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

Project Deliverable Report – D7.4

Title:	**Fabrication of modules for 10 m^2 system**
Work Package	**WP 7**
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EXECUTIVE SUMMARY

The purpose of this deliverable report is to describe the necessary power components for the demonstration direct solar to hydrogen generation plant with 10 m² active solar surface, that has to be built within the PECSYS project. Instead of pursuing a single concept, two different photovoltaic technologies i.e., silicon heterojunction (SHJ) and CuInGaSe (CIGS) were considered. Additionally, PEM electrolyzers, which differed in the use of precious metals (low loading compared to normal catalyst loading) were considered. The 2 m² silicon heterojunction PV modules and 0.74 m² CuInGaSe PV modules manufactured for this purpose can produce 364 W and 107.3 W, respectively, with an incident irradiance of 1000 W when the module temperature is held at 25°C. The 10-cell PEM electrolysr stack and the 21-cell PEM electrolyser stack achieve a maximum electrical power rating of ~170 W and ~373 W (@ 10 A), respectively, at 25°C with the electrical conversion efficiency averaging ~70 %. Thus, the designed power capacity of the PV modules and the electrolysers, under laboratory test conditions, is nominally the same. The next steps in the project are the integration of the components into the demonstration plant so as to investigate how the power matching is affected by fluctuating outdoor weather conditions, which are topics of separate deliverable reports.

TABLE OF CONTENTS

ABBREVIATIONS and ACRONYMS

CA	Consortium Agreement
CCM	Catalyst Coated Membrane
CIGS	CuInGaSe
CNR	Consiglio Nazionale delle Ricerche
DoA	Description of Action
EGP	Enel Green Power (formerly 3SUN)
FZJ	Forschungszentrum Jülich
GA	Grant Agreement
HJT	HeteroJuncTion (term used by EGP to describe their SHJ modules)
PEM	Proton exchange membrane
PV	Photovoltaic
SHJ	Silicon heterojunction solar cells, abbreviation used in the GA
SRAB	Solibro Research AB
UU	Uppsala Universitet
WP	Work Package

1 INTRODUCTION

This report presents an overview of the photovoltaic and electrolysis components that shall be included in the 10 m² demonstrator for solar hydrogen generation in the PECSYS project. As it turned out in the course of the project that an integration of the experimental alkaline electrolysis systems into the photovoltaic modules is not yet possible on a m², advanced PV modules were modified and provided by the manufacturers ENEL and Solibro, which are then combined with proton exchange membrane (PEM) electrolyzers, in cassette design, from Forschungszentrum Jülich GmbH (FZJ).

The electrolysis modules used were designed and produced by the workshops of FZJ. The electrolyzers are a new type of construction, which works with a low precious metal load and a new type of media supply concept (one hose) from the cathode side only. The latter configuration allows hydraulic operation thus also eliminating the use of pumps and reducing the overall system energy consumption. The crystalline silicon heterojunction and CuInGaSe PV modules were provided and modified by ENEL Green Power and by Solibro Research AB, respectively to provide and output power that is compatible with electrolysis cells. Preliminary characterization of the devices under laboratory conditions was necessary to check the power matching between the PV and electrolyser components.

2 DELIVERABLE OBJECTIVE AND RELATED TASKS

Deliverable objective: Fabrication of modules for 10 m² system

The contents of this deliverable are derived from activities performed in two tasks Task 7.3d and task 7.4

2.1 Description of the related task

***Table 1**. Overview of tasks related to deliverable D 7.4*

No.	Task description	Start date	End date
T 7.3d	Cassette design modules for 10 m² system PV modules for 10 m² system	Dec 2017	Dec. 2018
T 7.4	Realization of modules for 10 m² system	Aug 2018	Nov 2019

Task T7.3: Concepts for fabrication of components for 10 m² system (variable; M12-M24)

The implementers of each approach should present their concept for upscaling to the m² size until M24. Based on these concepts, the techno-economic model will be used to select one or more approaches (depending on the available budget) at mid-term review (M30) which will then receive additional funding and which will then be up-scaled. As the technical maturity of the concepts was different and the feasibility of the integrated systems within the project was not possible the only chance to fulfil the ambitious project goals was possible by following the cassette design (Task 7.3d).

