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

Project Deliverable Report – D7.6

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EXECUTIVE SUMMARY

The present deliverable contributes towards the main objective of WP7 that is the scale up of the selected device concept to the module size and the actual realization and testing of the 10 m² system including BoP and gas handling. A demonstrator with more than 10 m² active PV area was set up and the operation of the demonstrator during the year will be described.

The different tests can be divided into the analysis of a direct coupled PV and advanced PEM electrolysis system and on the other hand, an integrated system (PV and electrolysis in one housing). The test of the direct coupled system was performed during the whole year and the results can be divided into the verification of hydrogen production monitoring measurements, at the implementation phase in the first quarter of 2020. After that the dynamic hydrogen production and the systems stability was monitored. With all these measurements and after summarizing the results the continuous operation and reliability can be evaluated.

The integrated system was set up in the demonstrator in November 2020, thus the number of measured data is lower and the outdoor conditions (low solar radiation) to prove high yields, for example, are rather unfavourable.

During the operation, the hydrogen production was monitored by a mass flow meter and by measuring the current in all electrolysis modules. Additionally, the voltage and the temperature were measured and the solar radiation was also monitored. These data were then used to determine the solar to hydrogen efficiency. For the whole demonstrator, with different PV-EC configurations, the monitored efficiency is over the whole year in the range of 10 %. The whole demonstrator system was operated stable (one electrolysis stack with low catalyst loading failed) over the year and the time pattern of hydrogen generation immediately followed that of the solar radiation.

Due to lack of time, more detailed research in terms of systems reliability was not done and thus is necessary in the future. In addition, a more detailed investigation of how the different technologies behave on the long-term is necessary. Publication of results generated from the outdoor monitoring of the demonstration shall be presented in several conferences and at least one peer-reviewed publication of the results is planned.

TABLE OF CONTENTS

ABBREVIATIONS and ACRONYMS

BoP	Balance of Plant
CA	Consortium Agreement
CCM	Catalyst coated membrane
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)
IEK	Institut für Energie- und Klimaforschung
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
SHJ	Silicon heterojunction
SRAB	Solibro Research AB
TRL	Technology Readiness Level
WP	Work Package

1 INTRODUCTION

The overall objective of the PECSYS project was to demonstrate a system for the solar driven electrochemical hydrogen generation with an area >10 m². The system was to be designed in such a way that neither solar concentration nor solar tracking would be necessary and therefore the investment costs will be low. It was expected to produce more than 10 Kg of hydrogen over a six month-period of operation. The efficiency of the system was targeted to be >6% and was expected to have degraded by less than 10% relative after the six-month period.

This deliverable report presents the results of field testing of the 10 m² direct solar to hydrogen conversion demonstrator during under outdoor conditions from January 2020 until December 2020 at Forschungszentrum Jülich (50°55’ N, 6° 21’ E). The demonstrator consisted of different configurations of photovoltaic (PV) and electrolysis modules whose performance behaviour under variable outdoor conditions was studied. In January 2020, several commercial sized CuInGaSe or silicon heterojunction PV modules, each directly coupled to a PEM electrolyser stack, were installed on the rooftop test field. The operation and systematic monitoring, by Forschungszentrum Jülich (FZJ-IEK-14), of the performance started in April 2020. During the last months of the project (November 2020), a laboratory scale CuInGaSe PV module that was thermally integrated onto an alkaline electrolyser, from University Uppsala was also integrated into the demonstrator and its performance was monitored.

2 DELIVERABLE OBJECTIVE AND RELATED TASKS

The present deliverable contributes towards the main objective of WP7, that is, the scale up of the selected device concept to the module size and the actual realization and testing of the 10 m² system including BoP and gas handling.

The objective of the current deliverable is to present a final report on the system performance and on Milestone MS5. The activities reported in this deliverable are mainly related to Task T7.5 Realisation of 10 m^2 system and testing led by FZJ.

2.1 Description of the related task

No.	Task description	Start date	End date
T 7.5	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 systems efficiency. The FZJ shall also carry out maintenance of the system in that time.	Oct 2019 M34	Dec 2020 M48

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	×	
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 Direct coupled PV & advanced PEM systems

The following figure gives an overview of the test facility. All results shown in the following were achieved with the system configuration shown in Figure 1. Small and larger cuboids represent 10- cell and 21- cell electrolyser stacks respectively with low (0.42mg_{Ir}/cm² and 0.05 mg_{Pt}/cm²) or high (2.4 mg_{Ir}/cm² and 0.8 mg_{Pt}/cm²) catalyst loading. A more detailed representation of the setup can also be found in the Deliverable Report D7.5.

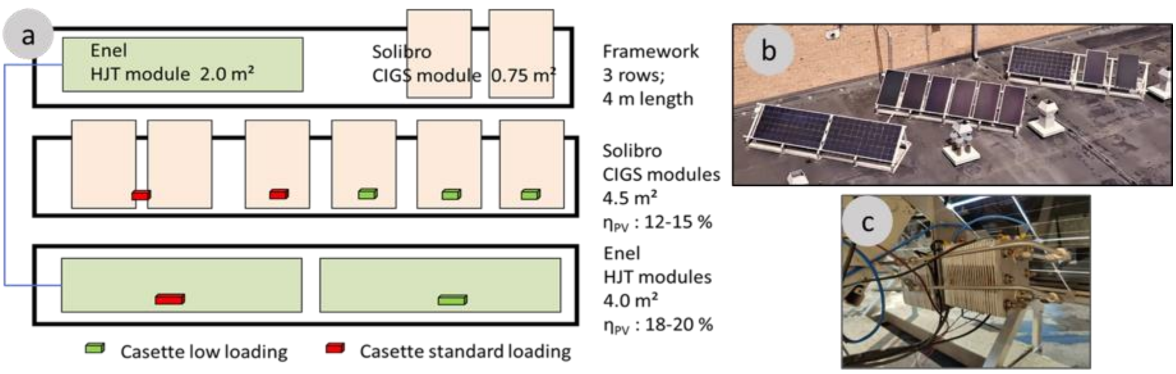

Figure 1. *(a) Schematic showing the different PV module + electrolyser (EC) sets. (b) Aerial view of the final setup of the 10 m² demonstrator plant, photographed in July 2020. The two modules on the top right-hand side are not connected to electrolysers. (c) Photograph showing the PEM electrolyser directly mounted onto the back of one the silicon heterojunction (HJT) PV modules PV module in the so-called cassette design.*

4.1.1 Verification of hydrogen production monitoring measurements

The first tests with the system started in January 2020 and unsupervised operation and data monitoring started in April 2020 when the required instrumentation had been commissioned. The hydrogen production rate was monitored using a mass flow meter and the electrolyser current was simultaneously measured in time synchrony with the solar irradiance monitoring. As can be seen in Figure 2, the hydrogen flow calculated by the Faraday law from the current of seven electrolyser stacks (each with 10 or 21 cells per stack) coupled to a 8.25 m² PV module array correlated very well with the measured mass flow indicating that, the hydrogen crossover in the measured power range is negligible. This is in good correlation with measurements of other PEM electrolysis devices.

