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

Project Deliverable Report – D7.5

Title:	**10 m² system operational**
Work Package	**WP 7**
Deliverable nature:	Demonstrator
Dissemination level:	Public
Lead beneficiary:	FZJ
Due date:	31st December 2019
Submission date:	19th January 2021
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This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement 735218. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

Document History

DATE	VERSION	RESPONSIBLE	DESCRIPTION
25.11.2020	0.1	D. Kaden (HZB)	Deliverable layout – Sent to Project Coordinator
26.11.2020	0.2	S. Calnan (HZB)	Approved by Project Coordinator
26.11.2020	0.2	D. Kaden (HZB)	Sent to the Deliverable Lead Beneficiary
10.12.2020	1.0	M. Müller (FZJ)	Sent to Project Coordinator for review
08.01.2021	1.1	S. Calnan (HZB)	Request for review
15.01.2021	1.2	M. Müller (FZJ)	Revisions submitted to Project Coordinator
19.01.2020	2.0	S. Calnan (HZB)	Checked and submitted to the EC by the Project Coordinator

Distribution List

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EXECUTIVE SUMMARY

This report describes the setup of the 10 m^2 demonstration system for direct solar hydrogen generation. The demonstration system consists of an array of commercial sized photovoltaic (PV) modules either based on CuInGaSe or silicon heterojunction technology, each directly electrically coupled to a PEM electrolyser stack. Prior to installation outdoors, each PV module was illuminated in a solar simulator to determine the expected performance of a directly connected electrolyser stack under ideal and reproducible conditions. This was followed by the installation of the PV modules, the electrolyser stacks and the balance of plant units on the test field (a south west-facing laboratory roof) at Forschungszentrum Jülich. The demonstration plant thus was completed and ready for operation in January 2020, one month later than originally scheduled.

Since the setup of the measurement technology was more complex than initially expected, the functionality of the system outdoors was preliminarily tested in manual operation. Already during these first tests, the operation with more than 10 % solar to hydrogen conversion efficiency could be proven. In February and March 2020, the monitoring components were fully upgraded so that systematic measurements for continuous monitoring could be started in April. In addition to recording the hydrogen volume flow and the solar irradiation, the temperatures of the PV and electrolysis modules are also recorded at various measuring points. An average solar to hydrogen conversion efficiency of more than 10 % was achieved, which exceeded the set target of 6%. The data was used to study the system behaviour presented in deliverable 7.6 and to provide an important basis for the planned system simulations in deliverable 6.5.

TABLE OF CONTENTS

ABBREVIATIONS and ACRONYMS

BoP	Balance of Plant
CA	Consortium Agreement
CIGS	CuInGaSe
DoA	Description of Action
EC	Electrolysis Cell
EGP	Enel Green Power
FZJ	Forschungszentrum Jülich GmbH
GA	Grant Agreement
HJT	Heterojunction (term used by Enel Green Power for SHJ)
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
SHJ	Silicon heterojunction
SRAB	Solibro Research AB
WP	Work Package

1 INTRODUCTION

In this report the installation, preliminary operation and testing of the 10 m² direct solar hydrogen generation system on the roof of the Institute for Electrochemical Process Engineering (IEK-14) at Forschungszentrum Jülich are presented. This activity contributes towards the overall objective of work package 7 to scale up the selected device concept to the module size as well as implementing and testing the 10 m² system including BoP and gas handling. The implemented system was operated and characterized for the first time in January 2020. However, as the measurement data acquisition could only start with a slight delay, the autonomous operation of all modules and sensors was started in April 2020.

While the electrolysis cells were made at Forschungszentrum Jülich, the PV modules were provided by the project partners Solibro Research AB and Enel Green Power. The first test showed a good performance of the combined devices. The new type of power supply for the stacks was also able to demonstrate its good function in field use. Solar to hydrogen conversion efficiencies of more than 10 % were achieved, which exceeded the set target of 6%.

2 DELIVERABLE OBJECTIVE AND RELATED TASKS

The objective of this deliverable was to ensure that the **10 m² system was operational by December 2019**. As already mentioned, in deliverables 7.3 and 7.4, problems in scale-up of the integrated device approaches, necessitated that we resort to developing innovations in directly coupling discrete PV modules to electrolyser stack.

2.1 Description related tasks

This deliverable reports the outcomes of some activities that were performed in tasks 7.5 and 7.6

No.	Task description	Start date	End date
T 7.5	Realisation of 10 m² system and testing	Oct 2019 (M34)	Dec 2020 (M48)
T7.6	Large area characterization of prototype panels and demonstrator panels	April 2019	January 2020

Task 7.5: Realisation of 10 m² system and testing

The fabricated modules shall be mounted requiring the installation of the procured balance of plant components. Performance shall be monitored by recording solar radiation and generated hydrogen, among others, to calculate the system's efficiency. The FZJ shall also carry out maintenance of the system in that time. Based on the technology selection, 10 % of the budget that will be set aside by FCH-JU until the midterm review and will then be allocated to the partners that are involved in the realization of modules for 10 m² and shall be used for their expenses for consumables and invest as required.