***Table 2**. Details of actions under Task 7.3*

Concept	Selection
Task T7.3a: PV-EC modules based on TF-Si solar cells for 10 m² system (FZJ (lead), 3SUN/EGP, HZB; M12-M24) Make cost estimations for techno economic evaluation until Mid-term review, ~month 27 (M27) (contributions EGP / CNR / FZJ), in case this approach will be scaled up, 3Sun	

Concept	Selection
is responsible for providing glass, TCO, silicon solar cells (a-Si:H/µc-Si:H tandem) and rear reflector, FZJ is responsible for laser scribing (P1, P2, P3), HZB is responsible for sealing approach, SRAB can provide large area atomic layer deposition (ALD) FZJ provides large area electrodes and electro-catalysts and membranes.	
Task 7.3b: PV-EC modules based on SHJ solar cells for 10 m² system (HZB (lead), EGP, SRAB; M12-M24) At HZB, SHJ fabrication of up to 6” wafer size is possible. Currently, processes are developed to fabricate one batch of 25 wafers per week (one day each: cleaning and texturing, PECVD, front TCO and rear TCO/metal contact, screen-printing and lamination). In case this approach is scaled up, EGP will provide SHJ cells, if this is not possible due to change in technology road map, HZB can provide SHJ cells. Alternatively, cells could be bought from external sources such as Meyer-Burger. Sealing and interconnection will be made at HZB while FZJ will provide large area electrodes and electro-catalysts and membranes. SRAB can contribute by making large area ALD layers.	
Task 7.3c: PV-EC modules based on CIGS solar cells for 10 m² system (UU (lead), SRAB; M12-M24) A concept for fabrication m² PV-EC modules based on CIGS, as well as the cost estimations for techno economic evaluation will be made by the due date of the mid-term review. SRAB and UU are responsible for all PV-EC module components.	
Task 7.3d: Cassette design modules for 10 m² system (FZJ (lead), CNR, EGP, UU, SRAB; M12-M24) A coating system at the IEK-14 in FZJ, that allows the manufacturing of large-scale electrodes in the m²-scale is used. Individual process modules can be integrated into the existing flexible line coater in order to carry out complex coating and treatment processes in a single cycle. With a coating width of up to 0.5 m and a web speed between of 0.1 and 1 m/min, the facility can implement development tasks using small amounts of material and can fabricate components for prototypes. The housing will be manufactured by external companies. For the assembly the pilot fabrication facilities at the IEK-14 were used. In this pilot fabrication facility, different automated production processes for cell and stack components are available for the further development of fuel cells with a view to commercialization and improved quality.	×

Details of the concepts for each approach were already submitted in deliverable 7.3.

Task T7.4 Realization of modules for 10 m² system (To be defined at Mid-term; M20-M35)

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.

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 3**. Contributions of deliverable D 7.4 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

Task 7.3d: Cassette design modules for 10 m² system (FZJ (lead), CNR, 3SUN/EPG, UU, SRAB; M12-M24)

Within this work package, the components for the construction of the demonstrator were manufactured according to the method of component manufacturing mentioned in subtask 7.3d in the DoA in the GA. Since large-scale production of the integrated modules did not yet make sense due to insufficient reliability, advanced commercial sized PV modules were combined with the PEM systems developed in work package 4 in a cassette design. The following table gives an overview of the components that have been manufactured.

***Table 4**. Overview of components manufactured and related activities for deliverable D7.4*

Item	Explanation
Manufacture of PV component including solar cells and PV module integration, where applicable	• Seven 0.74 m² area CIGS modules from SRAB • Three 2 m² area SHJ/ HJT modules from EGP • Electrolysis integrated PV module area of 100 cm² from UU development
Manufacture of EC component including electrodes, catalyst preparation, casing and sealing	• Production of electrodes, endplates and bipolar plates, systems components (FZJ-IEK-14). • A total of 8 stacks with CCMs for ~100 cells were completed
Packaging and transporting PV panels to FZJ	• SHJ PV module delivery from EGP in Catania, Italy

Item	Explanation
	• CIGS PV module delivery from SRAB in Uppsala Sweden to FZJ
Operation and maintenance (over 6 months)	• Systems pre-characterisation in laboratory conditions in FZJ • Installation at testfield in FZJ and operation for 6 months with online monitoring of hydrogen production

4.1 Silicon heterojunction PV modules from ENEL Green Power

EGP provided 3 silicon heterojunction modules with an active area of 2 m² per module. These modules were manufactured in the conventional production process. The special feature of these modules is the construction which is transparent from both sides, which also allows the use of the reflected diffuse light from the back side (bifacial). Although bifacial modules are also produced by other companies, for modules based on this technology, the combination with "cassette electrolysis modules" is interesting, because of the use diffusive irradiation from the backside to achieve higher efficiencies.