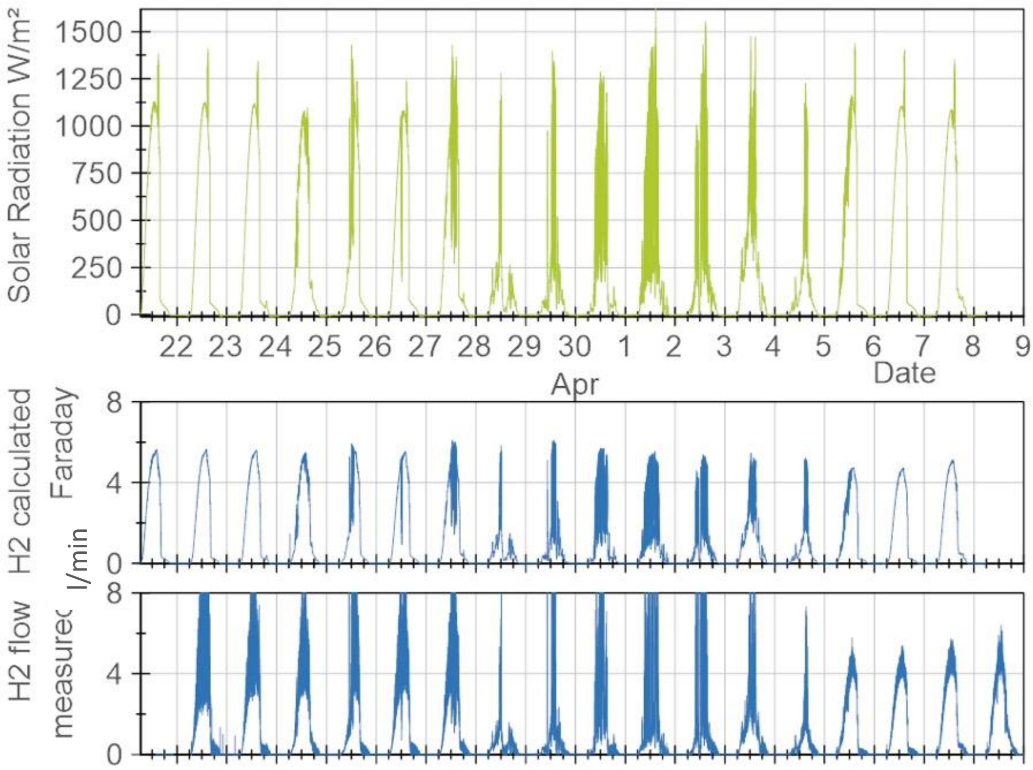

Figure 2. *Measured solar radiation, hydrogen production calculated from measured electrolyser currents by Faradaic law and measured hydrogen flow [l/min] for operation between 21st April to 9th May 2020 with 8.25 m² PV total area installed. One additional 2 m² SHJ PV panel was installed later.*

4.1.2 Dynamic hydrogen production and stability

The hydrogen production rate of an electrolyser that is directly coupled to a photovoltaic module increases with the irradiance (since photocurrent is directly proportional to irradiance). However, the hydrogen production rate is also dependent on the degree to which the decrease in PV output voltage at elevated ambient temperature is compensated by the reduced overpotential of the electrolyser. During operation, specific characteristic diurnal weather patterns that were expected to affect the operation differently could be identified as shown in **Figure 3** . The respective characteristic measured performance values for the respective patterns are shown in Figures 4-7. These values are used for the validation of the simulations for the techno-economic analysis performed at HZB and shall also be published in an article.

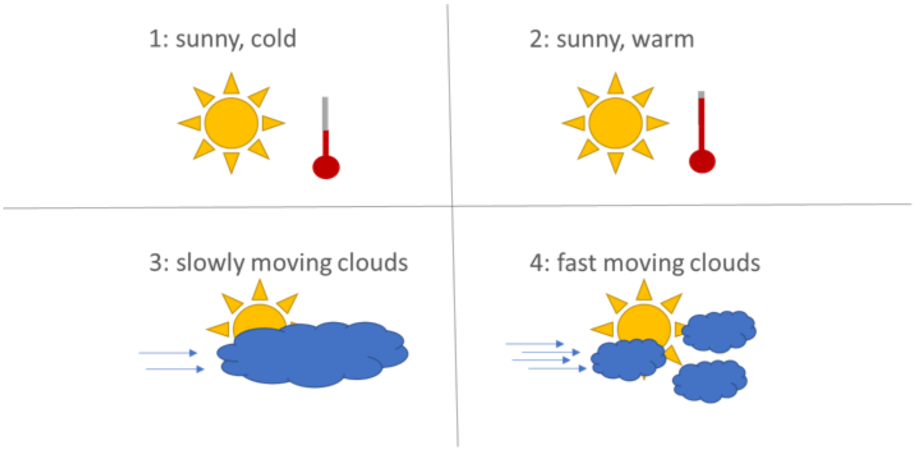

Figure 3: *Different characteristics of climatic conditions that determine the diurnal H_2 generation pattern*

On a sunny cold day, the maximum irradiance approached 1,000 W/m² while the maximum ambient temperature was less than 25 °C (Figure 4). These conditions are close to ideal for the operation of PV modules which favour high irradiance but moderate ambient temperature. The current pattern closely followed that of the irradiance and slightly exceeded ~ 8 A for a period of one hour while the voltage peaked early just after 10:00 at 34 V and steadily reduced. The abrupt drop in solar irradiance at around 16:00 is caused by shadowing by the wall of the experimental hall this is more strongly reflected in the electrolyser current than for the voltage.

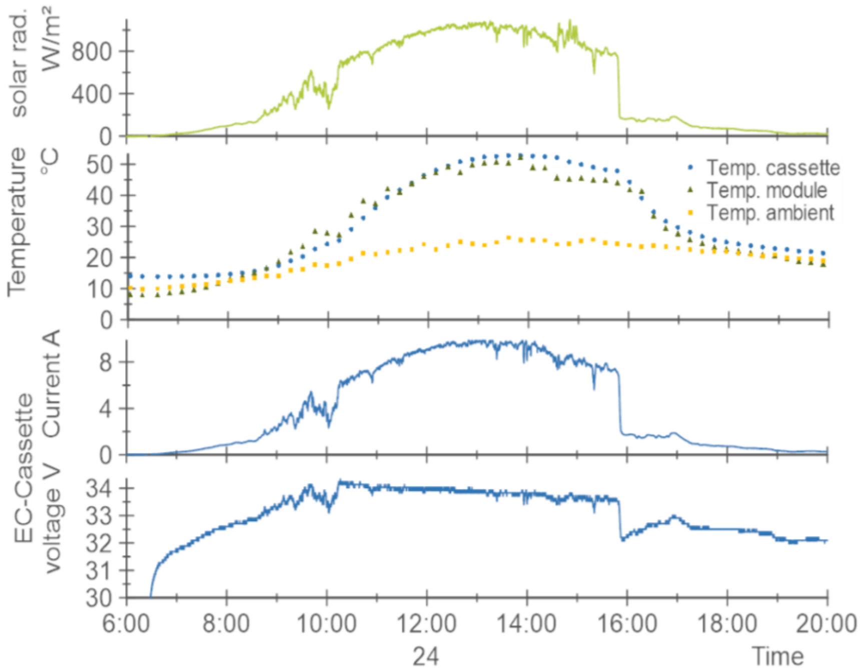

Figure 4. *Sunny cold day: diurnal variation of irradiance, temperature and electrical power reference values for operation of one HJT PV module from EGP directly coupled to a 21-cell PEM electrolyser stack (24th April 2020).*

On a sunny warm day, the maximum irradiance remained below 1,000 W/m² while the maximum ambient temperature approached 35°C. The maximum current closely followed the variation in incident irradiance slightly exceeded ~ 15 A (two HJT PV modules from ENEL coupled to one 21-cell electrolysis module). On the other hand, the electrolyser voltage followed the device temperature evolution peaking at an earlier point of the day and remained at a value of just over 38 V for nearly seven hours. In this case, a higher cassette voltage at around 38 V is needed to drive a maximum of

15 A as for the sunny cold day. The higher voltage is affected by the higher power density that was achieved in the electrolyser under these conditions.