Task 7.6: Large area characterization of prototype panels and demonstrator panels

The characterization of the temperature and illumination dependency would be extended to the real prototype panels developed in WP2, WP3, and WP4. We will measure performance and stability of the large area devices with large area continuous solar simulators available in Jülich. Additionally, we will also perform a pre-characterization of the large area panels manufactured for the 10m² demonstrator prior to the installation. Here the capabilities of the solar panel manufacturers are limited, since they usually use flash lamp systems to characterize the PV performance. In detail, we plan the following actions:

(i) Prototype panels with a size of ≥ 100cm², namely SHJ based devices, CIGS based devices and cassette approach

a. Characterize device performance (STH efficiency) by hydrogen production rate measurement

b. Testing illumination dependency of device performance

c. Testing temperature dependency of device performance

d. Examination of long-term stability of different approaches

(ii) Demonstrator panels, pre-characterization before outdoor installation

a. Characterize~1 m² PEC modules under standard test conditions

b. Compare illumination and temperature dependence of 1 m² PEC modules to prototype devices

c. Investigate the initial device stability (<10h)

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).

Table 1. *Contribution of deliverable 7.5 to the project objectives*

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	×	
Specific objectives		
To study and develop devices for integrated PV-EC concepts and scale viable concepts to prototype size > 100 cm²		×
To use socio-techno-economic analysis to predict and select concepts with levelised cost of hydrogen production below € 5/kg	×	
To scale the prototypes of the less mature but promising technologies to a demonstrator with active area > 10 m²	×	
To achieve a hydrogen production of 16 gH_2/h from the demonstrator resulting in a STH efficiency of at least 6 %	×	
To ensure that the initial demonstrator STH efficiency does not reduce by more than 10 % after six months of continuous operation	×	

4 DESCRIPTION OF COMPLETED ACTIONS

4.1 System setup and function

As mentioned in deliverable 7.4, there were two types of PEM electrolysers with low and standard catalyst loading and two types of PV modules with silicon heterojunction solar cells and with CuInGaSe solar cells available for installation at the test bed. Therefore, different configurations of PV module to electrolyser stack couples were implemented in the test field to understand how their behavior under outdoor conditions would vary from the predicted performance. The active geometric cell area of the electrolyser was 4.2 cm × 4.2 cm with the following catalyst loadings: anode: 0.42 mg_{Ir}/cm^2 (Stand.: 2.4 mg_{Ir}/cm^2); cathode: 0.05 mg_{Pt}/cm^2 (Stand.: 0.8 mg_{Pt}/cm^2). The area of each HJT PV module from EGP was 2.0 m² while that of the CuInGaSe (CIGS) modules from SRAB was 0.75 m². Table 2 lists the different electrolyser module pairs implemented at the test field.

Table 2. *List of different PEM electrolyser-PV module pairs installed at the test field*

Type of PEM electrolyser		PV configuration	Replications
Catalyst loading (anode; cathode)	Number of cells per electrolyser stack		
Low (0.42 mg_{Ir}/cm^2; 0.05 mg_{Pt}/cm^2)	21	One module Enel HJT	1
	10	One module Solibro CIGS	3
Standard (2.4 mg_{Ir}/cm^2); 0.8 mg_{Pt}/cm^2).	21	Two modules in parallel Enel HJT	1
	10	One module Solibro CIGS	1
	10	Two modules, in parallel, Solibro CIGS	1

The following figure gives an overview of the actual layout of the different PV-electrolyser sets at the test facility. All results shown in the following were achieved with the system configuration shown.