The modules were analyzed and characterized in a sun simulator at IEK-5-FZJ to study their function and determine the maximum power output. The following table shows the values depending on the module temperature. The maximum power output monitored is a bit lower than in the data sheet.

***Table 5**: Performance parameters of ENEL SHJ n-Type PV modules delivered in 2019 determined at FZJ*

PV module temperature, T / °C	PV module efficiency, η / %	Fill factor, FF / %	Open circuit voltage, V_{OC} / V	Short circuit current, I_{SC} / mA	Max power, P_{max} / W
55	16.82	74.31	48.72	9.25	336.4
50	17.06	74.49	49.39	9.23	341.2
45	17.33	74.86	50.05	9.20	346.6
40	17.58	75.15	50.68	9.19	351.6
35	17.78	75.26	51.27	9.17	355.6
30	18.02	75.51	51.91	9.15	360.4
25	18.21	75.62	52.49	9.13	364.2

The variation of the PV solar conversion efficiency as a function of irradiance from a sun simulator is presented in figure 1. The PV conversion efficiency peaks at about 18.3% for 600 W/m² but remains within 10% relative of this value over the range from 400 -1000 W/m² if the module temperature is fixed at 25°C. The sharp drop of efficiency at low irradiance is of concern as this amplifies the issue of hydrogen crossover at low current densities, this is not a problem at high irradiance because of the high gas production which minimises the effect of cross-over.

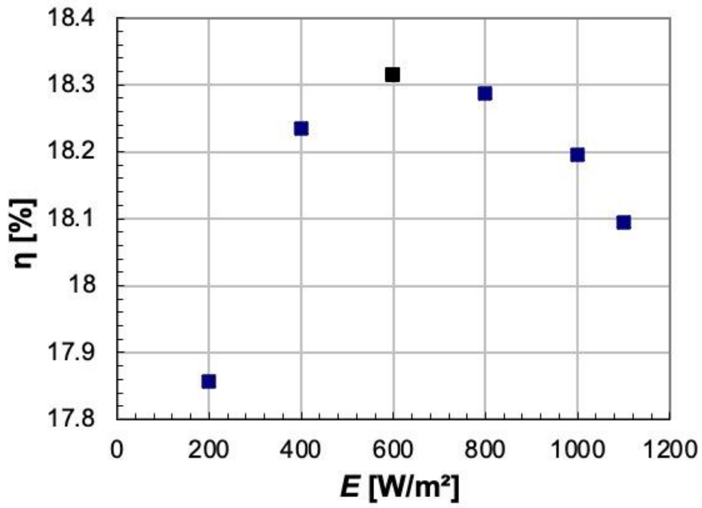

Figure 1. *Variation of the solar conversion efficiency η, of the SHJ n-Type PV modules delivered by EGP in 2019, with incident irradiance E, at a module temperature of 25 °C.*

4.2 CuInGaSe PV modules from Solibro Research AB

SRAB fabricated a 0.74 m^2 CuInGa PV module with a special design for driving electrolyzer for hydrogen generation. Assuming that stacking of electrolyzer is practically limited to 10, the PV module voltage was targeted at 20 V. This is achieved by wiring the module in 3 strings with each string composed of 38 monolithically integrated (using scribes as is typical of thin film PV technology) cell stripes as shown in Figure 2.

