

Proof-of-concept of an oscillatory flow solar photoreactor for solar fuel production in real sunlight

Overview & results from reactor validation in simulated and real sunlight

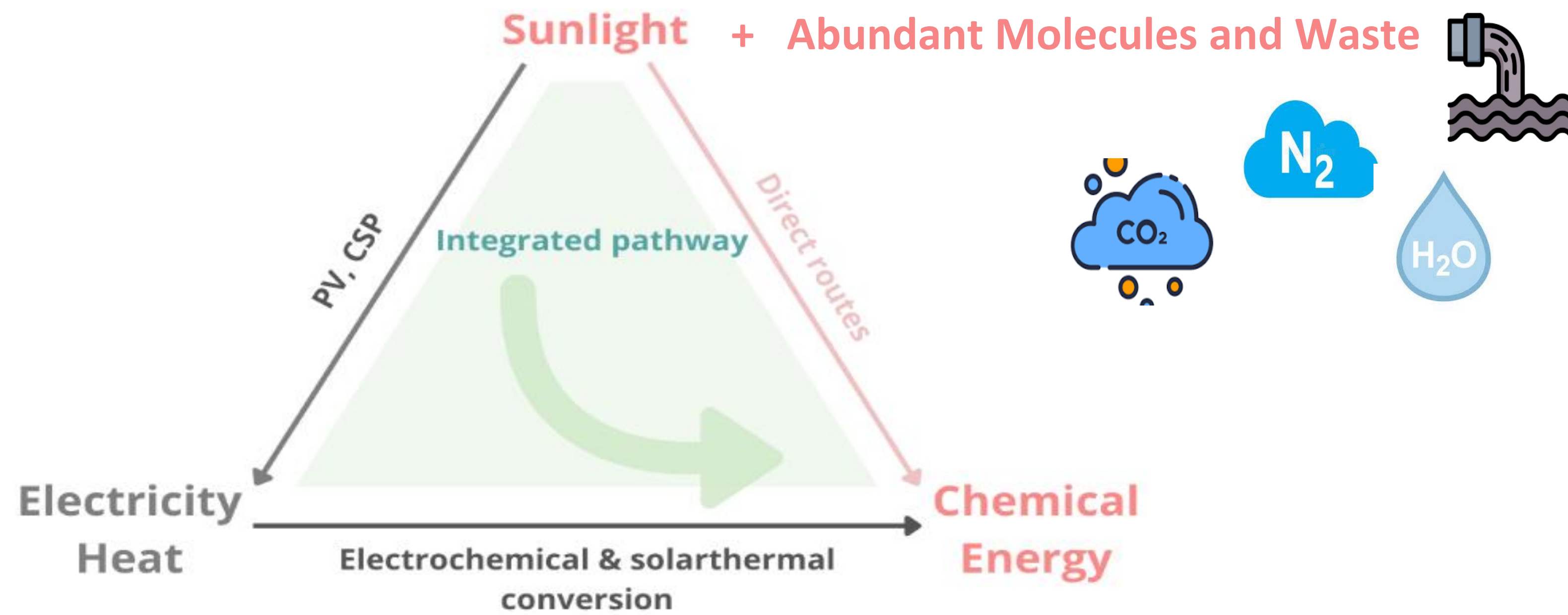


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Background

- Solar-to-X technologies, like photo-electrochemical (PEC) & photocatalytic (PC) processes, convert **solar energy into chemical energy**
- **Advantage of PEC/PC:** direct use of photons

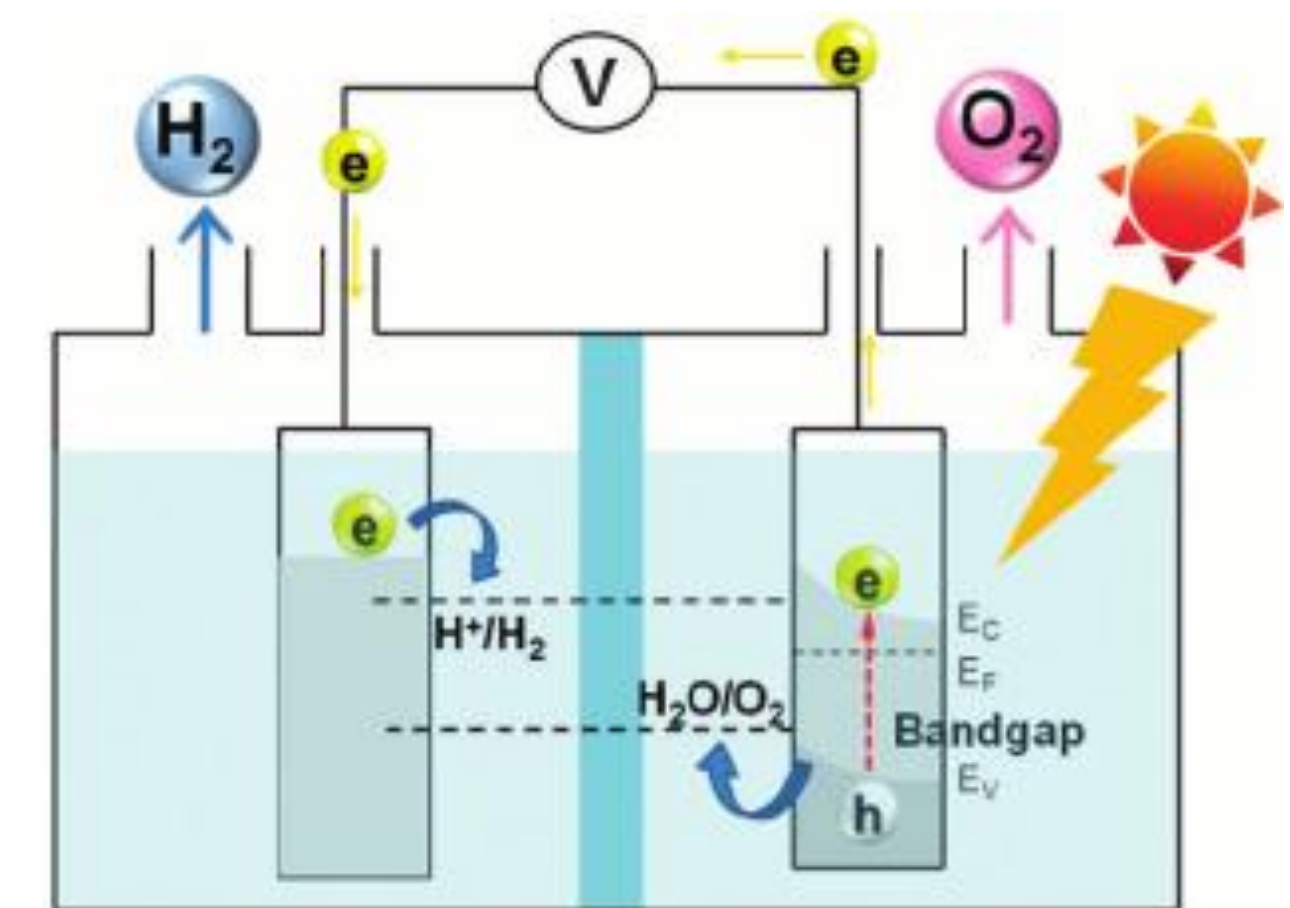


@ Bill Tumas (NREL, Mission Innovation)

Background

- Solar-to-X technologies, like photo-electrochemical (PEC) & photocatalytic (PC) processes, convert **solar energy into chemical energy**
- **Advantage of PEC/PC:** direct use of photons

- Example: Water splitting



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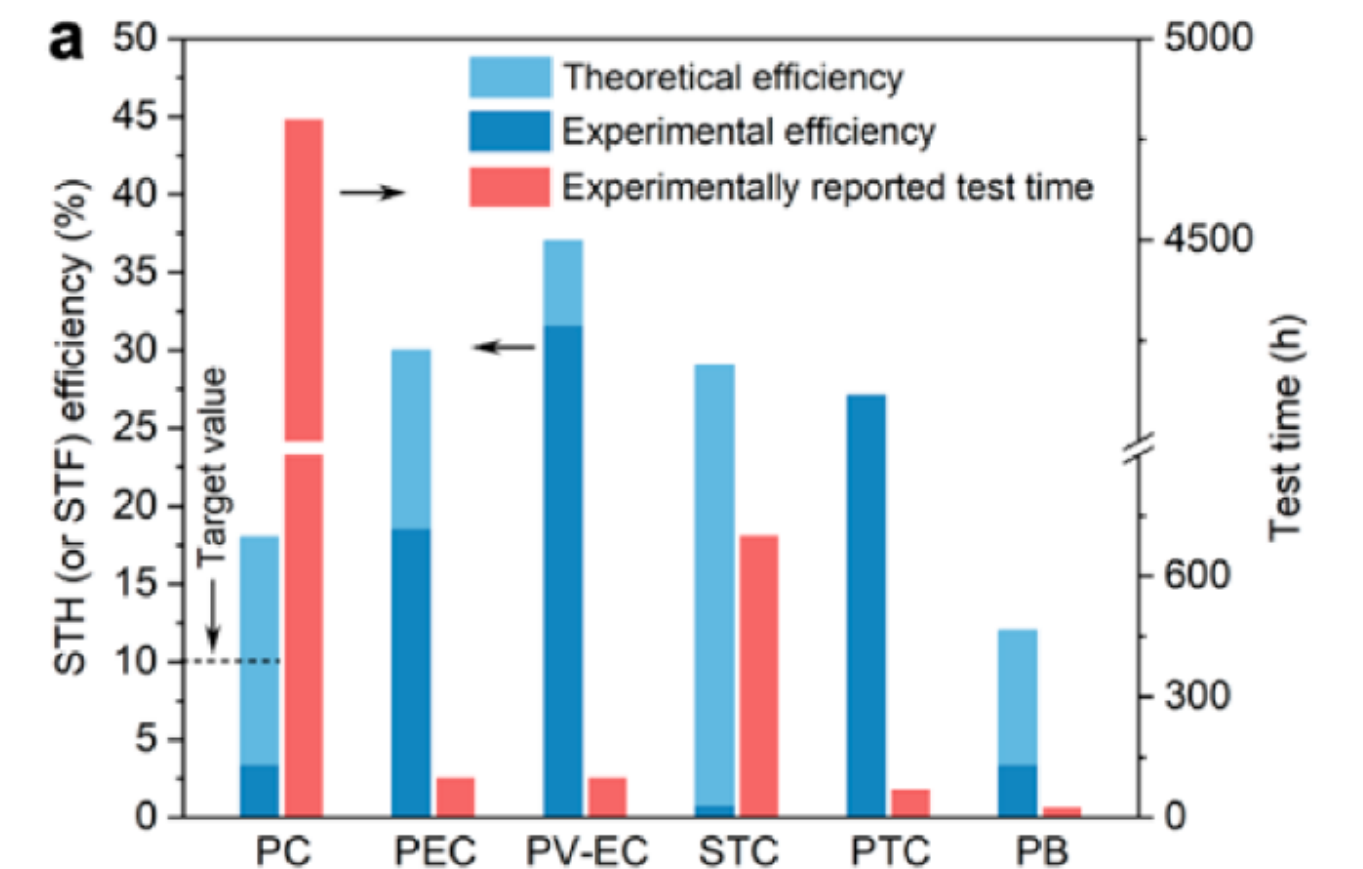
- Potential: usage of wastewater for oxidation of contaminants → serve as sacrificial agents and (potentially) increase H₂ yield



Limitations of existing reactors

- Solarreactors are available
→ **low TRL & low efficiencies** (mainly evaluated based on the Solar-to-Hydrogen ration; *STH*)
- Latest efficiencies for H₂ production:
 - PEC processes at 3-4%¹, max.~ 19%²
 - PC processes at 1-3%²; some show > 6%³
- **Problems: Comparability of results**
 - Experiments often performed in small lab scales &
 - At defined wavelength ranges in artificial light source
→ not comparable with real applications
- **Challenges:**
 - Adaption of processes to real sunlight
 - Catalyst development (from UV to visible light)
 - Scalability of systems, low area efficiencies