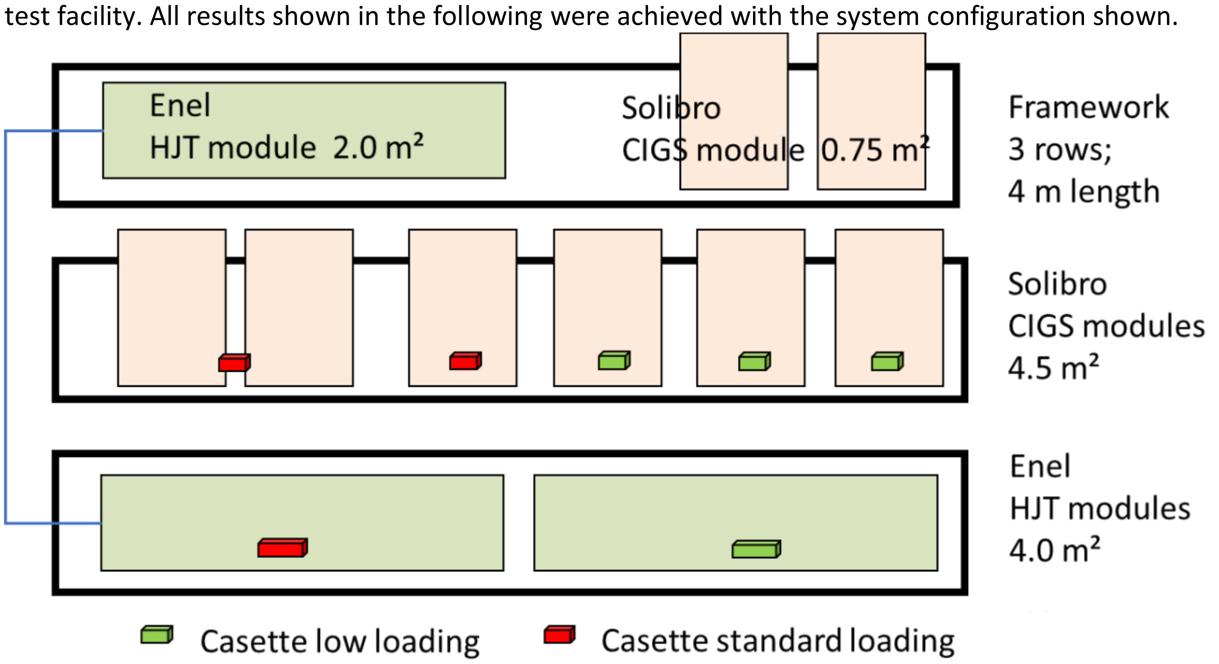

Figure 1*: Arrangement of the different PV-electrolyser systems in the 10 m² demonstrator field.*

In order to operate the system effectively, it was necessary to design a balance of plant system to manage the media (electrolyte) supply as well as the drying and separation of the product-gas **Figure 2** illustrates the setup of the balance of plant (BoP) system. From left to right, it starts with the water supply to the water reservoir and gas separator. Water can be driven by a pump (6) through the electrolysis modules (14). Unused water and the generated hydrogen comes back from the electrolysis module (13) into the separator. The separated hydrogen is dried (10) and measured by a mass flow meter (11). All components are listed and described in detail in **Table** .

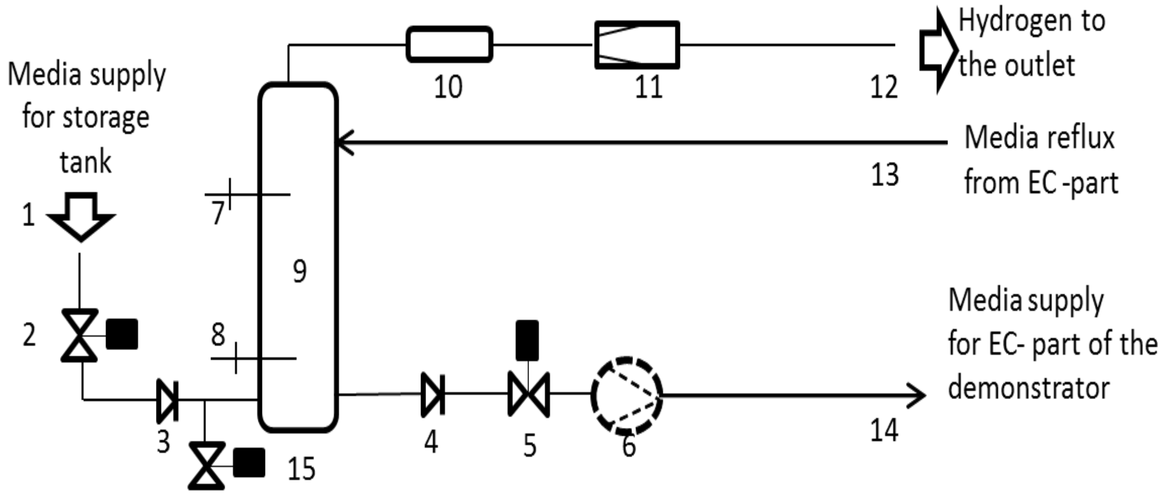

***Figure 2**: Setup for managing the media supply and product gas handling for PEM EC-System*

***Table 3**: Description of the Balance of Plant system components*

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, 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

Since a sufficient water supply of the electrolysis cells must be ensured to avoid damage of electrolysis cells by dry-out, a control system was developed. **Figure 3** shows the control logic with which the water level in the storage tank is kept at a constant level.