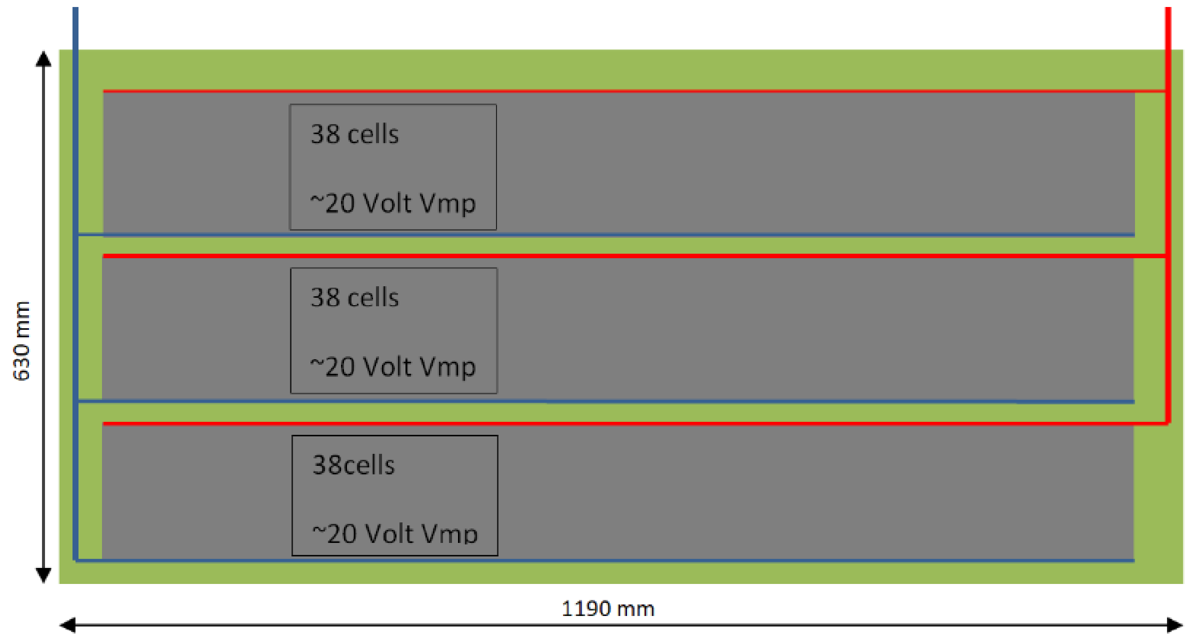

Figure 2. *Cell connection scheme in the CuInGaSe PV module from Solibro Research AB*

The modules were analyzed and characterization in a sun simulator at FZJ to test their function and determine the maximum power output. The following table shows the module parameters depending on the module temperature.

***Table 6**: Performance parameters of CuInGaSe PV modules from SRAB as a function of PV module temperature*

PV module temperature, T / °C	PV module efficiency, η / %	Fill factor, FF / %	Open circuit voltage, V_{OC} / V	Short circuit current, I_{SC} / mA	Max power, P_{max} / W
55	12.99	66.70	25.48	5.83	97.4
50	13.20	66.99	25.79	5.83	99.0
45	13.41	67.30	26.08	5.82	100.6
40	13.64	67.62	26.43	5.82	102.3
35	13.87	67.99	26.76	5.81	104.0
30	14.09	68.25	27.10	5.81	105.7
25	14.30	68.44	27.45	5.80	107.3

The variation of the PV solar conversion efficiency as a function of irradiance is presented in figure 3. Similarly, to the SHJ cells, the peak efficiency is at around 600 W/m². However, the relative drop in efficiency on either side of the peak is somewhat higher. For both technologies. The PV efficiency at a given irradiance reduces with increasing module temperature.

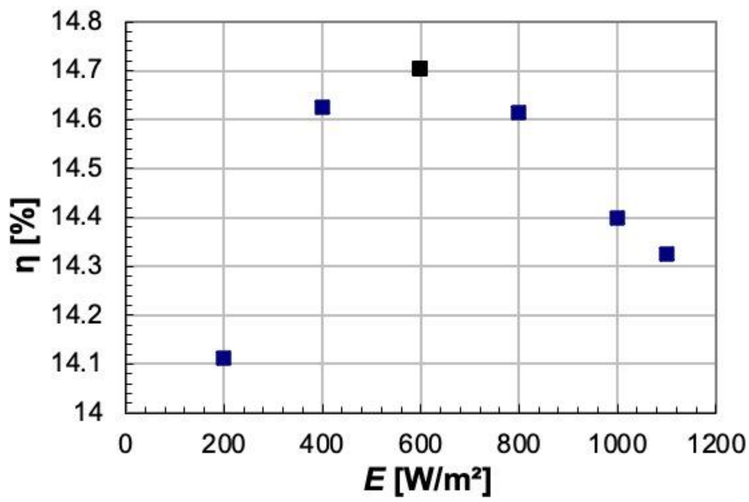

***Figure 3**. Variation of the solar conversion efficiency η, of the CuInGaSe PV modules delivered by SRAB, with incident irradiance E, at a module temperature of 25 °C.*

4.3 Electrolysis Cassette Design

The electrolysis cells developed within work package 4 were produced for the assembly of two different stack types. **Figure 4** shows the cell set up and the different components that are necessary. In total, about one hundred cells were produced and then integrated into eight stacks.