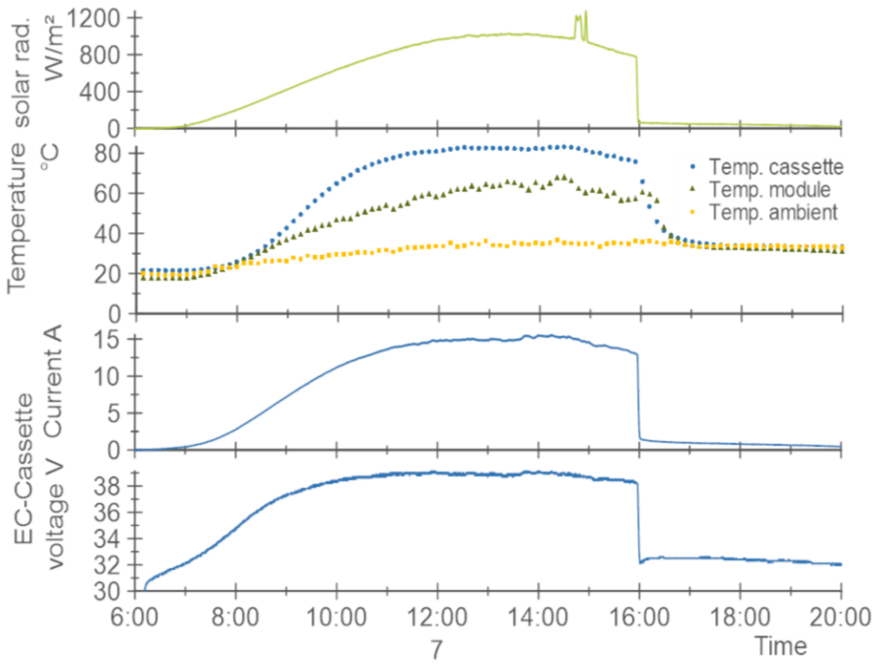

Figure 5. *Sunny warm day: diurnal variation of irradiance, temperature and electrical power reference values for operation of two HJT PV modules from ENEL directly coupled to a 21-cell PEM electrolyser stack (7th August 2020).*

In the above two cases, it can be seen that although the pattern of the voltage varied with that of the cassette temperature, the current was unaffected and followed the pattern of the irradiance.

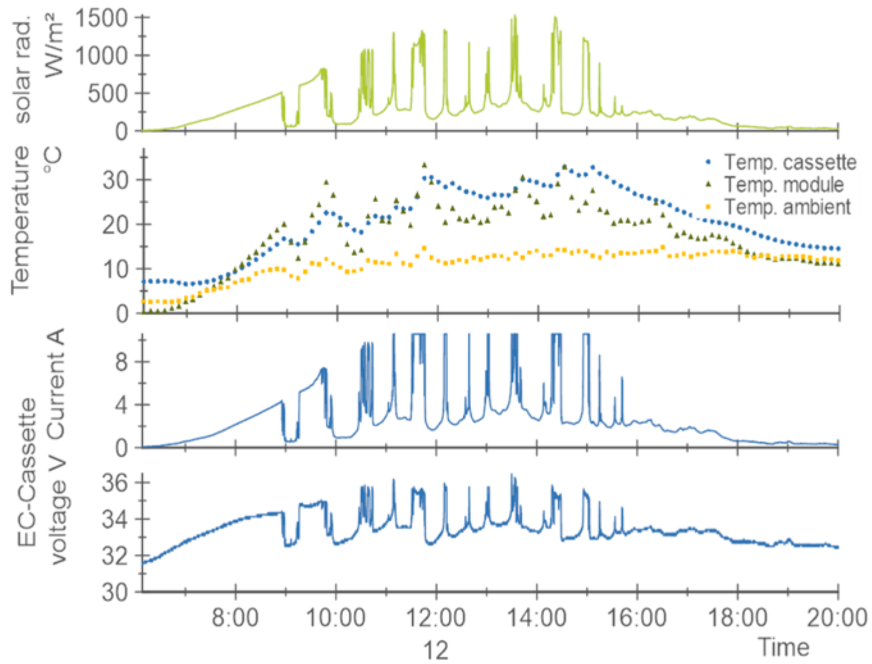

Figure 6. *Slowly moving clouds: diurnal variation of irradiance, temperature and electrical power reference values of one HJT PV module from ENEL directly coupled to a 21-cell PEM electrolyser stack (12th May 2020).*

Windy conditions that cause intermittent shadowing due to significant cloud movement, generate fluctuations in the incident solar irradiance and provide an opportunity to investigate the dynamic response and stability of the system. Figures 6 and 7, show the performance of the system in response to fluctuations caused by slow- and fast- moving clouds, respectively.

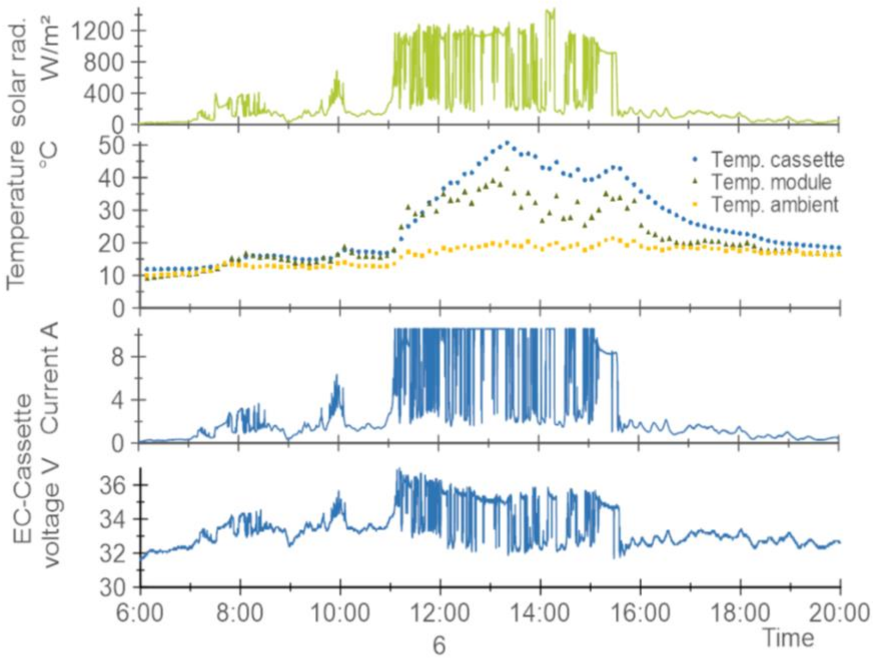

***Figure 7**. Fast moving clouds irradiance, temperature and electrical power reference values for operation of a xxx PV module directly coupled to a 21-cell PEM electrolyser (6th June 2020).*

Different to the clear sunny days, the patterns of both the electrolyser current and voltage closely follow the fluctuations in the irradiance. The response of the electrolyser temperature is damped because of the significant thermal mass of the stack. The peak current was cut-off at 10 A by a limitation of the measurement instrument. The higher maximum current resulting from highly fluctuating irradiance compared to days without fluctuations, may be a result of better mass transport, whereby momentary reduction in power results in bubbles, formed by previously produced gases being swept away, leaving behind a larger surface area on the electrodes for reaction.

In summary, it can be stated that the direct coupling of the PV and electrolysis systems works reliably together under all the conditions presented here and no failures were observed under certain conditions. The patterns that have been worked out can now be used for the evaluation of the large amounts of data. Thus, by assigning them to the four characteristic types presented here, subsequent evaluation can be simplified. This evaluation will take place in the coming months and the results will then be published in scientific journals. Further investigations must now show whether possibly the increased cell temperatures (sunny-warm) or the fast load changes (fast cloud movement) promote the degradation of the electrochemical cells. By clustering the measurement data into the groups mentioned, the evaluation should be facilitated.