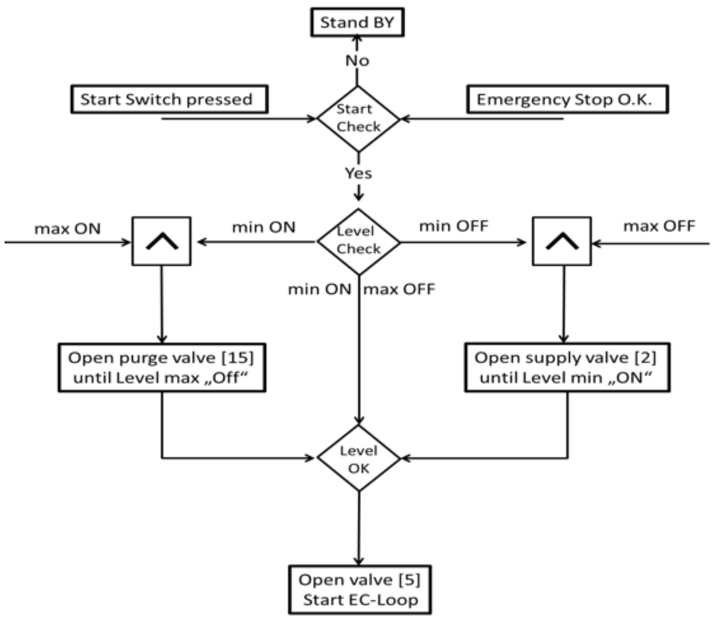

Figure 3: *Control strategy for water supply to the electrolyser*

4.2 Laboratory testing

To get a reference before the actual commissioning, the PV panels were tested together with electrolyser cassette modules in the sun simulator at FZJ-IEK-5. For these tests, each PV module was connected to a 21-cell electrolyser stack.

The following figure shows one of the 2.0 m² modules integrated in the sun simulator. The room is air conditioned, but there is no active cooling of the PV module. Therefore, the PV module reaches a certain equilibrium temperature at each radiation. During the tests, the electrolyser is placed outside the simulator, see next figure.

Figure 4: *PV module in the sun simulator at FZJ. The radiation intensity of the sun simulator is monitored using a monitor cell which is visible at close to the bottom left hand corner of the PV module and a pyranometer visible at the centre of the bottom edge of the photograph.*

The solar radiation intensity was varied by changing the lamp power in the range of 50 % (minimum) to 100 % and monitored with a monitor cell and pyranometer. The extent to which varying the lamp power to achieve different intensity levels, affected the spectral distribution was not investigated. However, since all technologies considered used single junction solar cell whose performance is only slightly varied by spectral variations, this was expected to have a minimal contribution to errors in the measurement.