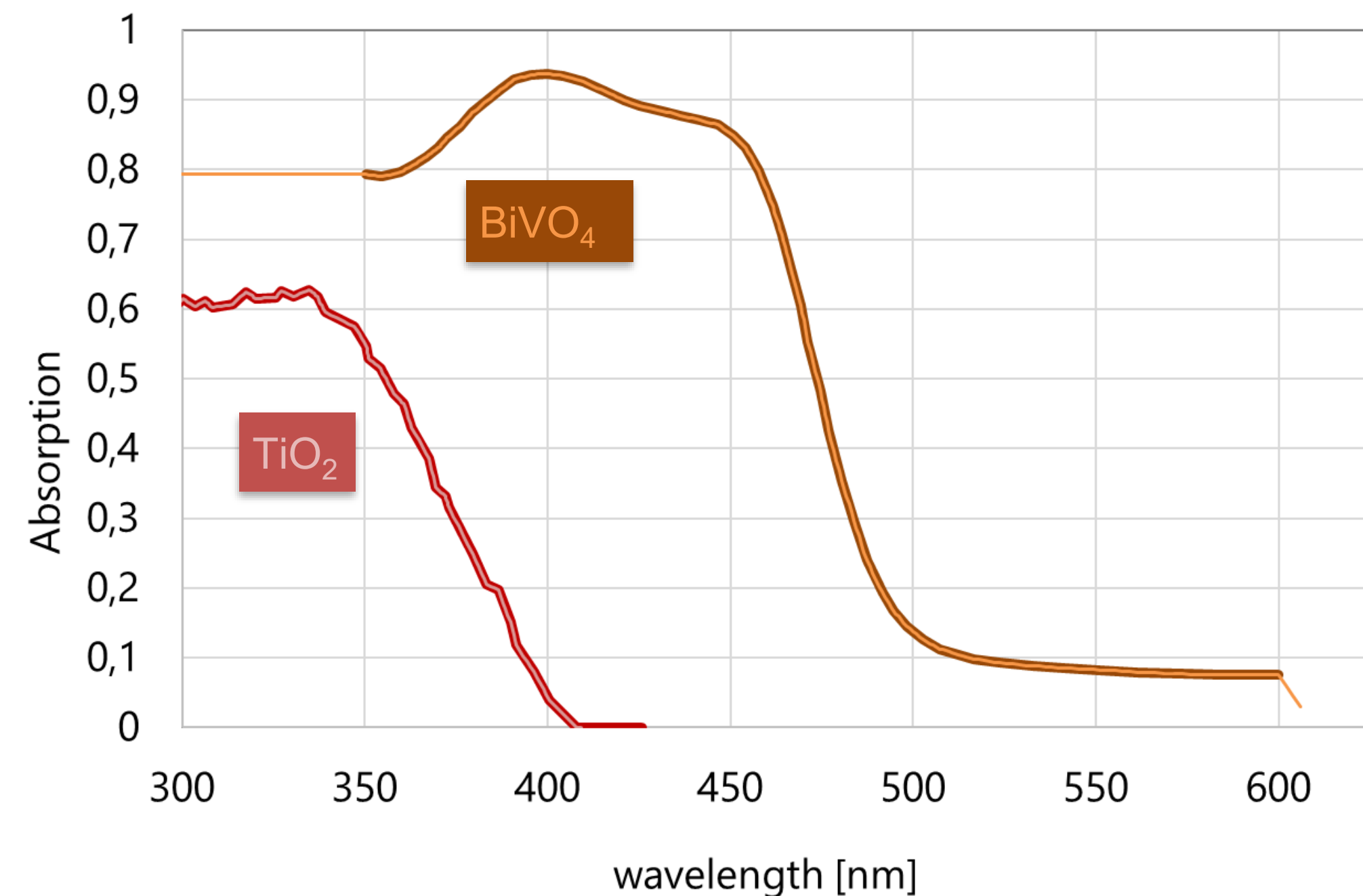
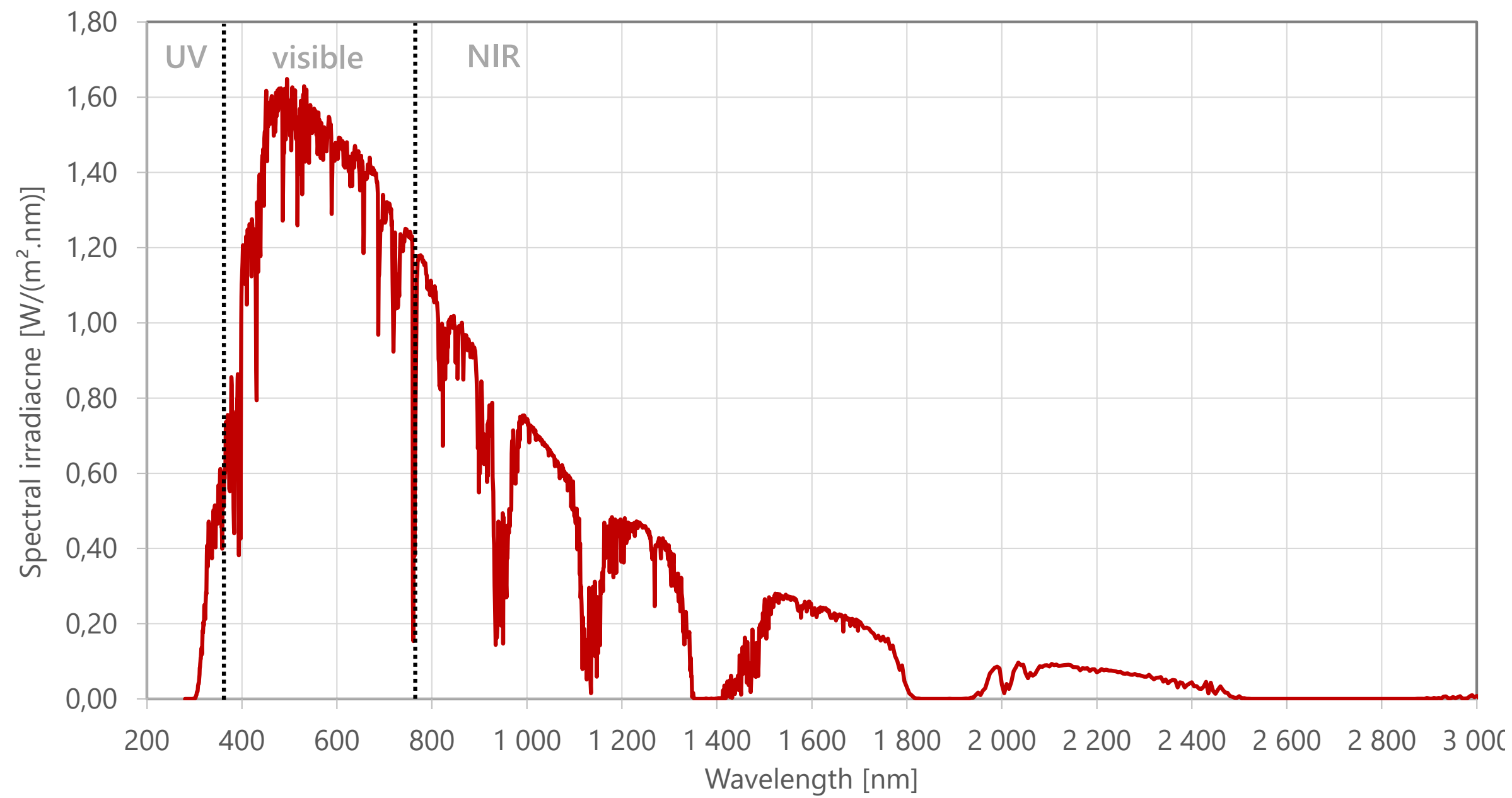
$$STH = \frac{\Delta G_{H_2}^0 * \Delta H_2}{Q_n} * 100 \%$$



ACS Energy Lett. 2022, 7, 3, 1043–1065 ; February 26, 2022

Development of electrodes for increased solar usage

- Photocatalyst needed for the conversion
 - PC → powder or immobilized catalysts
 - PEC → plated catalyst of electrodes
- **Main driver for processes efficiency → spectral absorption**



Feature	BiVO ₄	TiO ₂
Band Gap	2.4eV	3.2eV
Light Utilization	%43 of the solar spectrum	%4-5 of the solar spectrum

- **Main objective:** Development of an efficient solar reactor design and proof-of-concept under real solar irradiation
- This was achieved by:
 1. Development of **electrodes for increased solar usage** → from **mainly UV to visible light** ($BiVO_4$)
 2. Development of a new, innovative **solar reactor design** and **electrode integration**
 3. Construction of a **new test stand for tests** in the laboratory and under **real solar radiation**
 4. Experiments with different **wastewater** components for **reactor validation** and to identify the **effects on H₂ production**

Synthesis of BiVO_4

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Work from TU Vienna:
Jakob Blaschke, Hannah Rabl, Dorottya Varga, Stefan Pfaffel, Nick Parak, [Dogukan H. Apaydin](#)



BiOI (electrodeposition)