4.1.3 Continuous operation and reliability

Figure 8 presents an overview of the diurnal hydrogen flow rate monitored by a gas flowmeter over the operation time. It can be seen that there was a more or less random distribution of days with few or many load cycles.

During the first days of measurements, strong fluctuations in hydrogen production were measured. These were caused by the multiphase flow and are difficult to interpret. Therefore, the pressure in the cathode circuit was slightly increased on 5th May 2020 (see **Error! Reference source not found.**2). This led to a much more uniform gas discharge without sharp ripples we observed in the previous measurements affected by the discrete gas separation from two phase flow in the pipes. Figure 8 confirms that the system was still able to produce significant amounts of hydrogen even during the autumn and winter months of October and November.

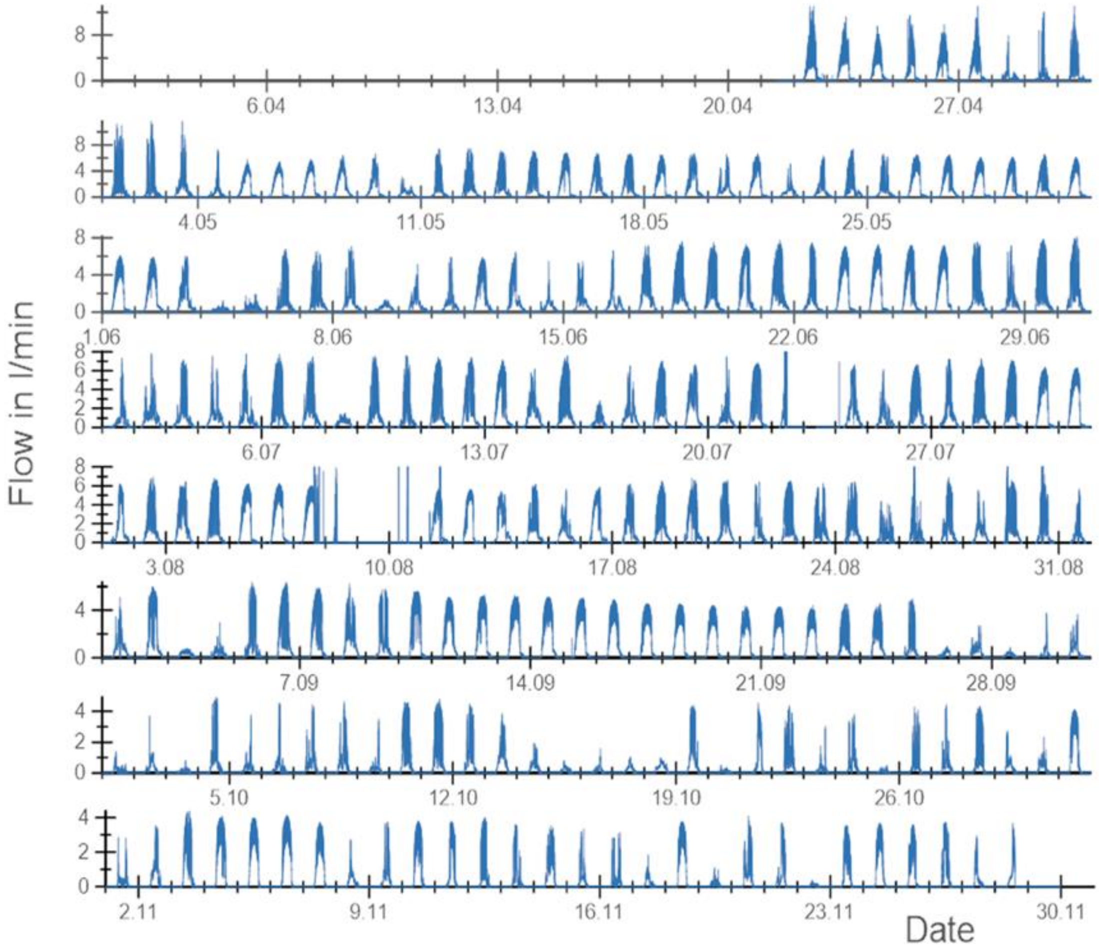

Figure 8. *Daily variation of hydrogen generation during the operation in outdoor conditions in Jülich, Germany for the period from April to November 2020 measured in the whole demonstrator.*

An important goal of the project was to determine both the hydrogen energy yield and the efficiency of the demonstrator. Therefore, both the solar irradiation on the plant and the hydrogen produced were measured during the entire operating period. The energy stored in the produced hydrogen was determined using the lower heating value of hydrogen (LHV 3 kWh/m³) as this is the common reference value in technical discussions for energy yield. If the upper heating value had been used, the storage and efficiency values would be 1.18 times higher. The cumulated incident solar energy and the energy stored in hydrogen were plotted as a function of time in **Figure 9**. The increasing steepness of the curve corresponds with both an increasing amount of incident solar energy and of the rate of hydrogen production. As expected, during the summer months, the hydrogen production was slightly higher than in the rest of the year, because of the higher solar intensity.

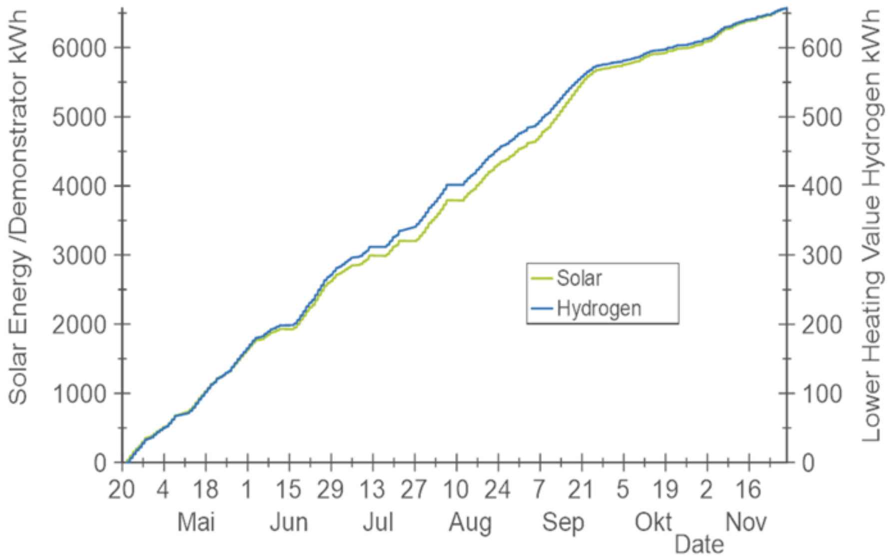

Figure 9. *Time evolution of the incident solar energy and stored energy (hydrogen lower heating value basis) over the operation period from 20th April to 2nd November 2020 of the entire 10 m² direct solar hydrogen generation demonstrator.*

The resultant plot of the cumulative volume of hydrogen produced is given in **Error! Reference source not found.**. From these data, the Solar to Hydrogen (StH) efficiency can be calculated. A slight increase during the summer months can be observed, which is probably caused by the increased ambient temperatures and thereby resulting higher electrolysis operating temperatures and increased electrolysis power densities.