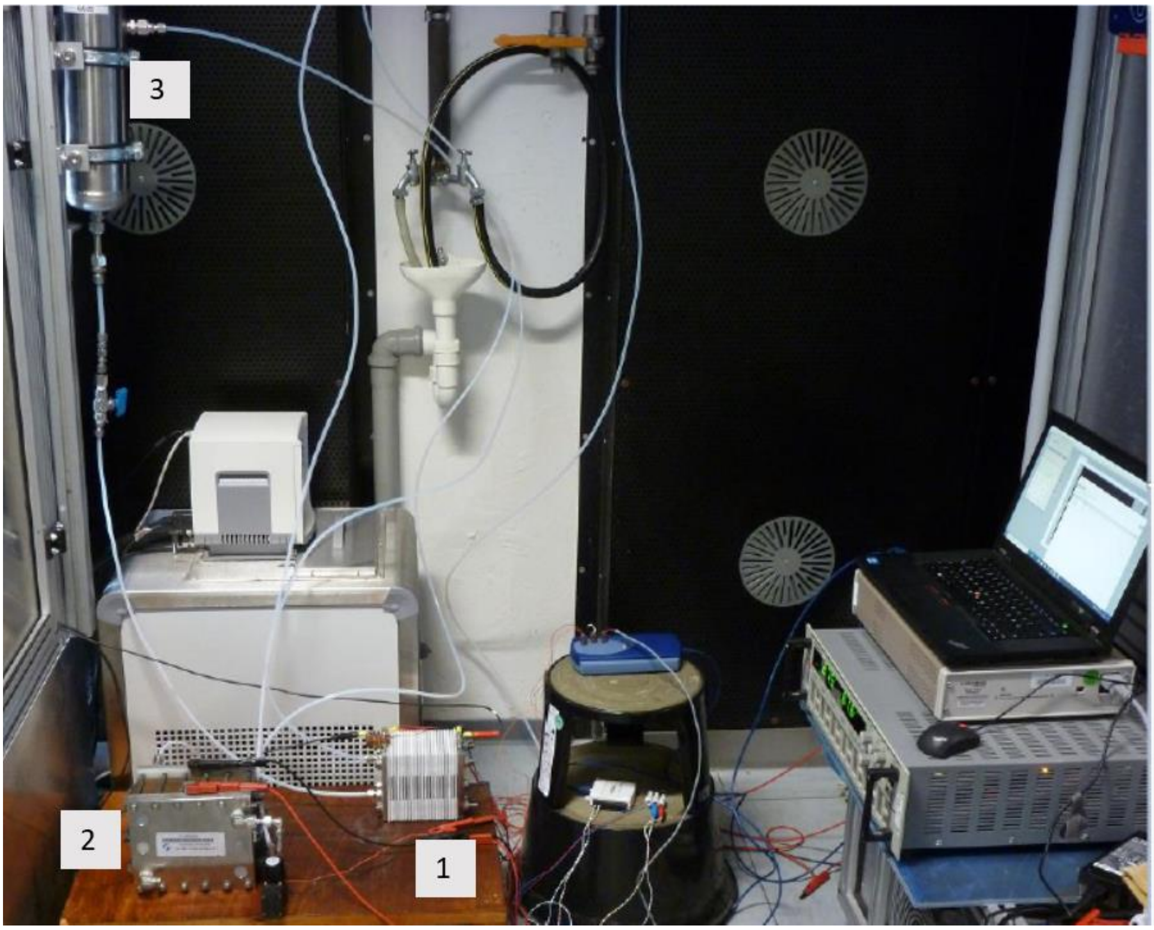

Figure 5: *Characterization of a 21-cell PEM electrolyser stack (1) powered by a photovoltaic module exposed to radiation in the sun simulator. The stack is located outside the sun simulator but connected to the PV module and the generated hydrogen was dried in (3) before being measured by a mass flow meter (not visible). The stack current was determined simultaneously by means of a defined resistance (2).*

The temperatures of the PV module and electrolyser stack were monitored using thermalcouples in which thevoltage signals were measured in 4-wire technique. The electrolyser temperature was monitored by a thermocouple with 3mm diameter embedded in the end plate of the electrolyser. The PV cell temperature was monitored by a flat film thermocouple attached on the back of the PV module.

The current flowing through the electrolyser stack was determined indirectly using shunt measurement while the mass flow rate of the generated hydrogen was monitored using a mass flow meter (ANALYT-MTC).

Table 4 below summarises the values of parameters measured during the tests and the performance data calculated therefrom.

Table 4*: Measured and calculated performance parameters of a 2 m² HJT Module from EGP connected to a 21-cell PEM electrolyser stack from FZJ during sun simulator tests.*

Parameter	Equation	Incident irradiance from sun simulator [W/m²]	
		1000	420
PV Module temperature, T_{PV} [°C]	measured	57	41
Maximum power point, P_{PV} [W]	measured	314	139
Power transferred to electrolyser stack, P_{EC} [W]	measured	297	119
Electrolyser current, I_{EC} [A]	measured	8.1	3.4
Electrolyser voltage, V_{EC} [V]	measured	36.65	35.00
Electrolyser stack temperature, T_{EC} [°C]	measured	32	28
PV module solar conversion efficiency, η_{PV} [%]	$(100 \times P_{PV})$/ (Module area × Incident irradiance)	15.7	16.5
Electrolysis (voltage) efficiency, $\eta_{electrolysis}$ [%]	$(1.25 \times 21 \times 100)/(V_{EC})$	71.6	75.3
Coupling efficiency, $\eta_{coupling}$ [%]	$(100 \times P_{EC})/P_{PV}$	94.6	85.6
Solar to hydrogen conversion efficiency, η_{STH} [%]	$\eta_{PV} \times \eta_{electrolysis} \times \eta_{coupling}$	10.6	10.6

The current-voltage curves of the PV module and the electrolyser stack under 1000 W/m² and 420 W/m² illumination are presented in Figures 6 and 7.

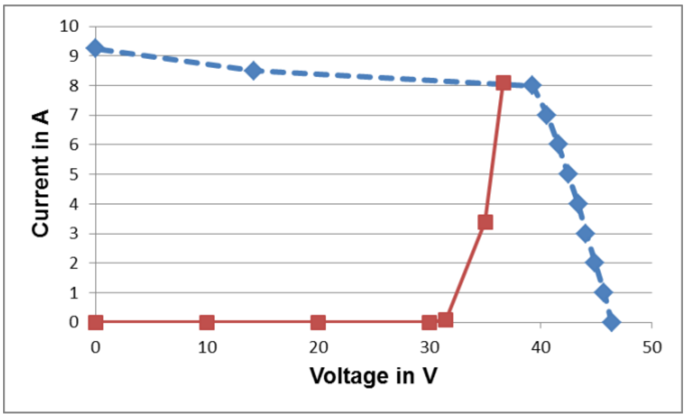

Figure 6: *Current-voltage curves of the 2 m² silicon heterojunction PV module (diamonds) and the 21-cell electrolyser stack (squares) taken during 1000 W/m² irradiation from the large area sun simulator at FZJ. (*

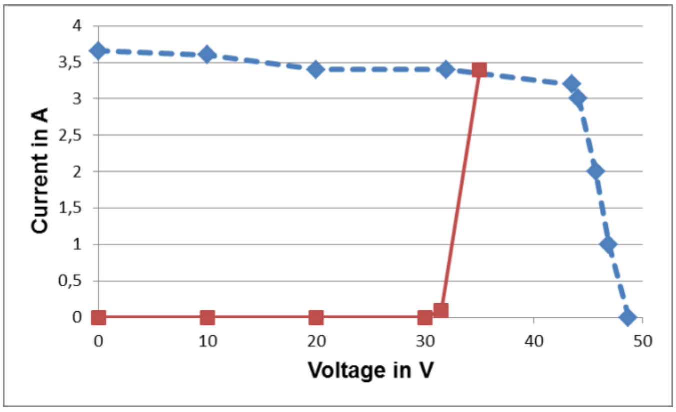

Figure 7: *Current-voltage curves of the 2 m² silicon heterojunction PV module (diamonds) and the 21-cell electrolyser stack (squares) taken during 420 W/m² irradiation from the large area sun simulator at FZJ.*

The H_2 production rate was calculated from the electrolyser current as (8.1 A × 21 cells)/ (2×96485 As/mol) = 0.000881 mol/s. this corresponds to a flow rate of 22.4 × 60× 0.000881 = 1.18 L/min at normal conditions. Since this value was also measured with the mass flow meter, the Faradaic efficiency under these conditions was close to 100 %.