0.2M $\text{VO}(\text{acac})_2$
in DMSO



@450°C
2h
Rate 2°C min⁻¹

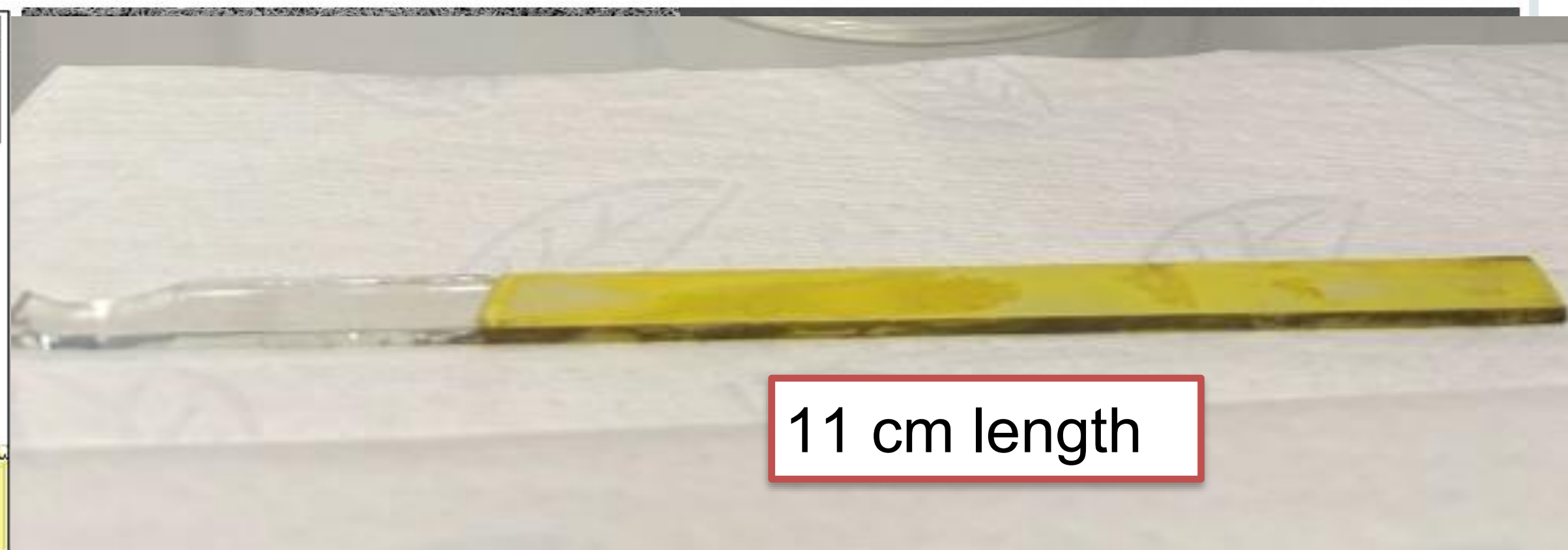
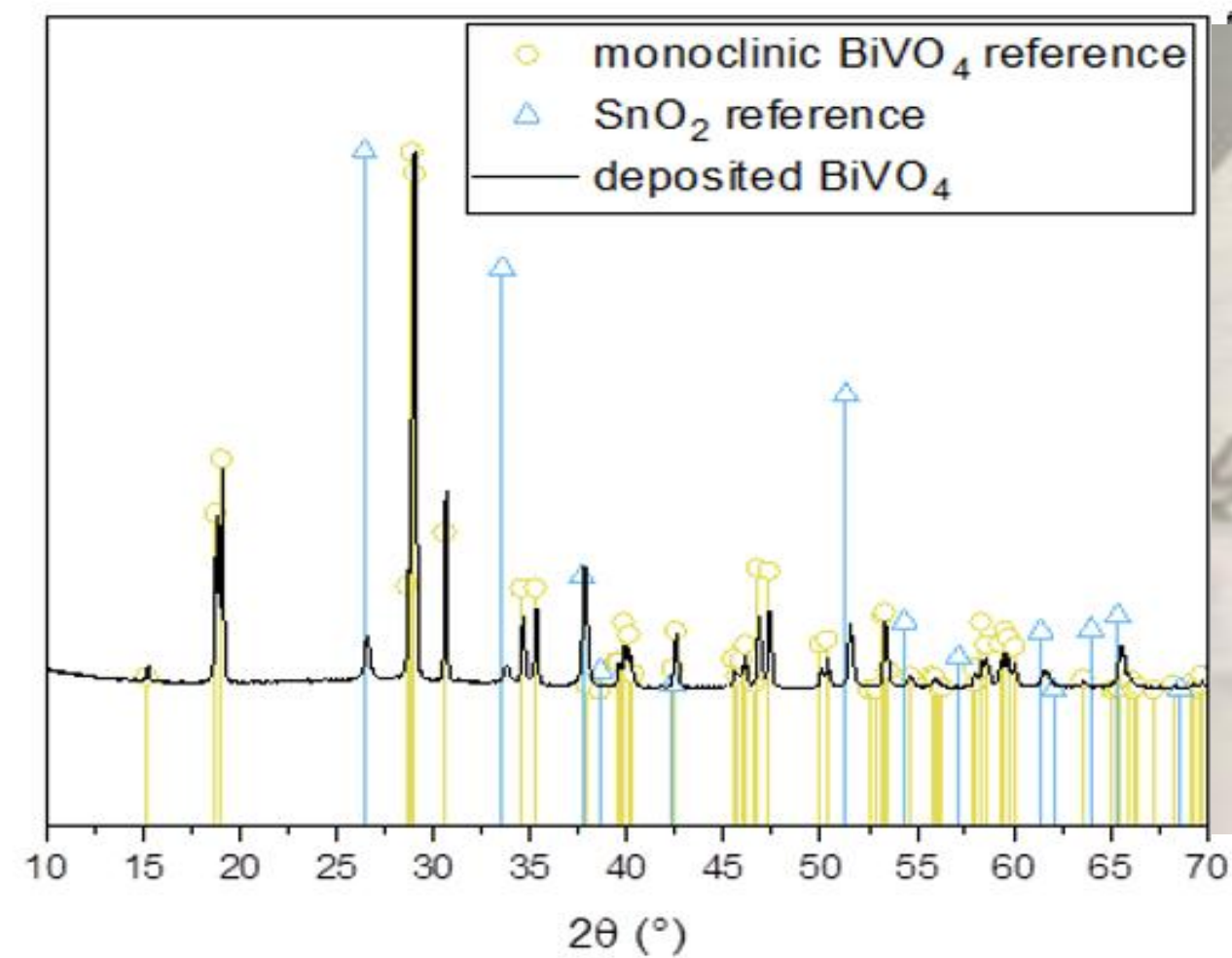


$\text{BiVO}_4/\text{V}_2\text{O}_5$

0.5M NaOH
30 min



BiVO_4



11 cm length

Science 2014, 343 (6174), 990–994.

Idea behind the solar photoreactor design

Catalyst (plated in PEC; powder or immobilized in PC)



&

Electrolyte – in this case waste water



Low Efficiency

**Limitations of SOTA
Photoreactors**

...

**Insufficient supply of
catalyst surface with
reactants**

**Delayed removal of products
(local concentration gradients)**

Idea behind the solar photoreactor design

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&

Electrolyte – in this case waste water



Oscillatory Flow Reactor



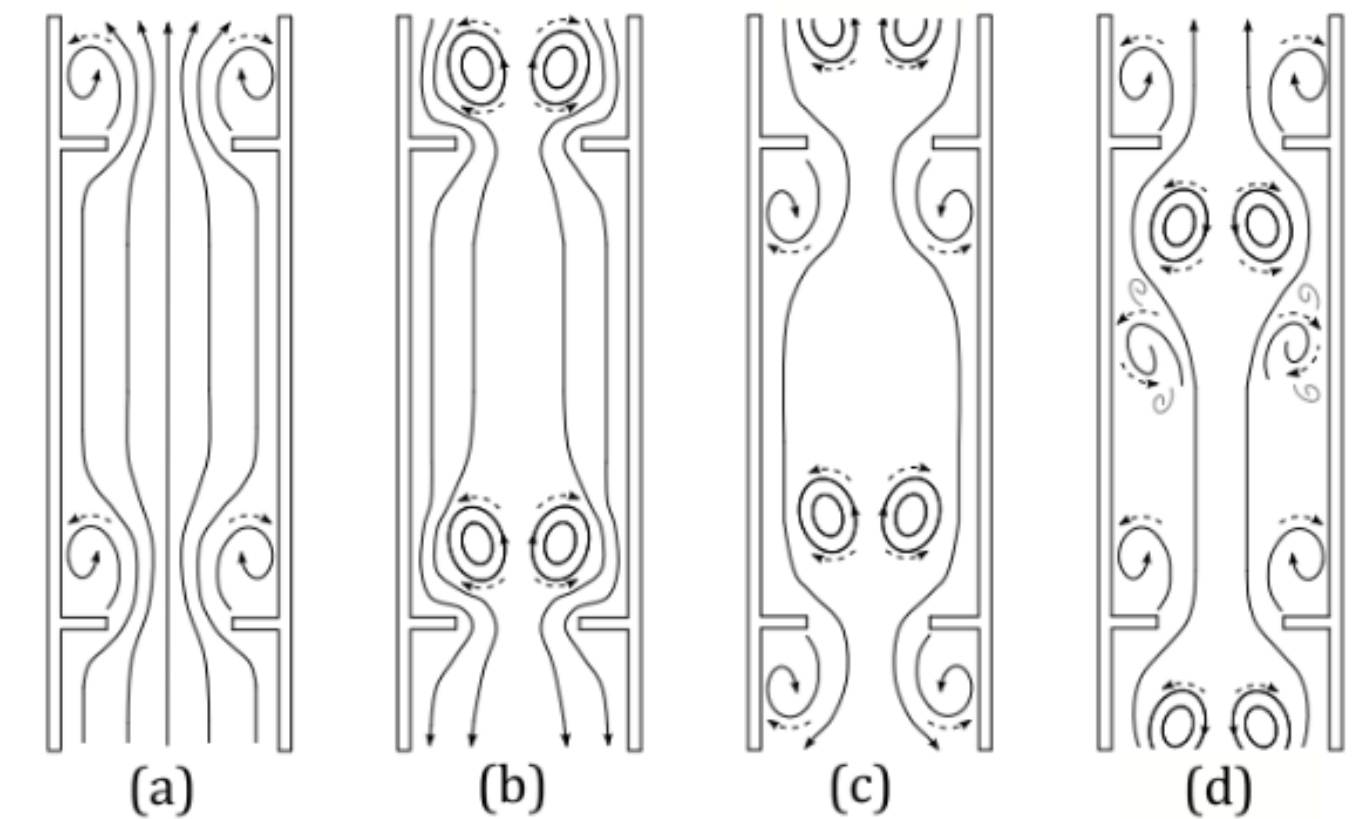
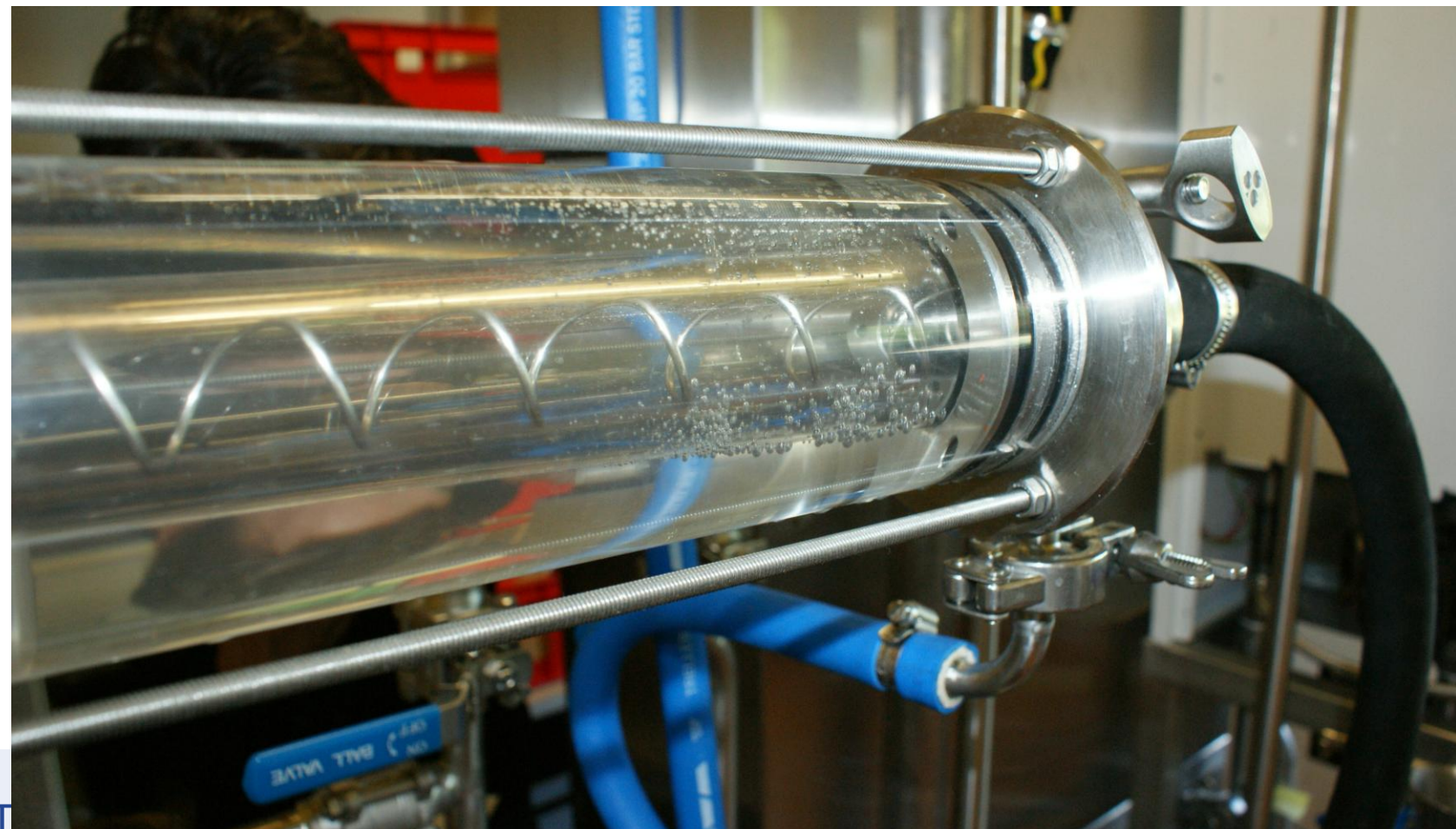
Baffle (Helix)