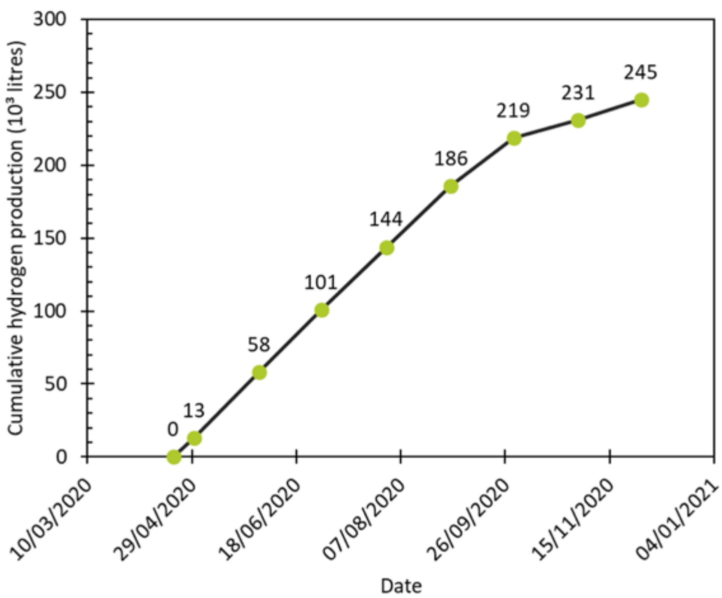

Figure 10. *Cumulative volume of hydrogen generated over operating duration from 20th April to 2nd November 2020 of the entire 10 m² direct solar hydrogen generation demonstrator. The cumulative hydrogen yield from this period was 735kWh.*

From these data, the Solar to Hydrogen (StH) efficiency can be calculated by multiplying the hydrogen production rate and the LHV. This results in the energy stored in the hydrogen, which in turn is divided by the radiation energy of the sun. The energy consumption for the monitoring instrumentation is not considered.

Figure 11 shows the evolution of the solar to hydrogen efficiency over the same period. The system operated continuously with a solar to hydrogen efficiency of ~ 10%. In D7.4 and 7.5, we showed an StH efficiency for selected HJT/PEM above 10 %, here we show average values for the entire system with two types of PV modules (max. efficiency 18 % ENEL SHJ n-Type PV and 14 % CuInGaSe PV). A slight increase during the summer months can be observed, which is probably caused by the increased ambient temperatures and thereby resulting higher electrolyser cell temperatures and power densities so that the configuration is closer to the maximum power point of the PV. The fall in efficiency during the second half of September 2020 was caused by a defect in one electrolyser stack with low catalyst loading. The cause of the degradation has yet to be clarified. During dismantling, traces of corrosion were discovered and more in-depth analyses is necessary to clarify the cause and how such effects can be avoided in the future. Nevertheless, the effective StH efficiency of the remaining PV+ electrolyser sets remained above 10% (from October to November 2020 in Figure 11).

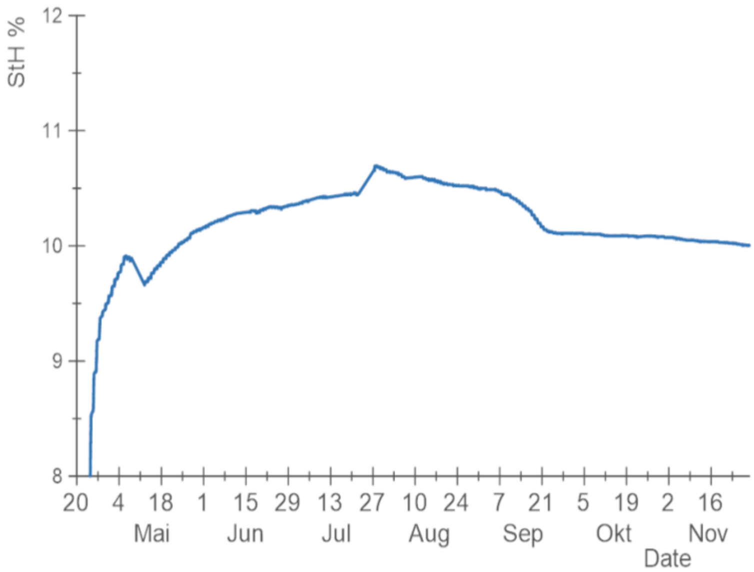

Figure 11. *Solar to hydrogen efficiency over the operation time from April to November 2020 of the entire 10 m² demonstrator plant.*

Since, load cycling can accelerate the dissolution and loss of catalysts from the electrodes in the electrolyser it is also important to check if this may have caused the failure. We extracted the frequency of cycling (with load cycles identified by changes in the electrolyser voltage) per day for the period from 20th April to 10th August and plotted as shown in Figure 12. It can be seen that although the electrolyser was cumulatively exposed to several thousand operating cycles in that time period, the corresponding STH efficiency was maintained close to 10% (compare with Figure 11). Thus, load cycling is unlikely to be the cause of the sudden failure shown in September 2020 but deeper analysis is necessary.

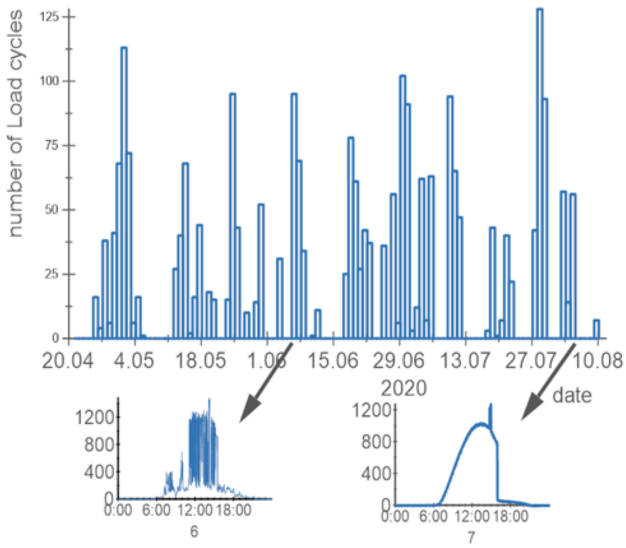

Figure 12. *The effect of fluctuations in incident irradiance on the dynamic operation (quantified by number of load cycles per day) of the PEM electrolysers driven by the photovoltaic modules.*

The load cycles refer to all stacks equally, which is why "only" the solar irradiation is shown here and not resolved to show individual stack voltages. With the stack voltages, the largest voltage jumps would probably be seen for the 21 cell stacks. A load jump event was defined by how often the solar power increased by at least 50 % within seconds.

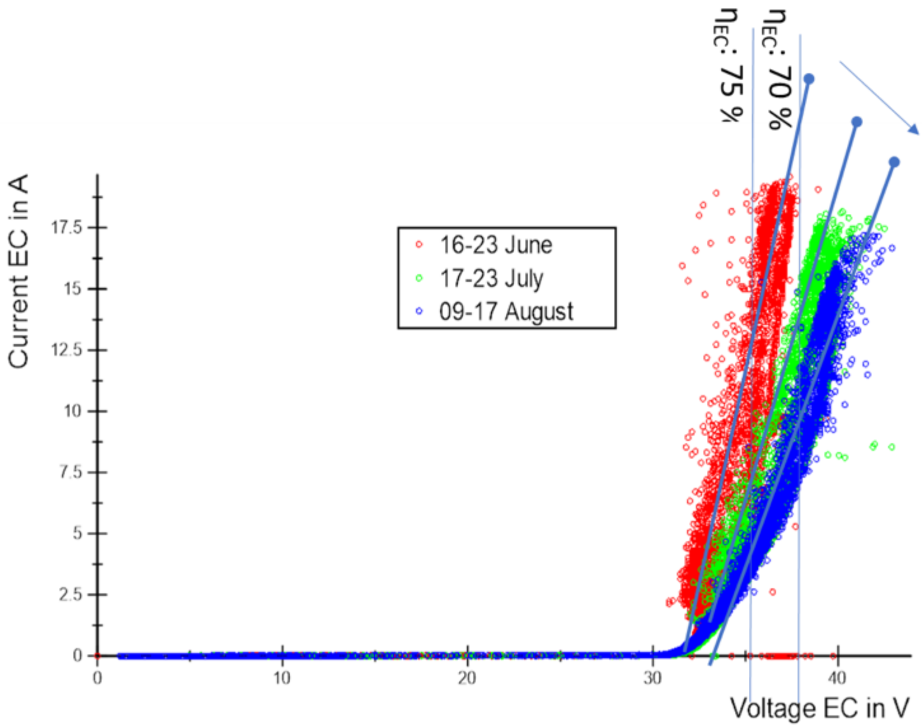

Figure 13*. Degradation of the a 21-cell stack with standard loading electrolysis cells that remained in service (directly connected to two HJT PV modules in parallel) up to and after the end of the project.*