4.3 Mounting of the system

After these successful tests, the system was assembled in the experimental halls of FZJ-IEK-14 and prepared for transfer to the laboratory roof. Figure 8 and Figure 9 show an intermediate status of the assembly work in the experimental halls of the research center and the construction of the plant with the help of a crane, respectively.

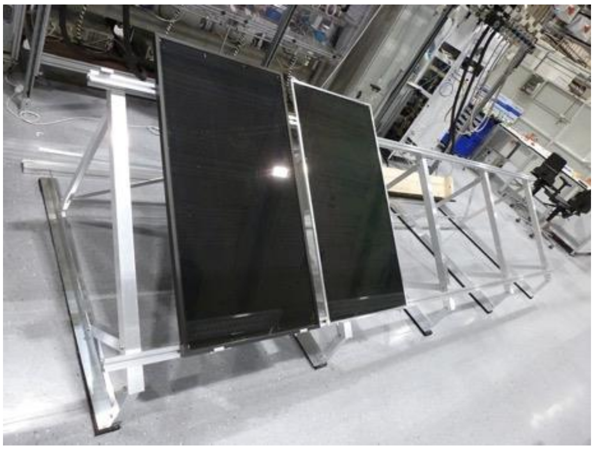

Figure 8: *Assembly of the racks and first assembly testing of the PV panels in the IEK-14 test hall.*

Figure 9: *Transfer of the test facility to the laboratory roof*

Figure 10 shows the installation of the first PV panels from ENEL on the laboratory roof. **Figure 11**11 shows the further progressed construction, where the modules from SRAB have also been installed in the second row. Figure 12 shows the final setup that is ready for operation. The first tests with the system were started in January 2020.

***Figure 10**: Integration of the PV modules (a)the SHJ/HJT modules from Enel Green Power and (b) the CuInGaSe thin film PV modules from Solibro Research AB installed at the test site of FZJ. As an example, a photograph (c) showing the PEM electrolyser (indicated by the arrow) directly mounted onto the back of one the CuInGaSe thin film PV modules PV module in the so-called cassette design.*

***Figure 11:** System with integrated PV and electrolysis modules, ready for operation*

***Figure 12:** Final setup of the 10 m² demonstrator plant, photographed in July 2020.*

4.4 First outdoor measurements

The system could then be put into operation for the first time in mid-January 2020 and hydrogen could be produced for the first time. During these measurements, not all modules were connected properly and therefore it was necessary to improve the setup. The results shown here are monitored with the HJT PV module from EGP (2.0 m² active area) combined with a 21-cell electrolysis stack. The other modules were then gradually upgraded and the automated data acquisition system was put into operation. However, the fully autonomous operation was not yet possible, because some adjustments of the system control were still necessary. Figure 13 shows the radiation measured during the implementation phase during January 2020. The abrupt cut-off in irradiance just after 1530 is caused by shading from the wall of the experimental hall.