Piston



Turbulent flow via oscillation



Flow behaviour [McDonough, Phan, und Hary, 2015]

Novel design of a Oscillatory Flow Solar Photoreactor

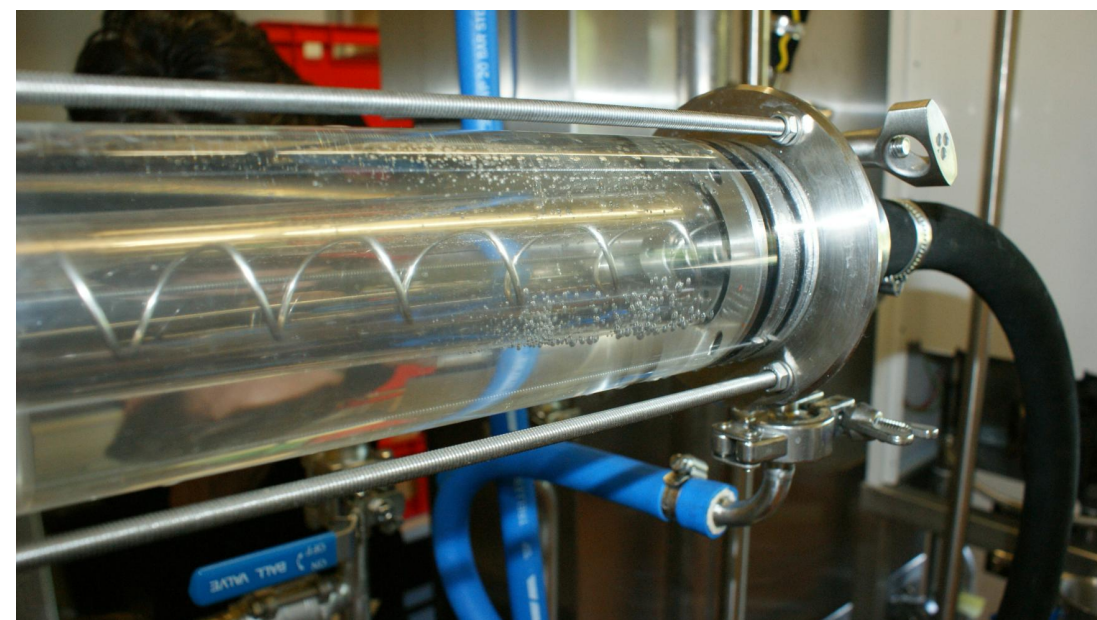
Catalyst (plated in PEC; powder or immobilized in PC)



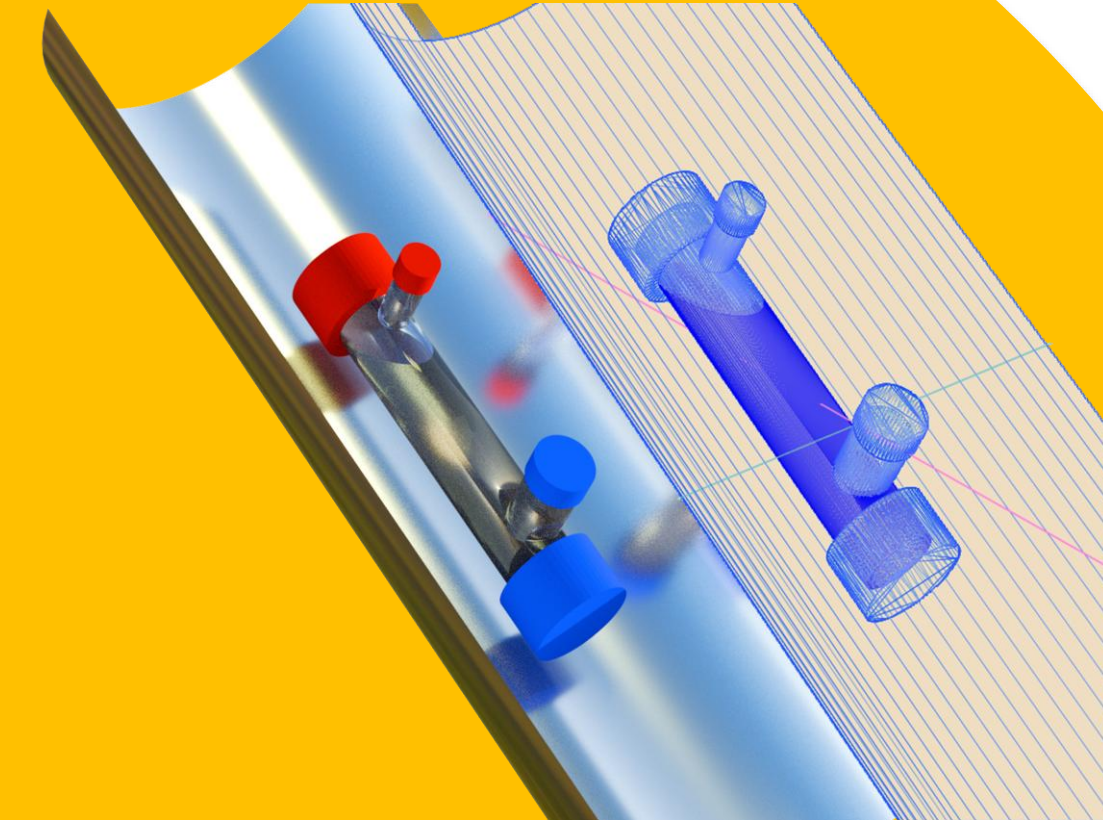
Electrolyte – in this case waste water



Oscillatory Flow Reactor



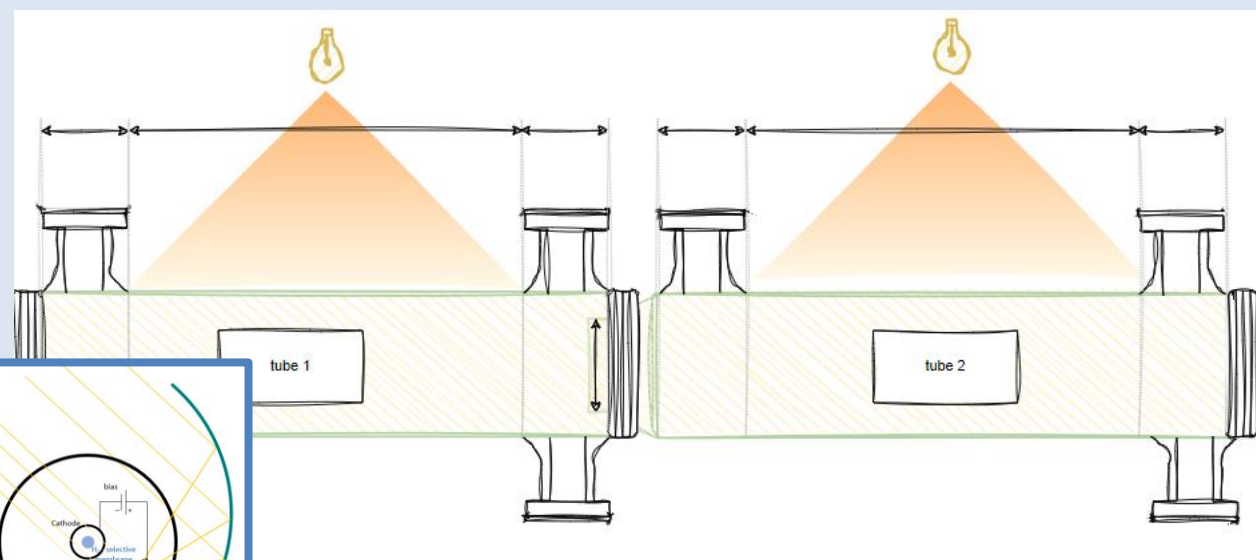
Oscillatory Flow Solar Photoreactor



Oscillatory flow enhances turbulences,
increases energy- and mass transfer,
reduces diffusion losses,
enhances product & reactant transport, etc.

Solarreactor Design

1. Design phase of reactor tubes



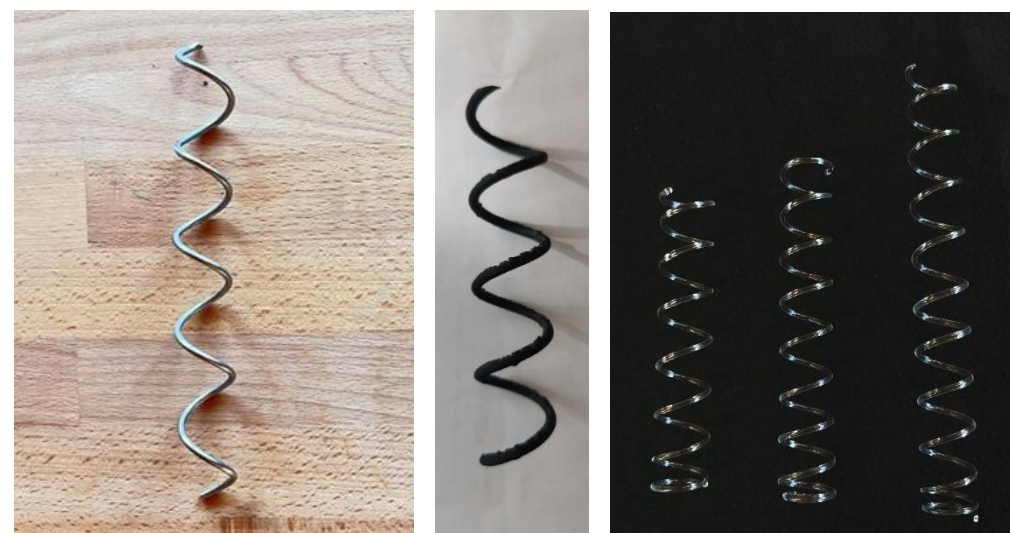
2. Realized Reactor Tubes (flexibel connections)



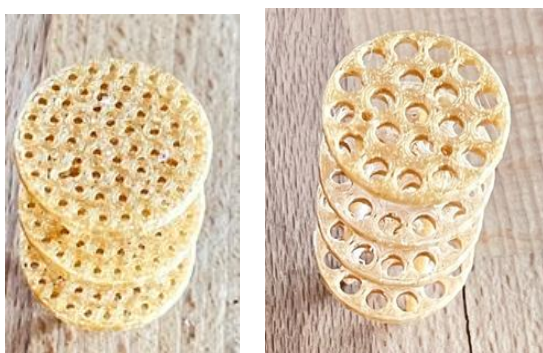
3. Reactor integrated with solar concentrator