Nevertheless, a closer look at the electrolyser characteristics reveals that a slight gradual degradation of the electrolyzers could be observed during the entire operating phase. This can be seen from the characteristic curves (Figure 13) extracted from the measurement data of a 21-cell stack with standard loading, that was coupled to two HJT PV modules in parallel. The current-voltage curves became flatter (less steep) and the intercept of the slope with the voltage axis shifted to higher potentials with time, indicating an increase in the internal resistance and a decrease in catalytic activity, respectively. This means that given the same PV module power output, a higher applied voltage is required to maintain the same production rate of hydrogen than in earlier months.

Additionally, during the autumn and winter months, the freezing of the stacks, which was already investigated in work package 4, could also be observed. After thawing, the systems were operational again as was also previously shown in separate tests[1]. One problem that can occur after such operating conditions is that the photovoltaic cell delivers power to the frozen electrolysis cell and this leads to degradation of the electrodes. It is possible that future systems should be equipped with a circuit breaker that separates the electrolyser from the PV cell at temperatures near freezing point.

Figure 14. *Frozen electrolyser stack during winter operation (30th November 2020).*

4.2 Integrated system from UU

In November 2020, a smaller laboratory scale prototype with a higher degree of component integration was also added the demonstration plant during the measurement campaign. This prototype consisted of a CuInGaSe PV module that was thermally integrated with an alkaline electrolyser from Uppsala University[2]. The PV module had an aperture area of 100 cm² with an active area of 80 cm² while the electrolyser electrodes had a geometric area of 100 cm². **Figure 15** shows how the module was integrated into the test field. The media (1.0 M KOH electrolyte) supply fed by two pumps, was installed behind the module. The hydrogen production was monitored with a mass flow sensor in time synchrony with the incident solar radiation (see **Figure 16**).

[1] M. Müller, W. Zwaygardt, E. Rauls, M. Hehemann, S. Haas, L. Stolt, H. Janssen, M. Carmo, (2019). *Energies*, 12(21): 4150.

[2] I. B. Pehlivan, J. Oscarsson, Z. Qiu, L. Stolt, M. Edoff, and T. Edvinsson. (2021). *iScience*, 24: 101910.

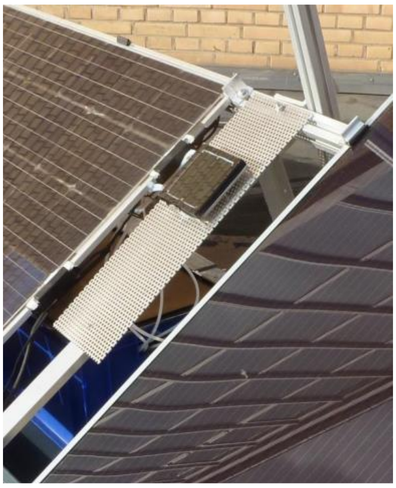

Figure 15: Installation of the integrated CuInGaSe -alkaline electrolyser module into the demonstator test field.

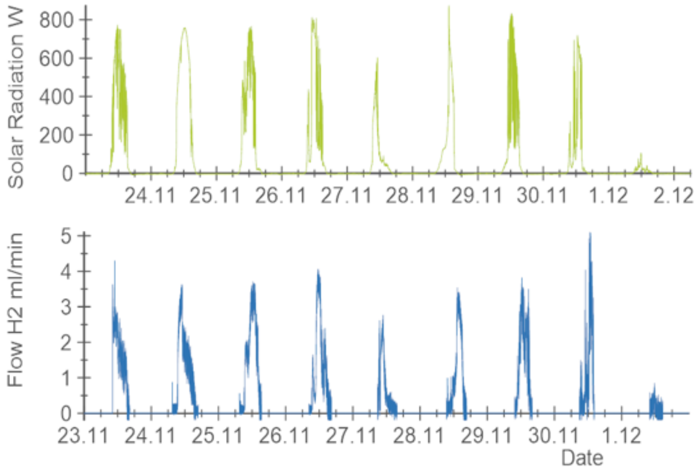

***Figure 16:** Solar radiation and hydrogen generation in the CuInGaSe photovoltaic integrated alkaline electrolyser showing operation from 23rd November to 2nd December 2020.*

It can be seen that the hydrogen production rate closely followed that evolution of the solar radiation. The solar to hydrogen efficiency was calculated using the measured hydrogen flow and using both the active area of the PV cell around 82.32 cm² and the aperture area of the device of around 100 cm² (see **Table 1**). The average daily solar to hydrogen efficiency varied from day to day because of the different radiation and the different temporal behavior of clouds passing by.

***Table 1**: Solar to hydrogen (StH) efficiency, calculated with 100 cm² and 82.32 cm² as reference area*

Date	StH_100cm²	StH_82,32cm²
23.11.2020	6.48	7.87
24.11.2020	5.63	6.84
25.11.2020	8.31	10.08
26.11.2020	8.24	10.02
27.11.2020	7.87	9.56
28.11.2020	8.75	10.63
29.11.2020	8.15	9.90
30.11.2020	9.35	11.36
1.12.2020	6.20	7.50
2.12.2020		

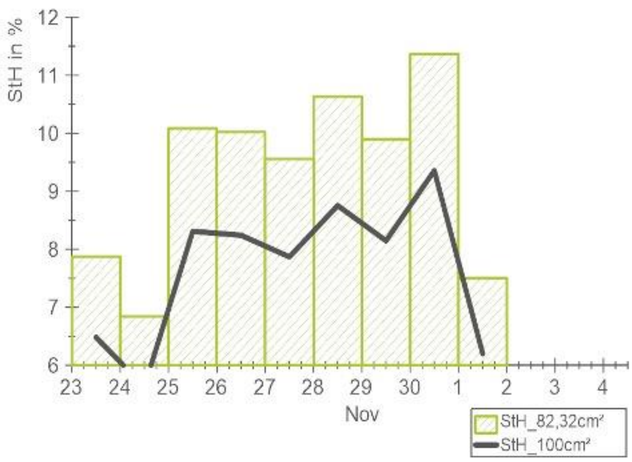

***Figure 17:** Solar to hydrogen (StH) efficiency in UU integrated system during November 2020.*

Since the module could only be integrated into the plant relatively late, data is available only for operation at low ambient temperatures. Figure 18 shows the diurnal variation of weather conditions and the hydrogen flow rate on a typical winter day. The hydrogen flow rate pattern still closely follows that of the incident solar radiation despite the close-to-freezing ambient temperatures. These results also illustrate an advantage of the alkaline electrolysis whereby the low freezing point of the electrolyte allows hydrogen production even for ambient temperatures close to 0°C. Therefore, ice formation is less likely to adversely affect the operation in the winter months unlike PEM electrolysers operating with pure water.