The manufacturing process included the production of the bipolar plates, sealing elements, end plates and clamping elements. The coating of the membranes was carried out on the IEK-14 coating machines. Two types of catalyst coated membranes with different catalyst loadings anode: 0.42

mg_{Ir}/cm^2 (Standard.: 2.4 mg_{Ir}/cm^2); cathode: 0.05 mg_{Pt}/cm^2 (Standard.: 0.8 mg_{Pt}/cm^2). The active geometric cell area is 4.2 cm × 4.2 cm/cell;

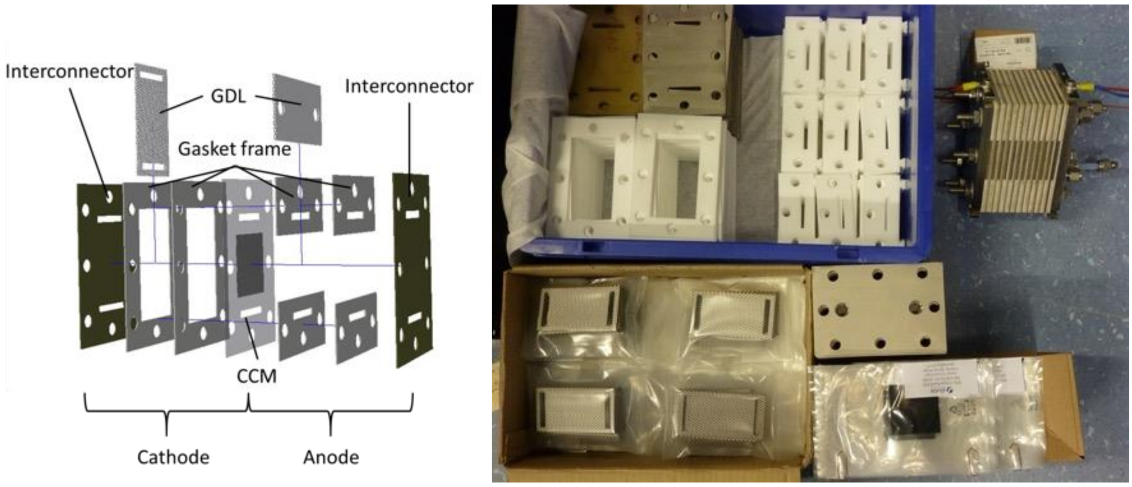

Figure 4. *Components of the electrolysis cells, (left) setup schematic and (right) photograph of components after the production in the workshops of Forschungszentrum Jülich.*

After the production process, the cells were integrated into the stacks shown in **Figure 5**, before integration into the demonstration plant.

Figure 5. *PEM electrolyser stacks that have been produced at Forschungszentrum Jülich GmbH. On the left-hand side are six 10- cell stacks while on the right-hand side, two 21-cell stacks can be seen.*

Performance analysis electrolysis

The electrolyzers developed in the project (cassette design) were characterized in terms of their performance. This characterization was carried out at moderate cell temperature in the range between 20 and 40 °C. Since the operating temperature varies depending on the ambient conditions and the current flow or voltage level, the data in the following table cannot be directly transferred to operation in the demonstrator.

In addition, different electrodes were used in the different setups, which lead to a scattering of the performance data. Therefore, each PV-EC combination is monitored again individually in the demonstrator. The values in table 7 and table 8 give an orientation of which performance values can be expected from the electrolysers in the field test, but they can't be used to study the degradation, therefore the values that will be measured in the demonstrator have to be considered.