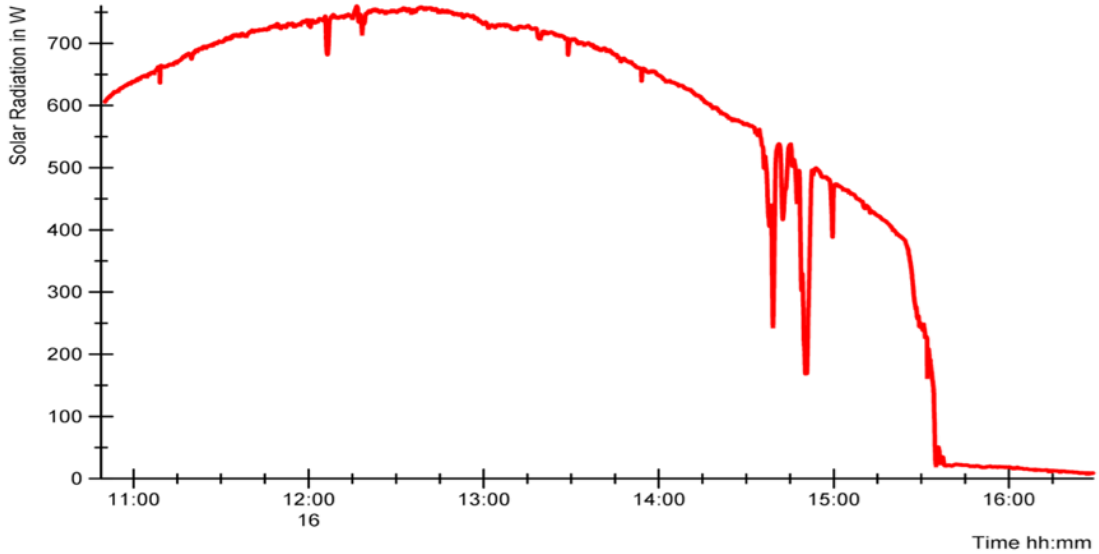

***Figure 13**: Measured solar radiation with radiation sensor (16th January 2020) at the test field in Jülich.*

Figure 14 Figure 14 shows the electrical output of the EGP-PV module / input to the electrolysis stack. All measurements presented here were acquired in time synchrony with the solar radiation presented in Figure 13.

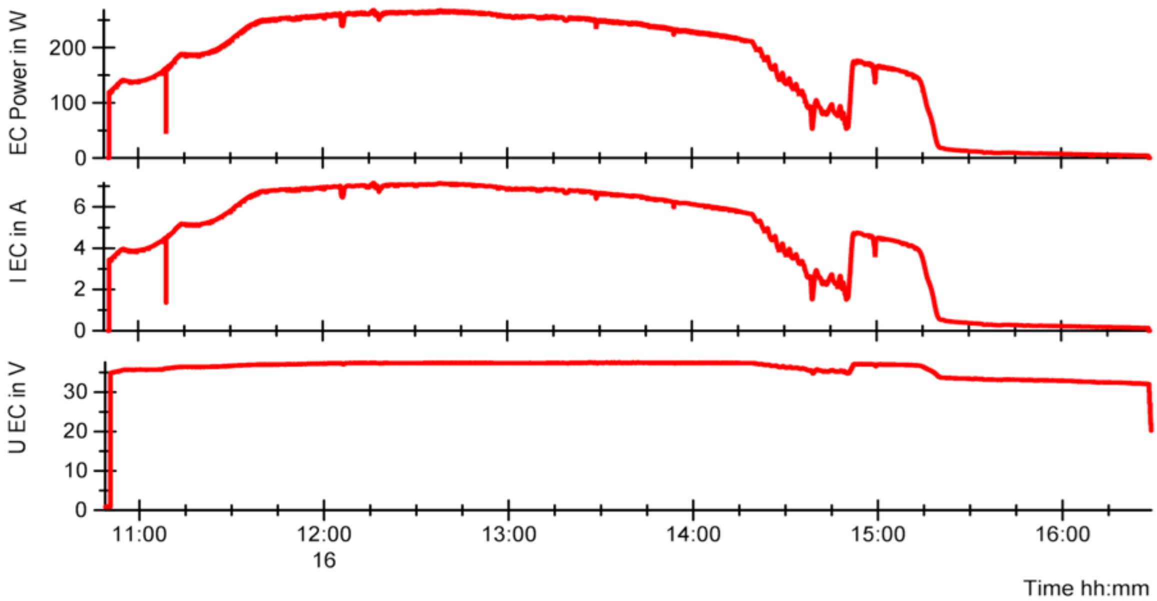

***Figure 14:** Time evolution of electrical parameters of the 21-cell electrolysis stack coupled to a HJT PV module from EGP (2.0 m² active area) on 16th January, 2020.*

With the previous shown results, it is possible to calculate the solar to hydrogen efficiency. **Figure 15** illustrates the measured numbers.