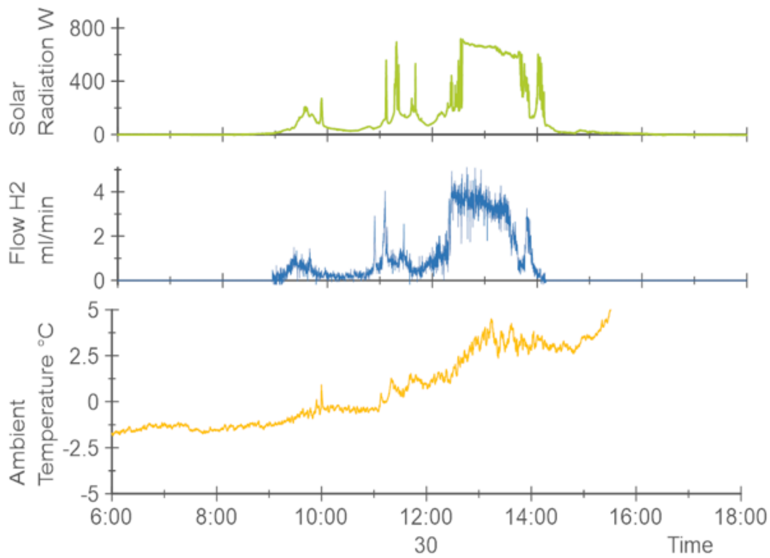

Figure 18: *Diurnal variation of solar radiation and ambient temperature and the resultant hydrogen flow rate illustrating low temperature operation of the CIGS integrated alkaline electrolysis prototype on 30th November 2020.*

It should be noted that the gas volumes generated with this setup are relatively small due to the small solar collection area and therefore, the analysis of the gas composition has a significant uncertainty. Initially, a rather high oxygen content of around 10 % was measured in the hydrogen gas. Gas chromatographic analysis was then used to examine the gas components in more detail and in addition to oxygen, nitrogen was also found, so there was probably still air in the system (maybe affected by a small leakage). If the amount of oxygen is corrected via the nitrogen content, an oxygen content of around 0.3 % remains in the hydrogen. This is a value that is tolerable from a safety point of view and does not lead to any significant losses in efficiency but would nevertheless need to be reduced in future designs.

5 DEVIATIONS AND CORRECTIVE ACTIONS

The thermally integrated photovoltaic-electrolysers could not be scaled up to ~m² scale in time for implementation in the demonstrator test field. To compensate, conventional systems consisting of commercial PV modules directly coupled to PEM electrolyser stacks with a number of novelties and variations were studied and compared namely:

(i) the effect of **reduced platinum group catalyst loading** (75 % and 94 % reduction in Ir and Pt, respectively) in the PEM electrolyser on energy conversion performance and durability under fluctuating operating and weather conditions. Although one of the four installed such electrolysers failed, it is not clear if the failure is due to low catalyst loading or other factors.

(ii) the effect of **cathode only water feed of the PEM electrolyser** on the energy conversion performance

(iii) a comparison of **coupling different photovoltaic technologies to PEM electrolyser stacks** under identical outdoor weather conditions

The demonstrator system design did not include storage of the generated hydrogen because the amount of hydrogen produced was too small to justify the economic outlay in a safe storage system. Since the demonstrator was located on a rooftop with restricted access to the public, it was safe enough to release the generated hydrogen gas into the environment after the mass flow controller measurements.

6 DISSEMINATION AND UPTAKE

6.1 Dissemination activities

A short video describing and showing the demonstration in action was made and published on the PECSYS website and posted on YouTube via the HZB YouTube channel[3]. Photographs of the demonstrator were used for information on the PECSYS website and for other communication tools such as the brochure and the announcement of the project workshop. The results of this demonstrator were also presented at the PECSYS project workshop held on 5th November 2020. Publication of results generated from the outdoor monitoring of the demonstration shall be presented in several conferences and at least one peer-reviewed publication of the results is planned.

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 Evaluation of demonstrator against key performance indicators

Different key performance indicators were used to measure the success of the demonstrator and were derived from the project call, the project's own targets as well as from the TRUST collection exercise of the FCHJU. Although, the activities in this deliverable describe a system prototype demonstration in operational environment which exemplifies TRL 7, a thorough study of the stability and long-term durability under outdoor operation still needs to be done. Thus, based on the results achieved in this study, we judge that the **technology readiness level reached is at least TRL 6** as was promised in the Grant Agreement.

7.2 Contribution of the demonstrator to the project impacts

The demonstrator allowed the comparison of the behaviour of a variety of configurations of PV modules directly coupled electrolyser in the same location under the same outdoor for several thousand hours of operation as well as several thousand operating cycles, which is the first study of its kind.

[3] https://www.youtube.com/watch?v=ImWk0HEfkbU

Table 7.1 *Contribution of the demonstrator towards expected impacts of the project and the call topic FCH-02-3-2016*

Expected Impact	*Contribution of the demonstrator*	*Comments*
	Call topic FCH-02-3-2016	
Full analysis with definition of materials, project of the system, Balance-of-Plant, effect of variable solar irradiation and thermal management of photocatalytic systems for direct hydrogen production from sunlight	✓	This demonstrator fully contributes to the following aspects of this impact whose details are discussed in the present deliverable report: • Definition of the materials and the entire system, • Definition of the balance-of-plant, • Full analysis of the effect of variable solar irradiation
Prototype system (exposed surface >10 m^2) including hydrogen and oxygen collection, purification, online analysis, storage. Optimized management of the prototype should be demonstrated	✓	All these aspects have been covered by the demonstrator with the exception of storage.
Specified targets to be obtained: (1) H_2 production demonstrated > 15 g/h or 10 KgH_2 over the complete running time, (2) Efficiency > 5 %, (3) Running time > 6 months with a degradation lower than 10% under harsh operating conditions (4) H_2 cost < 5 €/kg H_2	✓	All except the cost of hydrogen production which will be presented in a separate report
The materials selected and most promising should be upscaled and proved through in-field testing	×	As explained in the text of this deliverable, the thermally integrated approaches could not be scaled in time for inclusion in the demonstrator. A small 100 cm² sized CuInGaSe PV integrated alkaline electrolyser was added to the outdoor test field and the performance results are included in this report
A cost analysis of the developed technology must be performed	×	This shall be presented in a separate deliverable report D 6.5
	PECSYS	
New innovative products for European manufacturing sector	✓	Modified electrolyser feed
Develop new business models for European utility industry	✓	Technology suitable for hydrogen via autonomous generation of electricity from renewable energy sources
Provide clean, carbon free, diversified and politically uncritical alternatives for EU fuel imports	✓	The demonstration of the feasibility of direct solar hydrogen generation in temperate region of Europe therefore negating the necessity for solar concentration can contribute to sunny parts of the EU establishing an internal

Expected Impact	*Contribution of the demonstrator*	*Comments*
		fuel industry in the near future based on the carbon-free, H_2 economy
Allow sunny regions in the vicinity of EU to move to new, knowledge/technology -based industries and economies	✓	The very high solar irradiation in the African countries bordering the Mediterranean Sea will result in an even higher rate of hydrogen production than demonstrated here such that the LCOH will even be lower for these regions. Like PV, the solar to hydrogen technology demonstrated here can be decentralised and tends to have less sunk-cost than carbon-based investments and thus would favour competition.

The effect of reduced platinum group catalyst loading in the PEM electrolyser on energy conversion performance and durability under fluctuating operating and weather conditions has also not been published before.