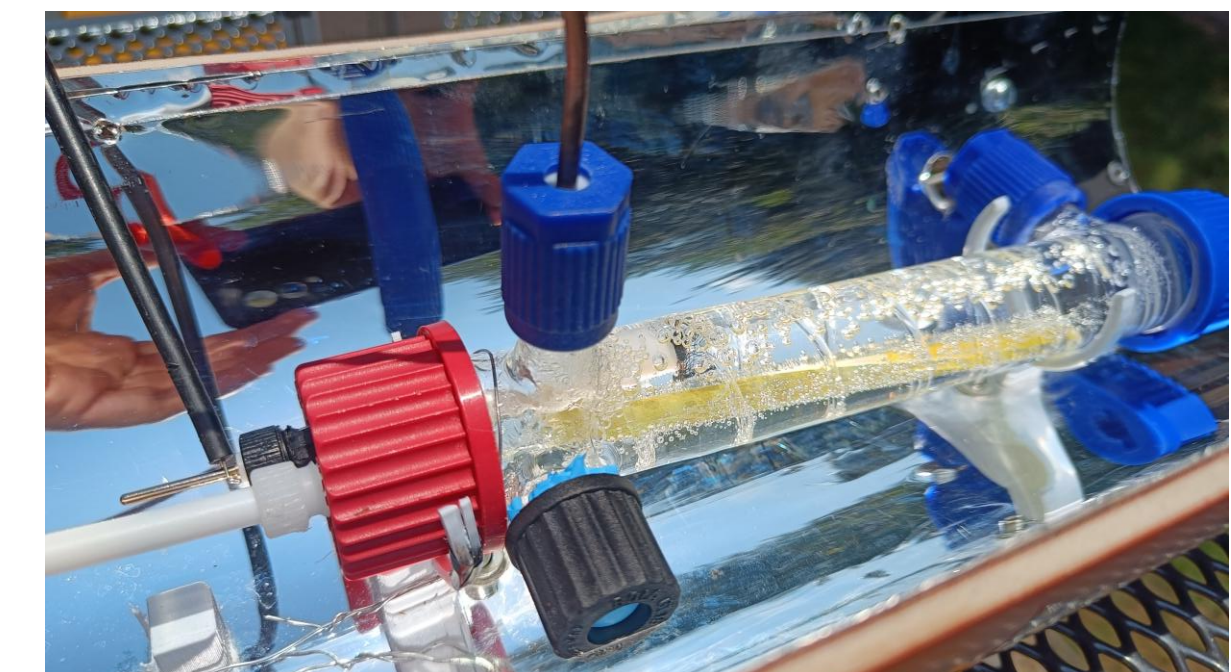
Helix (diff. Materials)



Perf. Plates



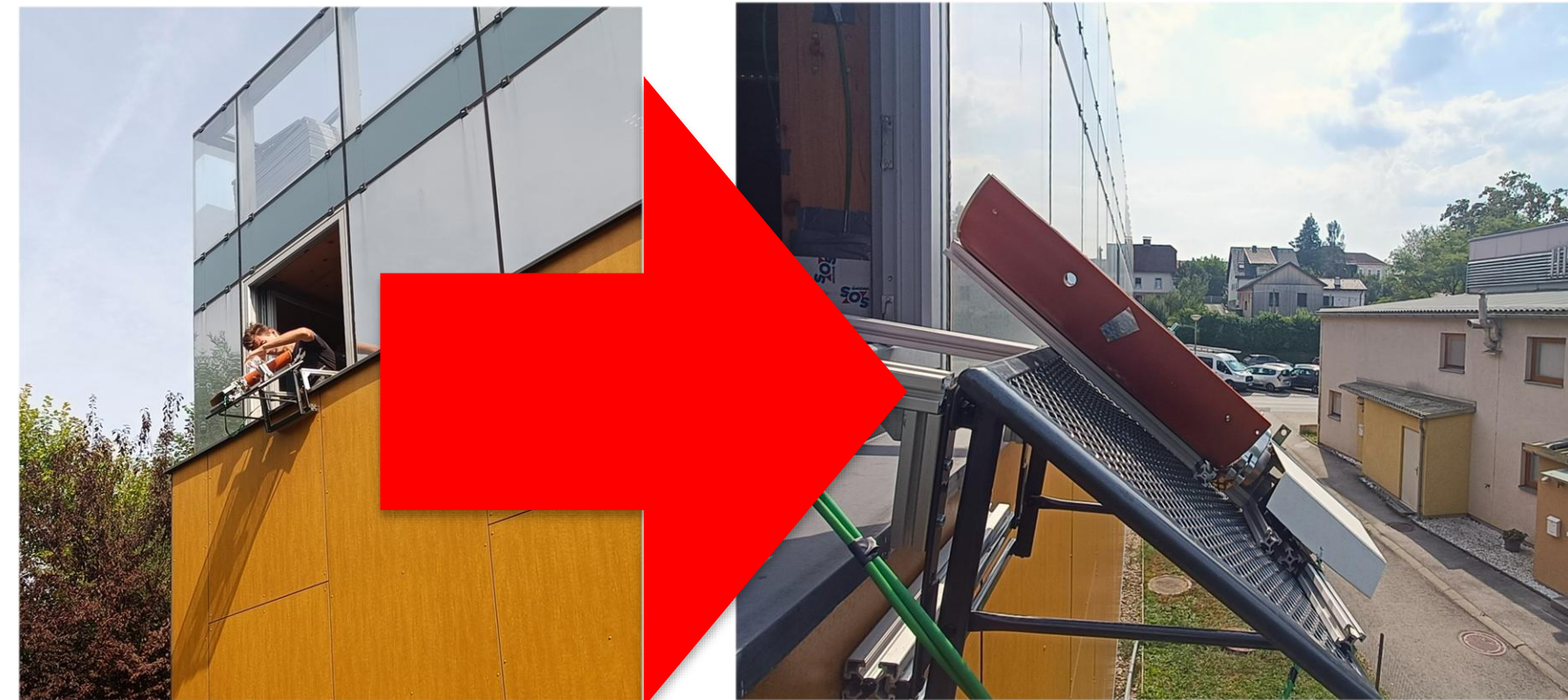
- Reactor geometry – cylindric/tube
- Baffles – helix, perforated plates → depending on application
- Concentrating mirror
- Flexible design
 - PEC for plated (Photo-) anode/cathodes
 - PC for powder or immobilized catalysts
 - Size variations possible (40 – 160 mL)
 - Single or multi-tube applications (serial/parallel)



OFS: Indoor- & Outdoor Testing

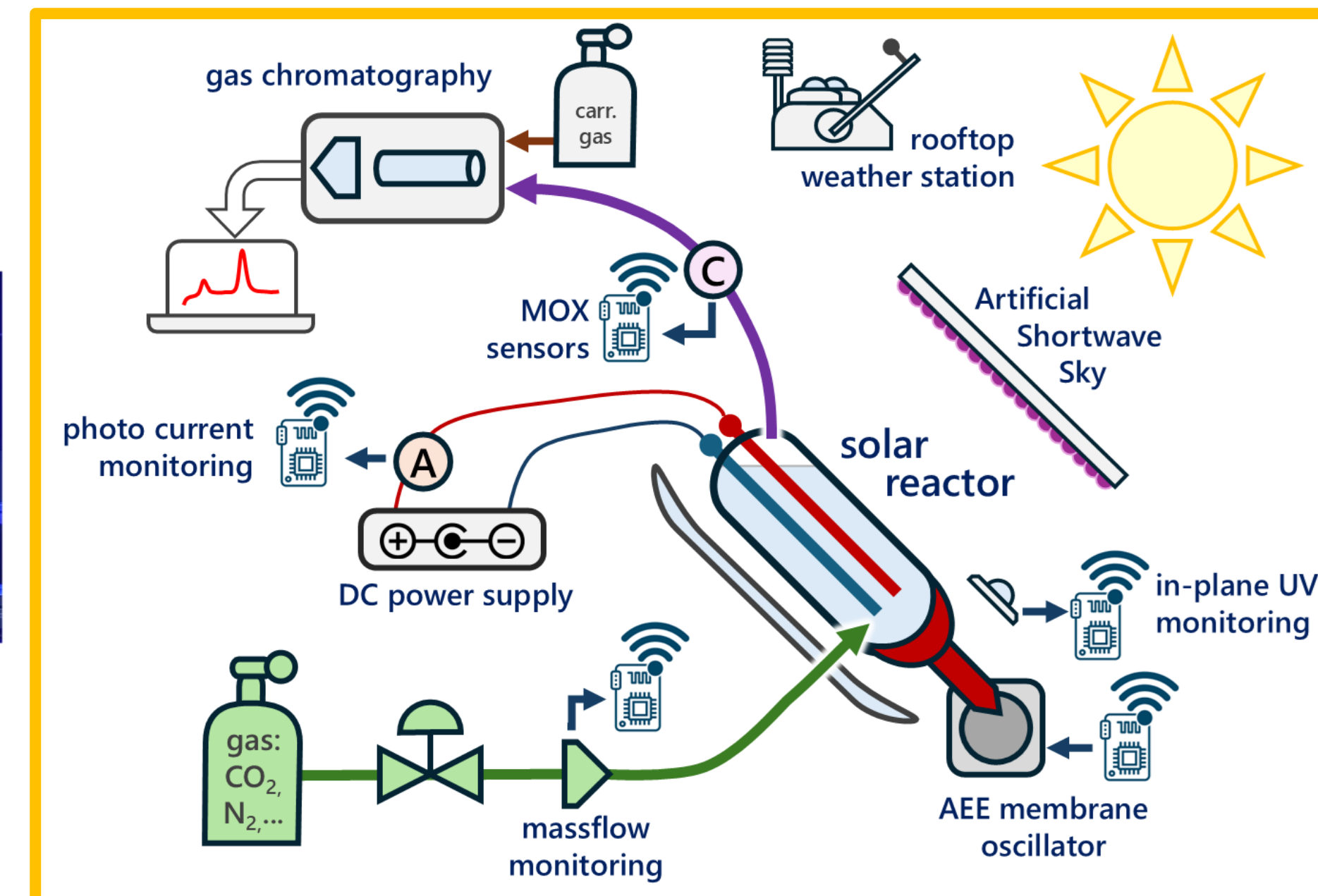
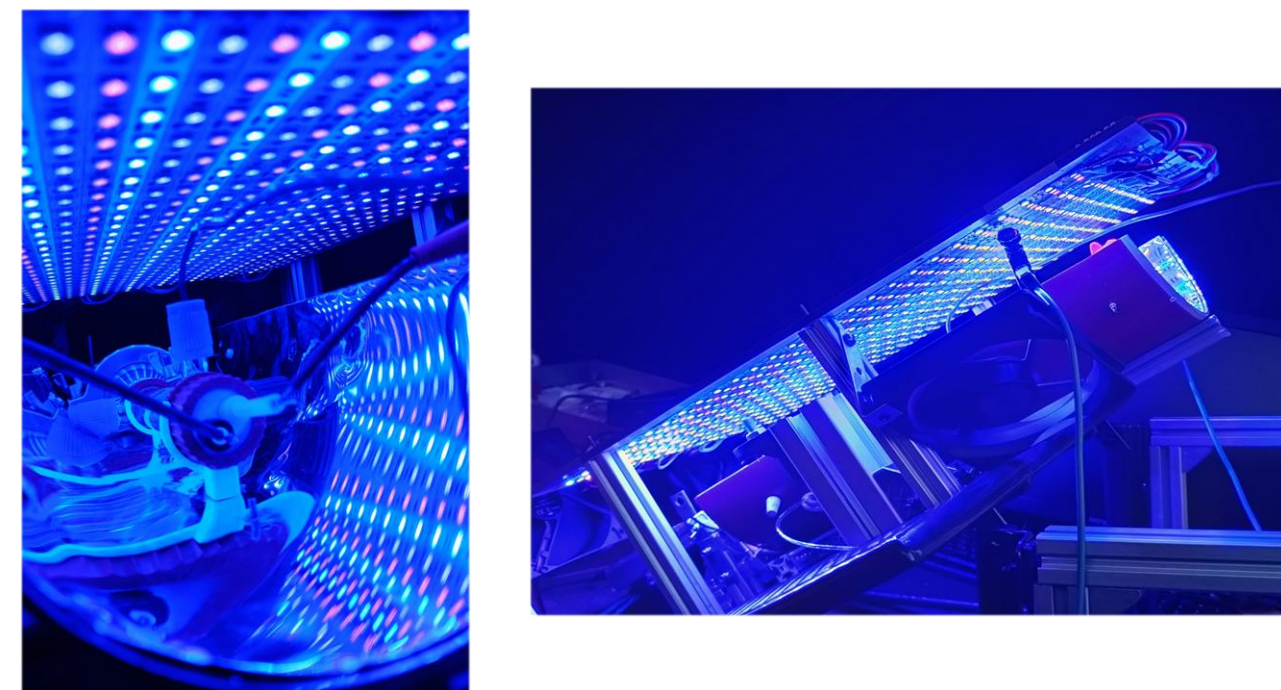
Outdoor Testing in Real Sunlight