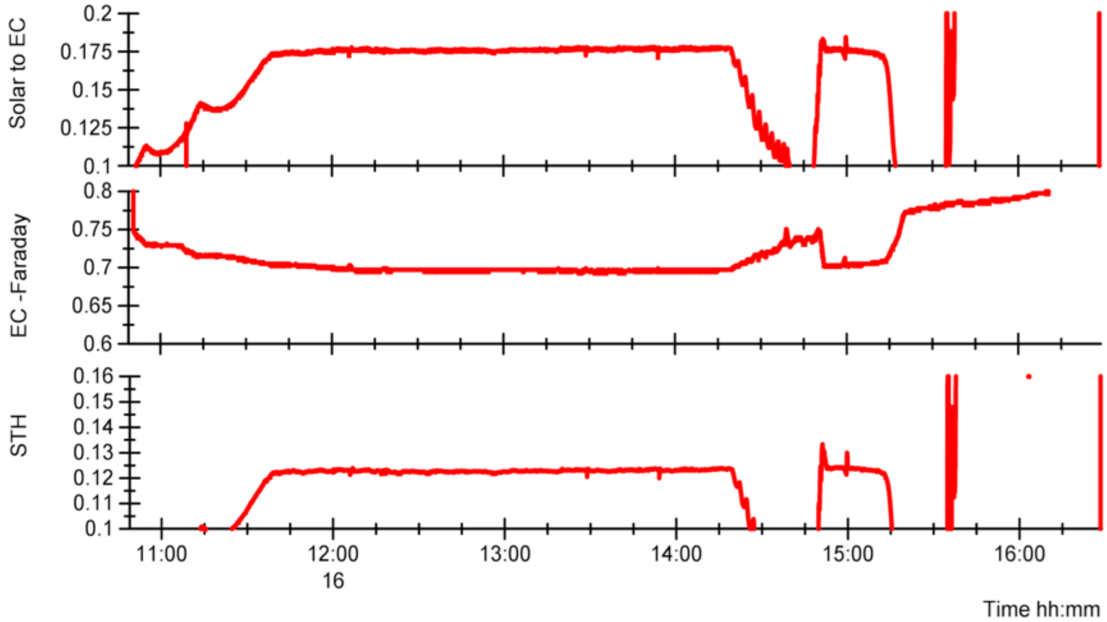

Figure 15: *Measured and calculated hydrogen evolution as well as calculation of the solar to hydrogen efficiency of the 21-cell electrolysis stack coupled to a HJT PV module from EGP (2.0 m² active area) on 16th January 2020.*

The operation and monitoring system implemented above provides the basic measurements required to determine the solar to hydrogen efficiency using gas flows. The next step after that was to implement the device temperature measurements and synchronise them with the already existing weather and electrical and gas flow measurements with which is necessary to develop simulation for models for the techno-economic and life cycle analysis.

5 DEVIATIONS AND CORRECTIVE ACTIONS

The setup of the test field was slightly delayed but corrective actions were not necessary as there was still enough time until the project's end to demonstrate a minimum of 6 months outdoor operation.

6 DISSEMINATION AND UPTAKE

6.1 Dissemination activities

Following table shows the dissemination activities related to the results presented in this deliverable.

Table 6.1 *Dissemination activities related with this deliverable*

*Type of activities **	*Title*	*Authors*	*Journal/Conference /Other Event*	*Target Audiences*
OP	WP 7: 10m² outdoor PV-EC test field	M. Müller, W. Zwaygradt, S. Haas,	PECSYS Virtual Workshop, 5th November 2020	Scientific and industrial researchers as well as academics

****Type of activities: OP****=Oral Presentation;* ***PP****=Poster Presentation;* ***P****=Publication.*

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

The results presented here demonstrate that the advanced PEM devices developed at FZJ perform well within the large-scale PV field. The performance is in the same range as when the electrolysers are coupled to the PV devices irradiated with the sun simulator.

Comparison with state of the art is difficult because of different measurement conditions, therefore there is a need for standardized benchmarking protocols. Nevertheless, one recent publication reports on a system installed at King Abdullah University of Science and Technology (KAUST) in Saudi Arabia with one crystalline silicon PV module with a smaller solar collection area of 1.5 m² achieving a maximum solar to hydrogen efficiency of 9.4% when connected to a PEM electrolyser stack [1]. That system achieved a hydrogen production rate of 1.2 (g/h/m²) relative to the solar collection area compared to the 2.3 (g/h/m²) that was achieved with our set-up.

We are not aware of published reports that report testing electrolyser stacks that are directly coupled to commercial scale (2m²) PV modules exposed to a continuous (and not flash) sun simulator. This is therefore, a foundation towards the development of benchmarking tests under controlled conditions similar to the standard test conditions for photovoltaic modules.

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

The implementation of the monitoring system took more time than originally expected because of sizing and settings so that smoother data readings especially of the hydrogen flow rate, could be obtained. The setup of the monitoring system should have been scheduled for months with a significant amount of solar irradiance i.e. earliest in spring and not during the winter to allow calibration of the instruments during conditions with significant hydrogen production rates.

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

The stack concept was developed in WP4 and reported in the associated deliverables. The work reported in this deliverable provides the foundations for other deliverables 7.6 and 7.7 in the project.

[1] Muhammad-Bashir, *et al*. 2020, *Comparison between the performance of high concentrated and nonconcentrated PV-cells for hydrogen production using PEM water electrolyzers*, Solar Energy, 205:461. (Test site KAUST, Saudi Arabia)

7.4 Limitations of the findings

There is still no internationally recognised standard benchmarking protocol and thus comparisons with performance reports from other researchers are difficult. Effects of variation in the spectral distribution of the incident irradiance on the performance of the PV coupled electrolysers was not investigated.

8 CONCLUSIONS AND NEXT STEPS

The objective of this deliverable was to ensure that the 10 m² system was operational by December 2019. The construction of the plant was completed by January 2020 since the PV modules and electrolyser stacks were readily available. However, the commissioning of the process engineering components took more time than initially planned, which led to slight delays. An average solar to hydrogen conversion efficiency of more than 12 % was achieved for a silicon heterojunction module directly coupled to a 21-cell PEM electrolyser stack, which exceeded the set target of 6%. After the successful erection of the plant, the real demonstration operation was now possible from February 2020 onwards allowing the monitoring of the overall system performance that will be reported in deliverable 7.6.

9 DECLARATION BY THE DELIVERABLE LEAD BENEFICIARY

Deliverable 7.5:

☐ 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