ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

BACHELOR PROJECT

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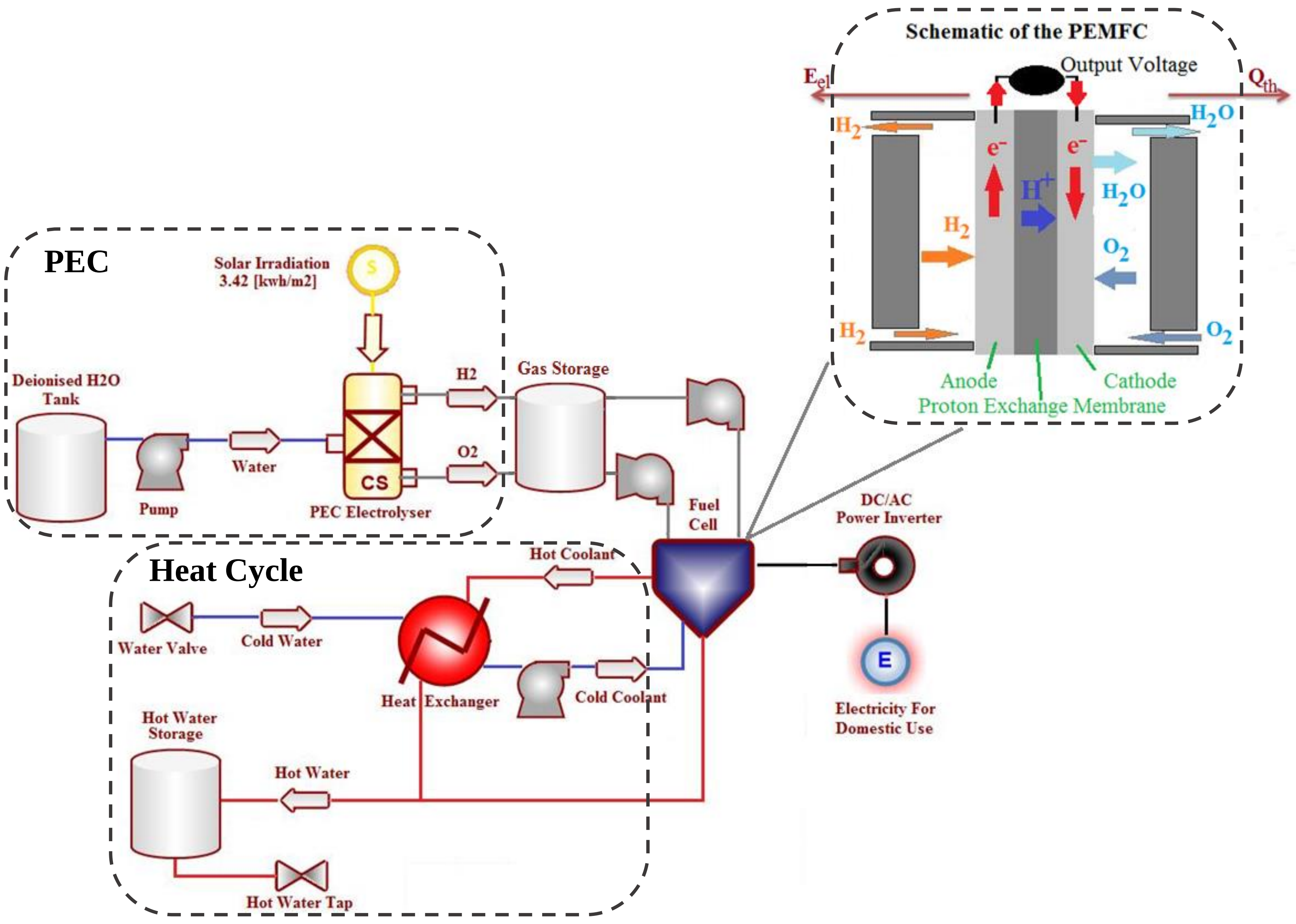
Technical and Economic Feasibility of a Small-Scale Hydrogen-Based Energy Production Plant

CONTEXT

The global yearly irradiance on land being 36'000 TW, the solar energy has the biggest potential for covering the current yearly global energy demand of 17 TW. Photo-electrochemical water splitting cells can convert this solar energy into hydrogen, which can be directly used in a fuel cell in order to co-generate electricity and heat. The present project estimates the technical and economic feasibility of using semiconductor-based photo-electrochemical (PEC) water splitting devices in conjunction with proton exchange fuel cells (PEMFC) for providing the energy services of a small scale, individual home. Two system types are investigated, focusing on either system efficiency (Design 1) or cheap and earth-abundant component choices (Design 2).