- suspended variable platform for reactor and concentrator assemblies
 - south-facing lab window
 - tilted platform at variable angle
- *optional location on lab roof-top possible*



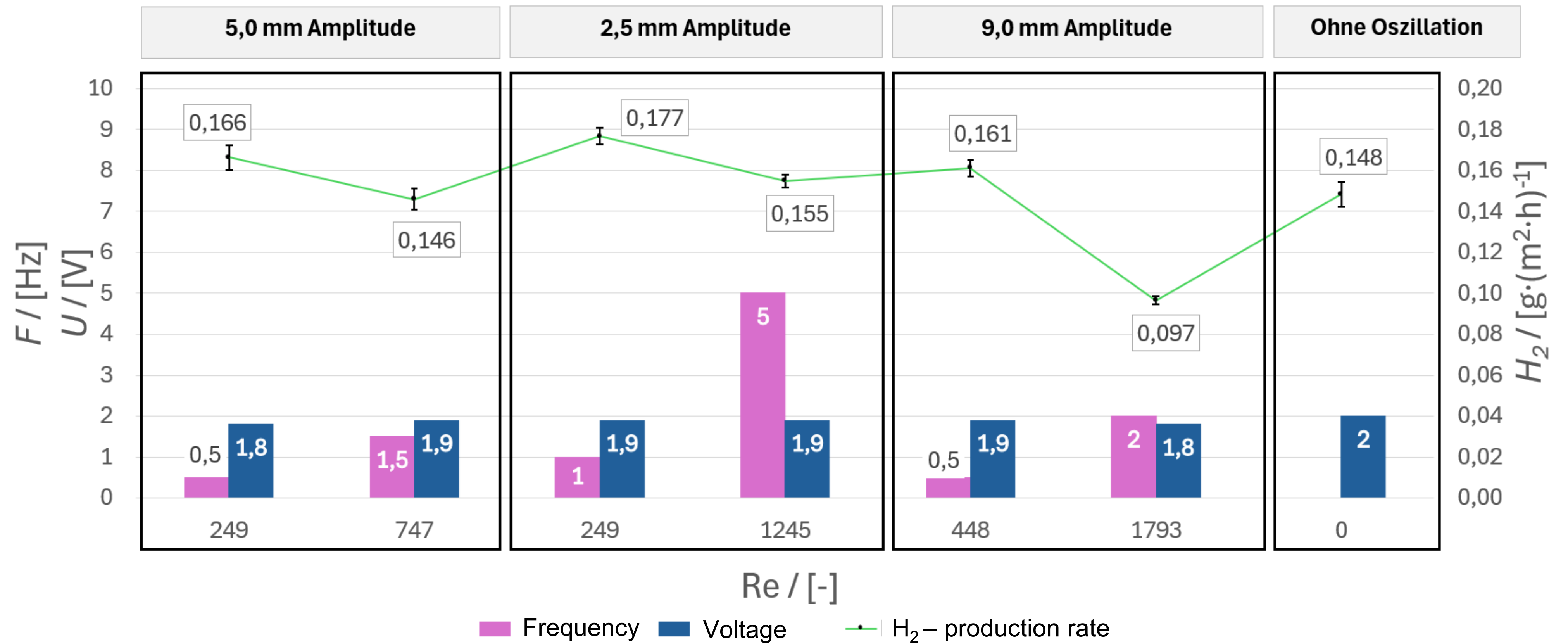
Indoor Testing with Artificial Sky

- artificial polychromatic light source (~370 to 470 nm range)



Results: Influence of oscillatory flow

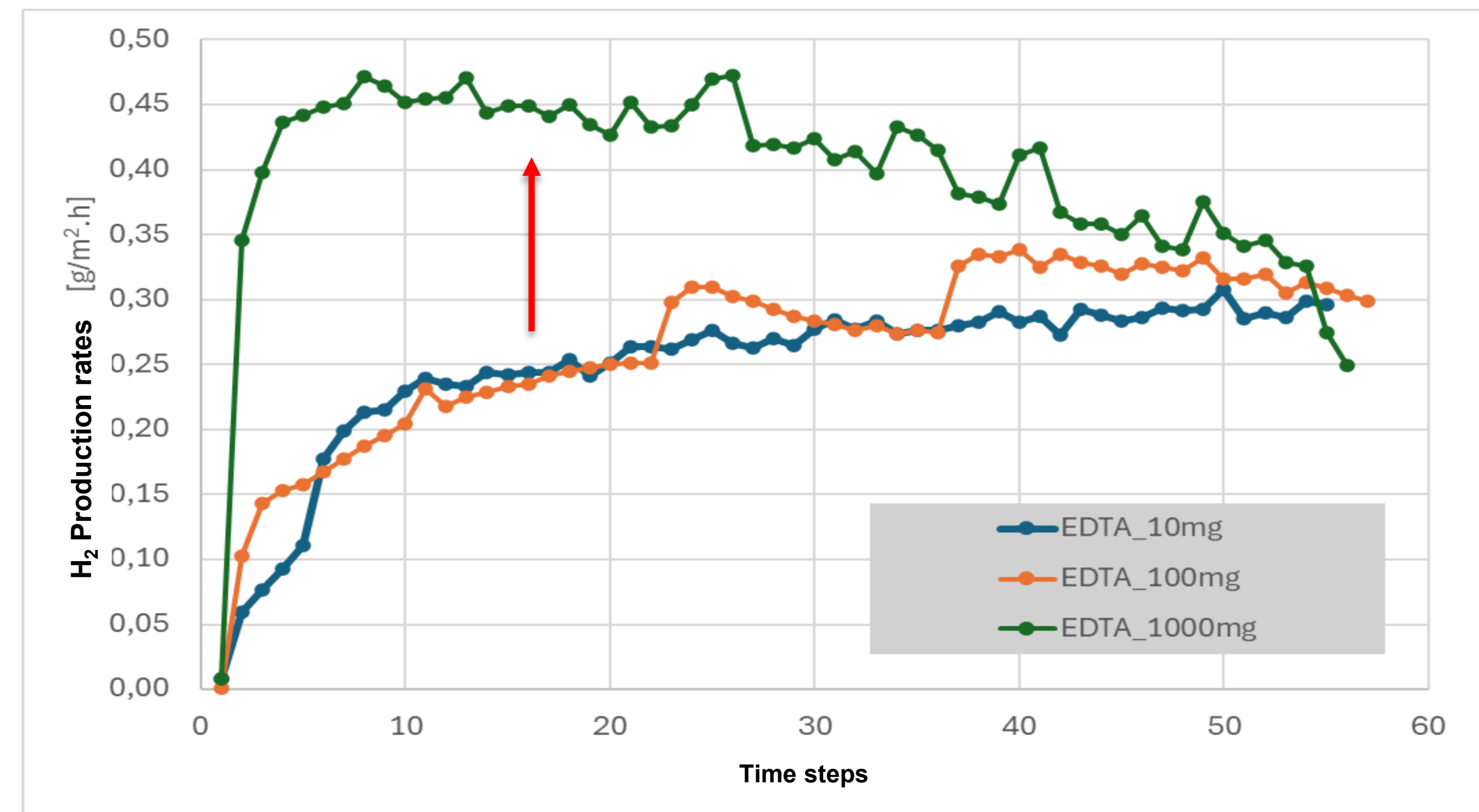
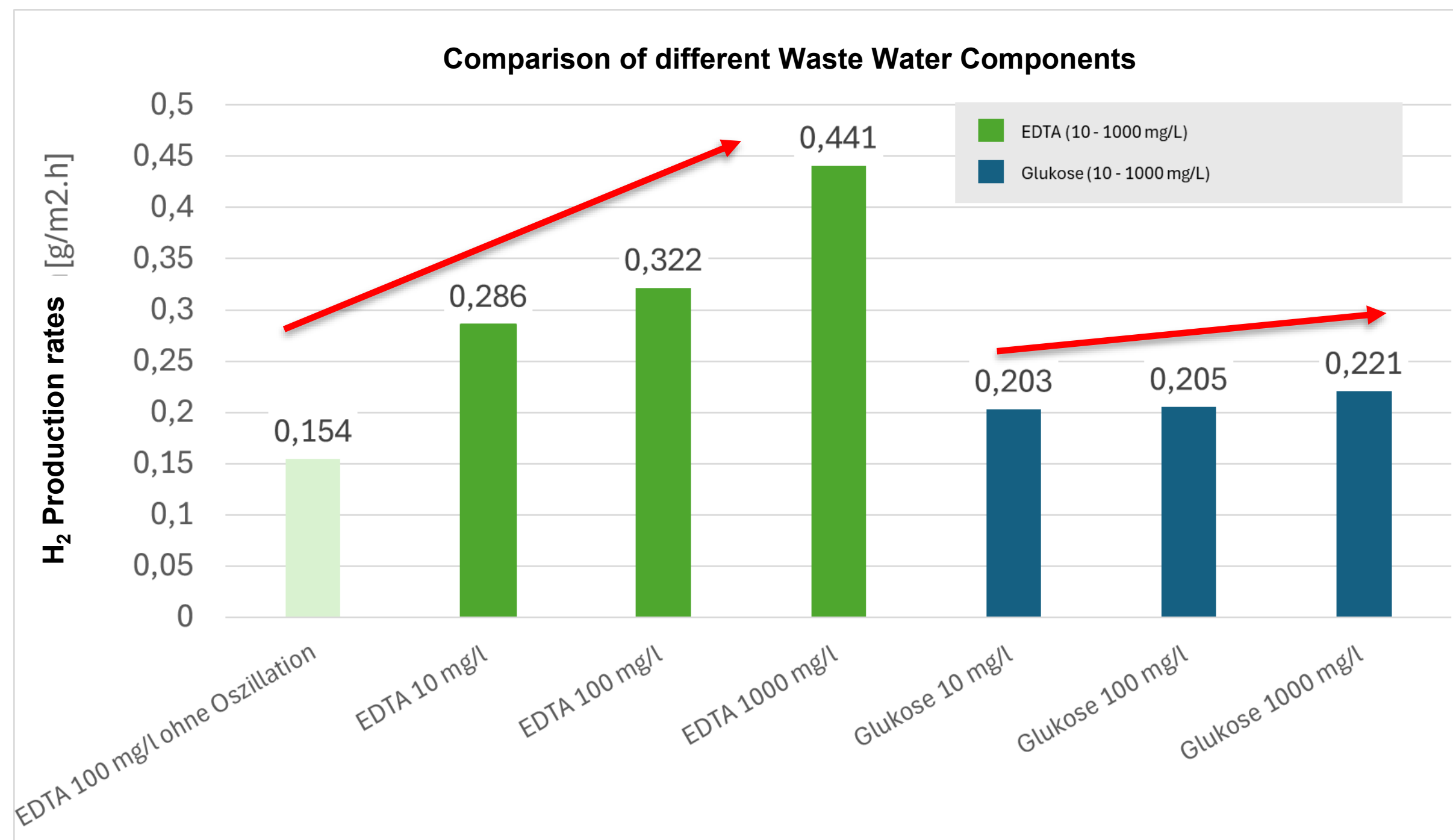
- Frequency = 0,5 – 5 Hz; Amplitude = 0 – 9 mm