7.3 Comparison with state of the art

Being a unique setup, a comparison of this demonstrator with other systems is difficult. This electrolysis system combined many recent developments in the technology including

(i) Reduced platinum group catalyst loading,

(ii) Thinner membrane 50 µm,

(iii) Water feed via the cathode and not the anode

(iv) Feed water supply using hydraulic effects and no pumping

(v) Coupling the photovoltaic modules to the electrolyser without power conditioning devices

(vi) Operation without active heating

The effect of reduced platinum group catalyst loading and a thin ~ 50 µm thick membrane in the PEM electrolyser on energy conversion performance and durability under fluctuating operating and weather conditions has also not been published before. The long-term study of the effect of cathode only water feed of the PEM electrolyser stack on the energy conversion performance under fluctuating outdoor conditions has also not been published before. Additionally, steps were taken to reduce the power requirements of auxiliary systems as listed in (iv) to (vi) above, resulting in a potentially higher overall system efficiency than with comparable systems.

The performance achievements in most cases, exceed the original project targets as shown in Table 3. A solar to hydrogen efficiency in the range of 10 % could be maintained of all over the year resulting in the generation of 245,000 litres of hydrogen with in the test period of just under 9 months. With the exception of the failure in one of the electrolysers (with low catalyst loading), durability of more than 6 months (~2,500 h) was demonstrated.

Table 2. *Comparison of the PECSYS demonstrator against the project targets listed in Milestone MS5*

	Targets	Demonstrator
Demonstrator size	10 m^2	>10.5 m^2
System type	Thermal integrated photovoltaic electrolyser	Cassette
Duration of operation	6 months (1825h)*	2680 h
Solar to hydrogen efficiency	> 6 %	~ 10 %
Hydrogen generation	10 kg_{H2} over 6 months	22 kg_{H2}
Stability	< 10 % efficiency reduction after 6 months	Demonstrated (figure 11)

* Assuming an average of 10 daylight hours

Most demonstrations of photovoltaic driven water electrolysis for hydrogen generation are already larger than the systems developed in the PECSYS project. However, most have been designed to store excess electricity produced by renewable energy sources and provide support to the grid in times of increased load demand. Those that are operated autonomously employ power conditioning between the electrolyser and the PV modules[4]. Although there are some presentations of directly coupling PV to electrolysers as listed in Table 4, the operation of such systems is limited to at most a few days, as part of an extended study to compare different connection topologies. A comparison with these systems shows that the performance of the PECSYS 10 m^2 demonstrator system is among those with the largest power capacities with high efficiency and stability and offering promising scalability. Our demonstrator is also unique in that it allowed a comparison of the behaviour of a variety of configurations of PV modules directly coupled electrolyser in the same location under the same outdoor conditions with several thousand operating cycles over several thousand hours of operation.

Table 3. *Comparison with other systems with PV directly coupled to electrolysers demonstrated in the last 10 years. The time in operation corresponds to the timeframe of measurements for the data published.*

Project; Location	Year	PV technology	PV size (m^2; kW_{el})	Electrolyser type	Time in Operation (h)	Average StH efficiency (%)
PECSYS; Jülich, Germany	2020	Silicon HJT and CuInGaSe	10.5; 1.73	PEM	>2680	~ 10
Saudi Arabia[5]	2020	Polycrystalline silicon	1.5; 0.27	PEM	~10	9.4
Japan[6]	2013	Polycrystalline silicon	21.2; 2.6	PEM	~20	~5*

*Calculated using hydrogen generated and input solar energy values reported in the publication

[4] A. Ursua, I. San Martin, E. L. Barrios, P. Sanchis. (2013). *International Journal of Hydrogen Energy*, 38:14952-14967.

[5] S. Muhammad-Bashir, M. Al-Oufi, M. Al-Hakami, M.A. Nadeem, K. Mudiyanselage, H. Idriss. (2020), *Solar Energy*, 205:461.

[6] T. Maeda, Y. Nagata, N. Endo, M. Ishida (2016), *Journal of International Council on Electrical Engineering*, 6:1, 78-83, DOI:10.1080/22348972.2016.1173783.

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

In the course of preparing for and operating the demonstrator several positive learnings were achieved. We showed that if the power of the PV module and the electrolyser is matched, direct coupling without power conditioning is reliable and cost effective.

The electrolyser's hydrogen production rate directly follows the changes in the incident irradiance thus any system with a PV module directly coupled to an electrolyser would require a buffer to stabilise the supply of hydrogen to downstream equipment such as compressors and fuel cells. However, since the electrolysers were operated at nearly at atmospheric pressure, the hydrogen cross-over is expected to be minimal. Nevertheless, operating without power electronics control, requires a safety mechanism to prevent hydrogen cross-over at extremely low current densities that could occur during periods of low solar irradiance.

Since one of the electrolysers failed and a gradual reduction of the electrolysis performance was observed, a more detailed investigation of the causes and mechanisms of the degradation of electrolysis components is required. Areas to consider monitoring in the future include the electrical contact resistance as well as corrosion and contaminations.

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

All systems have been developed within the different work packages of the other project tasks. Especially the development in WP 4 – Cassette Design was important to demonstrate a solar hydrogen generation in this size. Data derived from the system monitoring were used for the techno-economic and lifecycle analysis in WP6.

7.6 Limitations of the findings

Due to lack of time more detailed research in terms of systems reliability is necessary. In addition, a more detailed investigation of how the different technologies behave on the long term is necessary. Unfortunately, the learnings for alkaline electrolysis and thermally integrated devices were limited because of the delay and problems with scaling that technology such that the performance and behaviour during summer months could not be investigated. Also, scaling up the integrated alkaline electrolysis is necessary to attain analogue data for comparison with the PEM electrolyser.

The system design did not include a control system to manage the response, especially of the electrolyser to dynamics arising from fluctuating irradiance conditions. For example, a mechanism to prevent the possible accumulation of explosive gas mixtures during low irradiation levels when H_2 cross-over to the anode side might occur should be implemented in conventional electrolysis systems. In case of the open anode configuration, permeated hydrogen is diluted in the air.

8 CONCLUSIONS AND NEXT STEPS

During operation, the required proof was provided that the direct coupling of photovoltaics and electrolysis without power conditioning can achieve conversion efficiencies of around 10% with the current state of the art. For the first time, a new electrolyser stack supplied exclusively via the cathode could be used, which works with very simple piping. The system was to be operated reliably for more than six months. However, a slight degradation of the electrolyzers with low catalyst loading was also observed which reduced the overall demonstrator performance. Nevertheless, the overall solar to hydrogen efficiency of the remaining components was still 10% until the end of the project in December 2020.

It is necessary to analyze the exact reasons for the observed failure and gradual performance loss within the scope of further research projects and thus to develop systems which allow a stable operation even over longer periods of time. This will be possible by a detailed analysis of the data monitored during the operation.

The fully integrated systems (electrolysis directly in thermal contact the photovoltaic module) could not yet be set up on a 10 m² scale, as development has not yet progressed far enough. In general, it is questionable whether such systems can be operated at all under slight overpressure or whether the flat construction is not rather disadvantageous. The advantage of this system when alkaline electrolytes are used, is that even at temperatures close to freezing point there is no freezing of the device allowing hydrogen production if there is sufficient incident irradiance. An integrated small system was tested (~100 cm²) and also here efficiencies in the range of 10 % could be achieved. Unfortunately, it was only possible to characterize this system during the winter months. Further investigations of this configuration therefore would be interesting. In general, more detailed research in terms of systems reliability is necessary for both technologies to further improve and to reach higher technology readiness levels.

9 DECLARATION BY THE DELIVERABLE LEAD BENEFICIARY

Deliverable 7.6:

- ☐ 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