Table 7. *Characteristics of the electrolysis cassette design modules with 21 cells at room temperature ~ 25°C without heating*

Current, I / A	Module Voltage, U_M / V	Power, P / W	Cell voltage, U_C / V	Efficiency, η / %
0	~30	0	1.430	0
0.1	31.5	3.15	1.500	83
3.4	35	119	1.667	75
8.1	36.65	297	1.745	72
10	37.3	373.4	1.778	70

The 21-cell stack achieves a power of 373 W while the 10-cell stack achieves 178 W with a power ratio of 2.1 indicating a linear increase in input power capacity as theoretically expected. The power rating of the 21-stack cell is close to the maximum power point of the 2 m² SHJ PV module from Enel Green Power. Two parallel connected 0.74 m² CIGS PV modules from Solibro Research AB could provide a power input of ~ 200 W with sufficient voltage to run the 10-cell stack. The actual power matching of the PV and electrolyser components however depends on the prevailing irradiance and ambient temperature conditions as well as the temperature of the electrolyser stack which is operated without active temperature control. This behavior of the coupled systems shall be investigated in activities that shall be reported in deliverables D7.6 and D 7.7.

Table 8. *Comparative values of the cassette design with 10 cells (calculated by cell voltage) at room temperature ~ 25°C without active heating*

Current, I / A	Module Voltage, U_M / V	Power, P / W	Cell voltage, U_C / V	Efficiency, η / %
0	14.3	0	1.430	0
0.1	15	1.5	1.500	83
3.4	16.7	56.8	1.667	75
8.1	17.5	141.8	1.745	72
10	17.8	177.8	1.778	70

5 DEVIATIONS AND CORRECTIVE ACTIONS

Since the production of scaled integrated electrolysis modules covering an area of 1 m², yet 10 m² were required, proved to be impossible during the project period, commercial sized PV modules with separate electrolysers (cassette design) were developed from work package 4. The silicon heterojunction and CuInGaSe PV modules were produced by the project partners Enel Green Power and Solibro Research, respectively. The PEM electrolyzers were manufactured and assembled at the Research Center Jülich, according to **subtask 7.3d** in the DoA.

6 DISSEMINATION AND UPTAKE

6.1 Dissemination activities

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

Table 9. *Dissemination activities related with this deliverable*

*Type of activities **	*Title*	*Authors*	*Journal/Conference /Other Event*	*Target Audiences*
P	Characteristics of a new polymer electrolyte electrolysis technique with only cathodic media supply coupled to a photovoltaic panel	M. Müller, W. Zwaygardt, E. Rauls, M. Hehemann, S. Haas,L. Stolt, H. Janssen and M. Carmo	Energies2019,12, 4150; doi:10.3390/en12214150	Electrolyser research community in both academic and research settings

****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

A PEM stack system in this configuration with fluid field on the cathode side has never been built in this size before. The electrolysis is an advanced development of the PEM technology, which has not yet been directly coupled with photovoltaics on a large scale. Additionally, the monolithic integration of three strings in a single CuInGa PV module to provide an output voltage tailored for a specific number of electrolyser cells in a stack.

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

Integration of electrolysis into the PV-panels is difficult. Especially the sealing and corrosion are difficult to handle in the flat setup.

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

The developed concepts were analyzed in the other work packages. In particular, the implemented electrolysis concept (cassette design) was developed in work package 4. In general, the development has benefited from synergies with a large number of electrolysis projects in IEK-14.

7.4 Limitations of the findings

The 10 m² system components for electrolysers focus on PEM electrolysis, because of a lack of technical feasibility of the integrated systems. The hydrogen production of the PEM electrolysers was not tested at this stage.

8 CONCLUSIONS AND NEXT STEPS

The components necessary to construct the demonstration plant have been designed and assembled and are now ready for outdoor operation. Preliminary characterization tests were done to estimate the power capacity of the components. The 2 m² silicon heterojunction PV modules and 0.74 m² CuInGaSe PV modules can produce 364 W and 107.3 W respectively, with an incident irradiance of 1000 W when the module temperature is held at 25°C. The 10-cell stack and the 21-cell stack has a maximum electrical power rating of ~170 W and ~373 W (@ 10 A) at these conditions, the electrical conversion efficiency is ~70 % at 25°C. The power capacity of the PV modules and the electrolysers, for laboratory test conditions, is nominally the same and it remains to be seen how the power matching is affected by prevailing weather conditions. The next steps in the project are the integration of the components into the demonstration plant. This was planned for the start of 2020 and has since been executed and will be reported in deliverable reports 7.5 to 7.7.

9 DECLARATION BY THE DELIVERABLE LEAD BENEFICIARY

Deliverable 7.4:

- ☐ 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