→ Oscillation shows increase in H₂-production rate of around ~20%

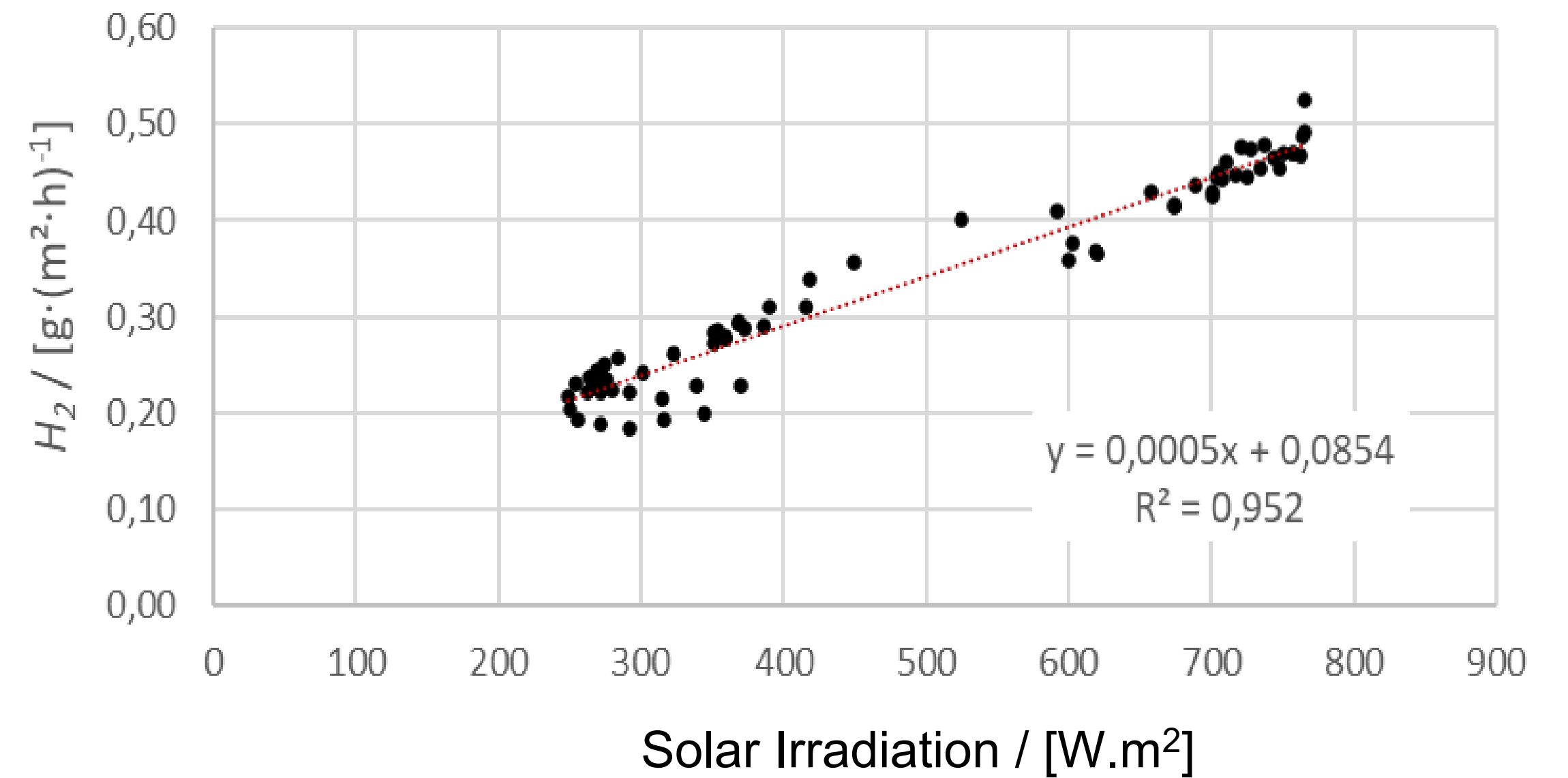
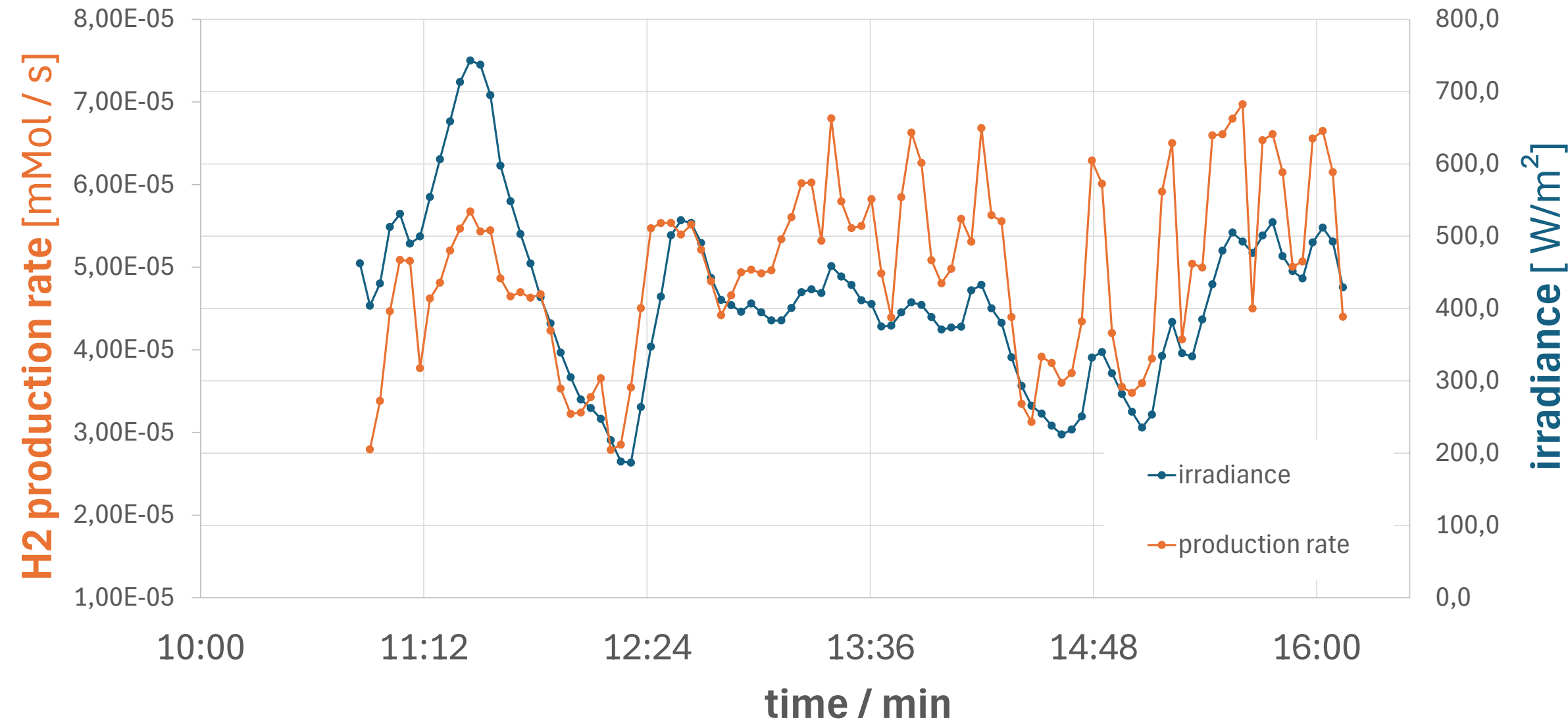
Results: Influence of waste water - (single) components

- Experiments with
 - EDTA - pulp and paper industry (10 mg/L, 100 mg/L, 1.000 mg/L) and
 - Glucose – food industry (10 mg/L, 100 mg/L, 1.000 mg/L)



