important one for calculating the energy balances is the mass flow meter [11]. Additionally we require a few extra sensors, described in **Table 3** for monitoring the system.

Table 3 *Additional sensor equipment for measurement*

Sensor	Method	Comments	Number TRUST list
EC Current	shunt	Measurement to calculate the electrical power of the EC –Device	905
EC Voltage	direct	Measurement to calculate the electrical power of the EC –Device	905
Hydrogen pressure	Pressure sensor	In case of cassette design a operation at elevated pressures is possible	922
PV Current	shunt	Measurement to calculate the electrical power of the PV -Device	
PV Voltage	potential divider	Measurement to calculate the electrical power of the PV -Device	
Solar radiation	pyranometer	Measurement to calculate the Solar to Hydrogen (STH) efficiency	904
MFM	H_2 volume	Measurement to calculate the Solar to Hydrogen (STH) efficiency	908
Temperature	PT-100	Parameter which influences PV and EC efficiency 1. Temperature of EC (Endplate) 2. Temperature of PV (Middle backside) 3. Ambient Temperature (in shadow)	932 923

All data which are recorded, receive a time stamp which allows a clear temporal allocation of the measured values. The time recording runs based on Central European Time (CET), used in most parts of Europe, which is 1 hour ahead of Coordinated Universal Time (UTC).

The hydrogen purity is not measured continuously but gas chromatographs (GCs) are available to analyze gas composition. In case of PEM electrolysis, the purity is very high, because we use a platinum catalyst at the cathode and oxygen that is may be crossing the membrane reacts at the catalyst layer with hydrogen to form water.

5 DEVIATIONS AND CORRECTIVE ACTIONS

The development of the 10 m² demonstration test bed is now focused on the PEM cassette design, because this configuration shows till now the highest technical maturity and has the best chance to reach a long term stable operation. The parameters for media input are not available for the integrated design. We have not yet decided in the consortium which system configuration (alkaline or PEM) will be used in the final setup. It is necessary that this will be decided soon.

6 DISSEMINATION AND UPTAKE

6.1 Dissemination activities

Up to now, there have been no dissemination activities associated with these activities. In the future, the demonstrator test bed shall play an important role as a site for visitors to view the operation of the demonstrator developed in the project.

6.2 Uptake by targeted audiences

As indicated in the Description of the Action (DoA), the audience for this deliverable is:

(PU) – General public	×
(PP) – Project partners, including the Commission Services	×
(CO) – Confidential; only for Consortium Members and the Commission Services	

7 EVALUATION OF THE REPORT FINDINGS

7.1 Comparison with state of the art

Integrated PV-EC concepts have been developed in the lab scale but till now not in the m^2-size. The cassette concepts developed within the project show the highest TRL level and therefore are most suitable to achieve the project goals. The PEM system has the disadvantage of using precious metals but the amount is very low (In case of 10 m^2 PV → 60 € for precious metals). The advantage of PEM is the use of pure water instead of potassium hydroxide. In February 2019, University of Leuven reported an integrated 1.6 m^2 PV-EC panel with a solar to hydrogen conversion efficiency of 15 % based on calculations but details of the design and measurement conditions are not given[1]. The researchers mentioned that field tests to prove the calculated STH are being planned. It is not clear if they consider higher or lower heating value.

7.2 Lessons learnt – both positive and negative that can be drawn from the experiences of the work to date

To achieve a higher hydrogen output we decided to build up a framework where the modules can be mounted in south orientation and with ideal orientation to the sun. The innovative PEM cassette design allows easy supply with water only for cathode side and a generation of pressurized hydrogen (up to 10 bar) from cell operation without additional compression.

7.3 Links built with other deliverables, WPs and synergies created with other projects

We have a strong interaction with work package 4.

[1] https://nieuws.kuleuven.be/en/content/2019/belgian-scientists-crack-the-code-for-affordable-eco-friendly-hydrogen-gashttps://www.greencarcongress.com/2019/03/20190308-kul.html

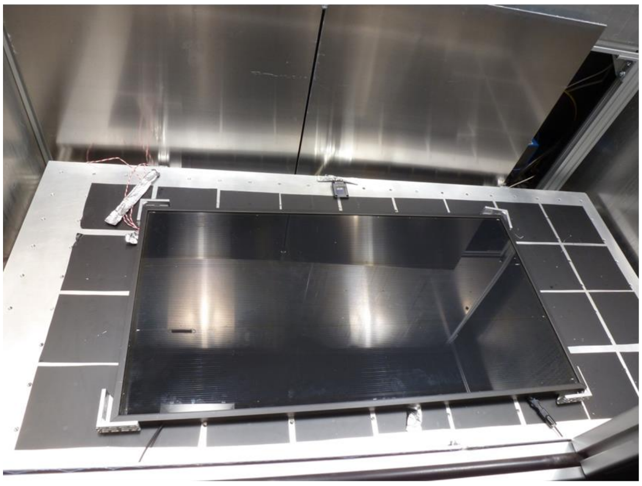
7.4 Limitations of the findings

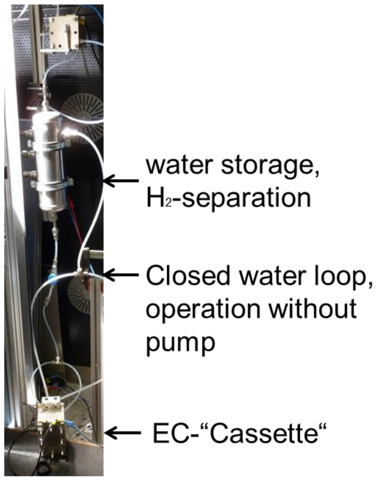
The system design is now focused on providing water to the electrolysis modules and we are able to measure the amount of hydrogen that will be produced. This was shown in WP 4, where the setup tests in the solar simulator are presented. We have found that the generated hydrogen is very pure and we have a good correlation with the values calculated by faradaic law. The systems is adapted to the one pipe water supply concept that is used within the cassette design. The concept presented is not suitable for alkaline media supply and thus if an alkaline cell is used, it is necessary to add another pipe and to adapt the materials.

Also, in the system considered so far, the PV module is coupled directly with the electrolysis via cables and no integrated systems have been considered because they are not yet available on a big enough size.

8 CONCLUSIONS AND NEXT STEPS

When we have the final decision about the setup of the whole system (integrated or cassette), we can start with the erection of all components and with first test runs of the entire system. The already performed system tests have been presented in work package 4. To achieve reproducible results a solar simulator test bench at IEK-5 is used. This test bench is available for testing different setups under exactly the same operating conditions.





Sun simulator with PV solibro module (630x1190mm; 0.75m²)

9 DECLARATION BY THE DELIVERABLE LEAD BENEFICIARY

Deliverable 7.2:

- ☐ Has fully achieved its objectives and technical goals
- ☑ Has achieved most of its objectives and technical goals with relatively minor deviations
- ☐ Has failed to achieve critical objectives and/or is not at all on schedule