OVERALL PLANT DESIGN



PEM FUEL CELL

- ❑ The conversion of hydrogen in the fuel cell is conducted in two main reactions :

$$\begin{aligned}&Anode: && H_2 \rightarrow 2H^+ + 2e^-\\ &Cathode: && O_2 + 4H^+ + 4e^- \rightarrow 2H_2O\\ &Overall: && H_2 + \tfrac{1}{2}O_2 = H_2O \qquad \Delta H = -286\ [kJ/mol]\ (\rightarrow exothermic)\end{aligned}$$

- ❑ For the PEMFC performance, we based our computations on a net electrical efficiency η_{el} of 39% and a thermal efficiency η_{th} of 56%, resulting in an overall efficiency of 95%. We assume 8 hours of production per day :
  - Electric power supplied by the fuel cell:

$$P_{el} = \eta_{el} \cdot \dot{m}_{H_2} \cdot LHV_{H_2} \rightarrow \begin{cases} P_{el,design1} = 1.35\ [kW] \\ P_{el,design2} = 0.847\ [kW] \end{cases} \rightarrow \begin{cases} E_{el,design1} = 3'942\ [kWh/year] \\ E_{el,design2} = 2'473\ [kWh/year] \end{cases}$$

  - Thermal power supplied by the fuel cell:

$$P_{th} = \eta_{th} \cdot \dot{m}_{H_2} \cdot LHV_{H_2} \rightarrow \begin{cases} P_{th,design1} = 1.943\ [kW] \\ P_{th,design2} = 1.217\ [kW] \end{cases} \rightarrow \begin{cases} Q_{th,design1} = 5'674\ [kWh/year] \\ Q_{th,design2} = 3'551\ [kWh/year] \end{cases}$$

COGENERATION AND ENERGY CONSUMPTION COVERAGE

❑ The average Swiss household consumes per year : $\begin{cases} E_{el} = 3'500\ [kWh/year] \\ E_{th,SW} = 4'700\ [kWh/year] \end{cases}$

$$\text{Coverage ratio of electrical energy} \rightarrow \begin{cases} \tau_{el,design1} = 112.6\ \% \\ \tau_{el,design2} = 70.6\ \% \end{cases}$$

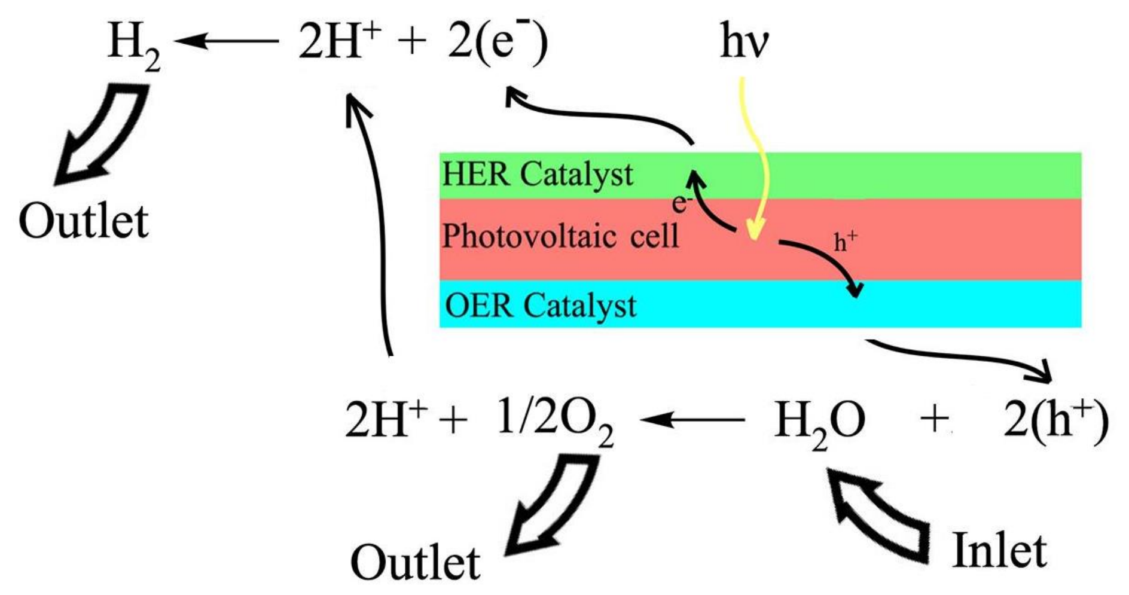
$$\text{Coverage ratio of thermal sanitary water energy} \rightarrow \begin{cases} \tau_{th,design1} = 120.7\ \% \\ \tau_{th,design2} = 75.56\ \% \end{cases}$$