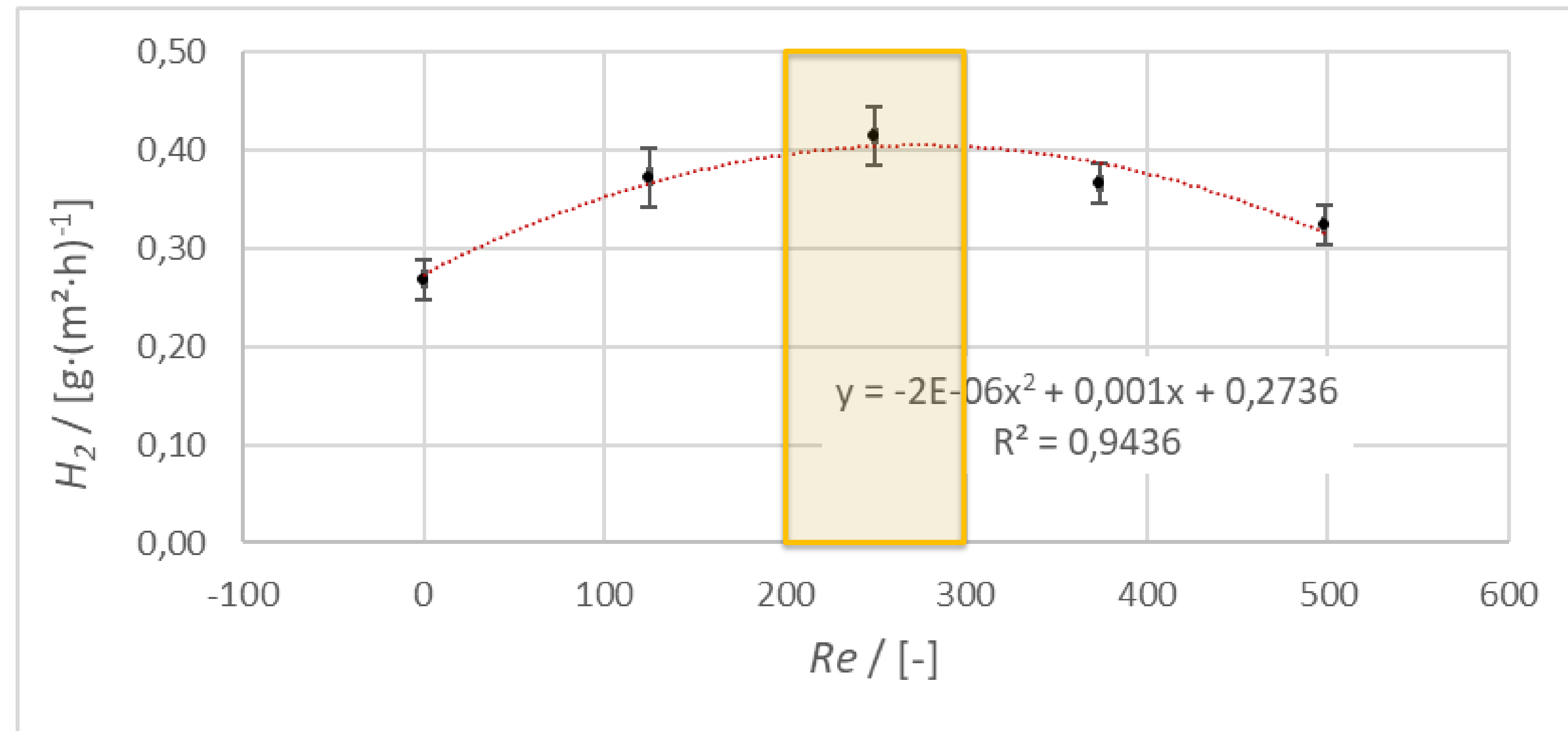
Results: Validation under real sunlight

- Correlation of H₂ production and solar irradiation



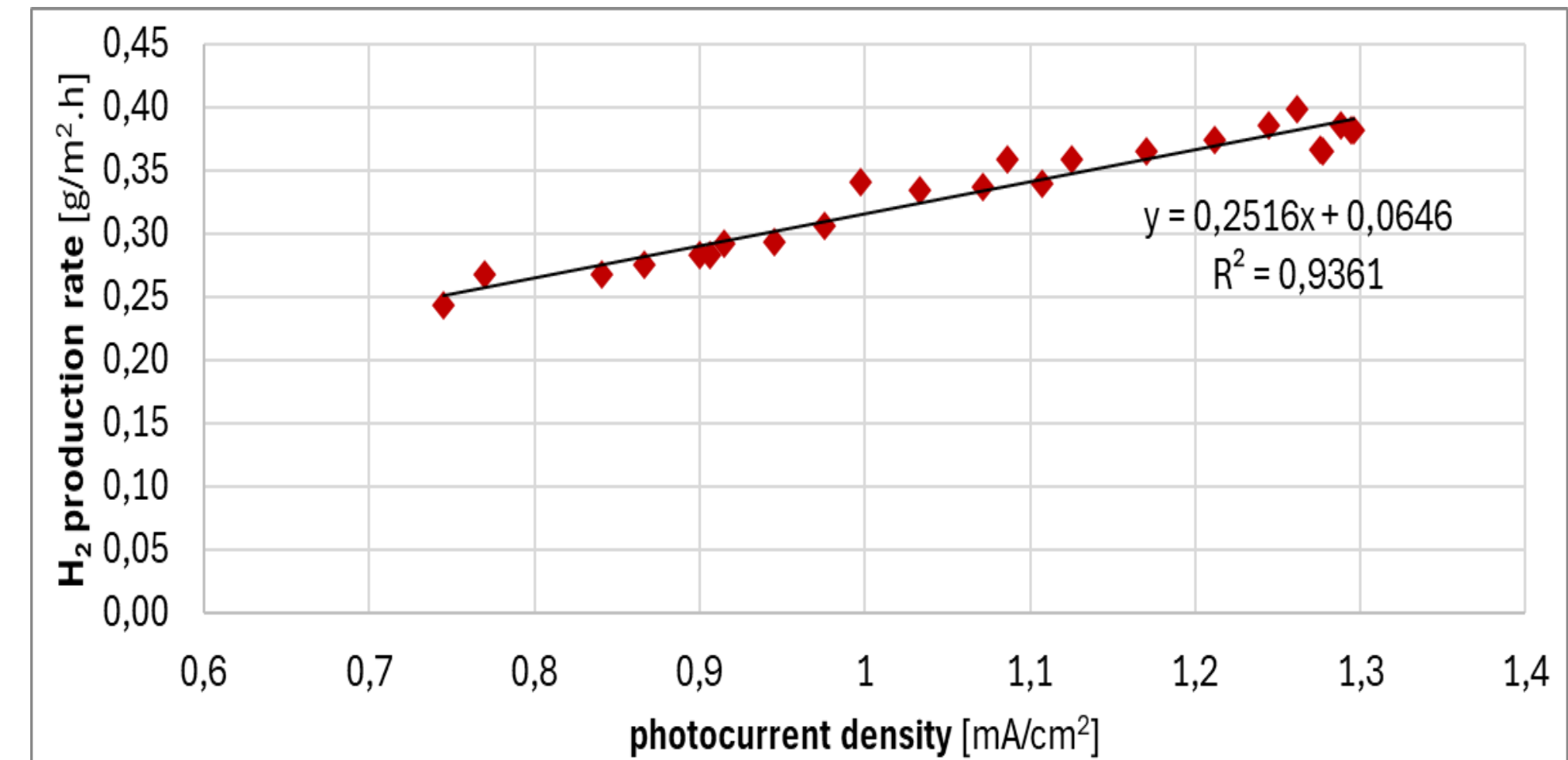
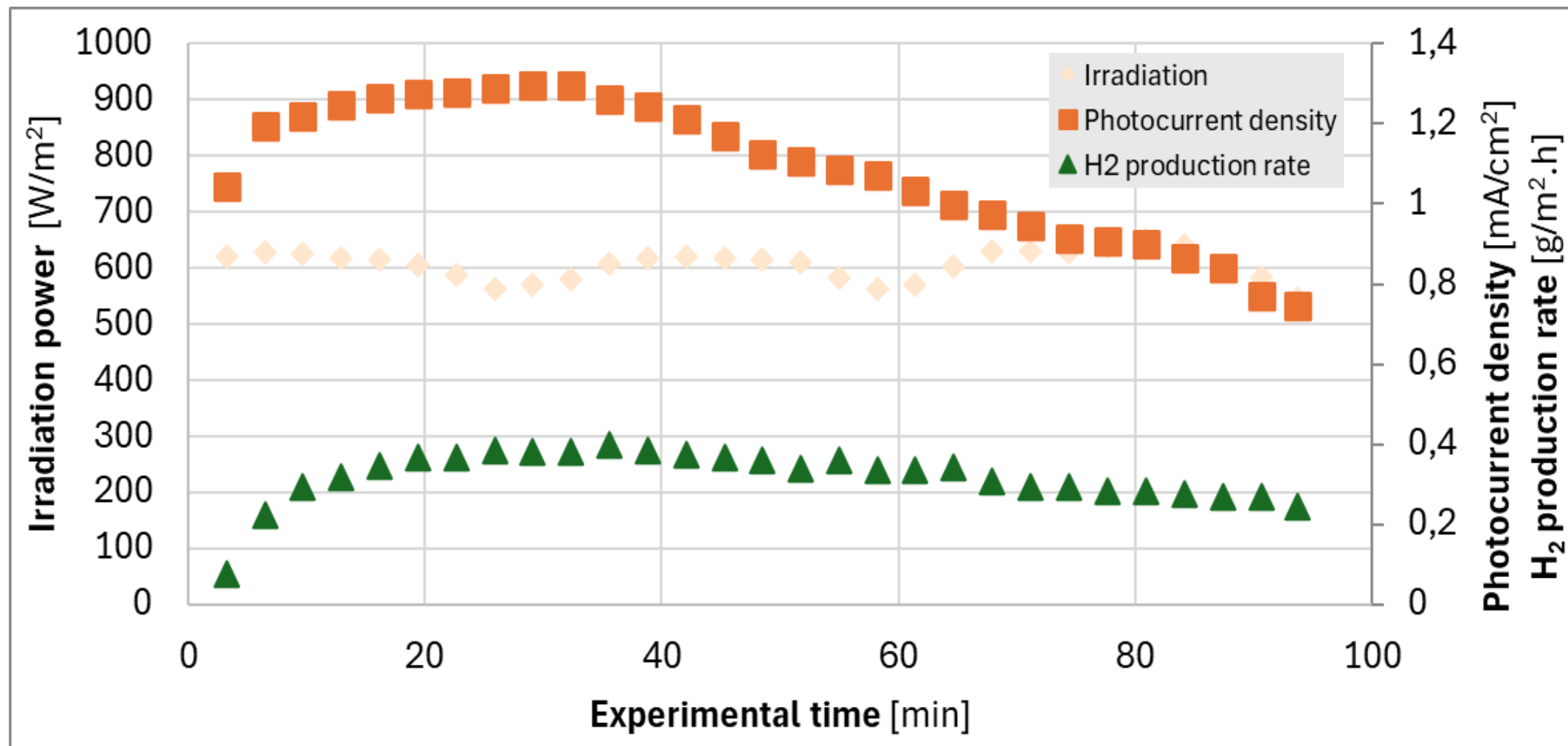
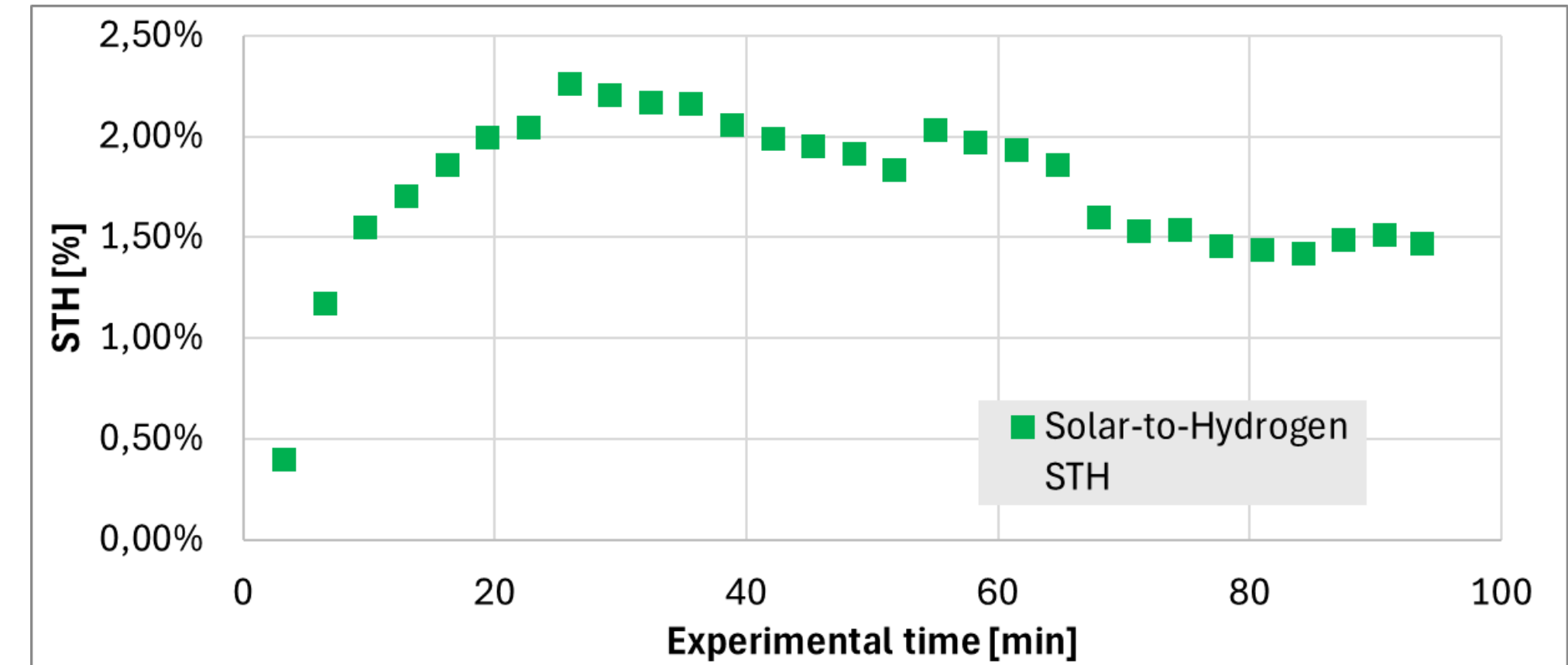
Results: Validation under real sunlight

- Influence of oscillatory parameters
- Optimum at Re 249 (=Reynolds oscillatory)



Results: Validation under real sunlight

- Exemplary results from outdoor tests
- Maximum STH 1,5 – 2% reached
- H₂- production rate 0,2 – 0,4 g/m².h



Summary

- **Photoelectrodes** for increased solar usage are important for (area) efficiency → BiVO_4 realized and up-scaled
- New solar photoreactor **design realized & validated** → important to **fit photocatalyst development with reactor design**
- **Experiments** with different wastewater components and in oscillatory flow for H_2 production were **successful**
 - EDTA shows highest H_2 production (stability?); Glucose showing best stability
 - Oscillation showing positive impact on product yield – increase ~20% in H_2 product rate possible; optimum $\text{Re}_o = 249$
 - Real sunlight experiments successful → STH 1-2% at 0,2 – 0,4 $\text{g/m}^2\cdot\text{h}$ of H_2 produced → further improvements to be made also towards **increase of land area efficiency**



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IDEA TO ACTION

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