SUMMARY OF THE COSTS [CHF]

	PEC Panels Costs	PEMFC Costs	Pumps and Pipes Costs	Deionised Water Costs	Control System Costs	Total Costs	Final Cost of produced Hydrogen
Design 1	16'630.-	20'189.-	700.-	8'280.-	7'900.-	53'699.-	**11.02 CHF/kg**
Design 2	9'632.-	20'189.-	700.-	5'220.-	7'900.-	43'641.-	**12.33 CHF/kg**

PEC DESIGNS AND SIMULATIONS

❑ The electrolysis of water is conducted in two main reactions as shown below :



Overall reaction and energetics :

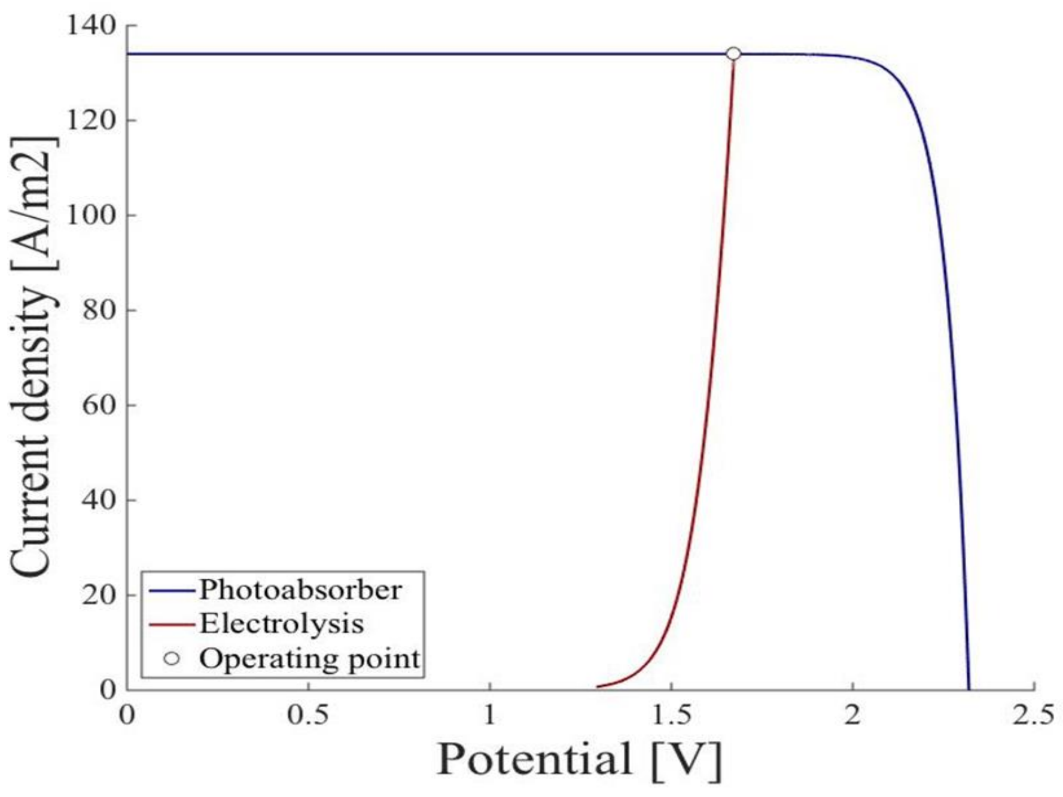
$$H_2O \rightarrow \tfrac{1}{2}O_2 + H_2$$

$$E^o_{ox} = -1.23\,\mathrm{V} \quad (OER)$$

$$E^o_{red} = 0.00\,\mathrm{V} \quad (HER)$$

$$\Delta G = +237.2\ [\mathrm{kJ/mol}]$$

❑ **Design 1:** Tandem $\mathrm{GaInP_2/GaAs}$ photovoltaic cell that lies on a GaAs substrate, coated with two platinum catalysts that drives the HER and OER.



Ex. Cur. Density : $J_0 = 5.21 \cdot 10^{-15}\ [A/m^2]$

Short Current Density : $J_{SC} = 134\ [A/m^2]$

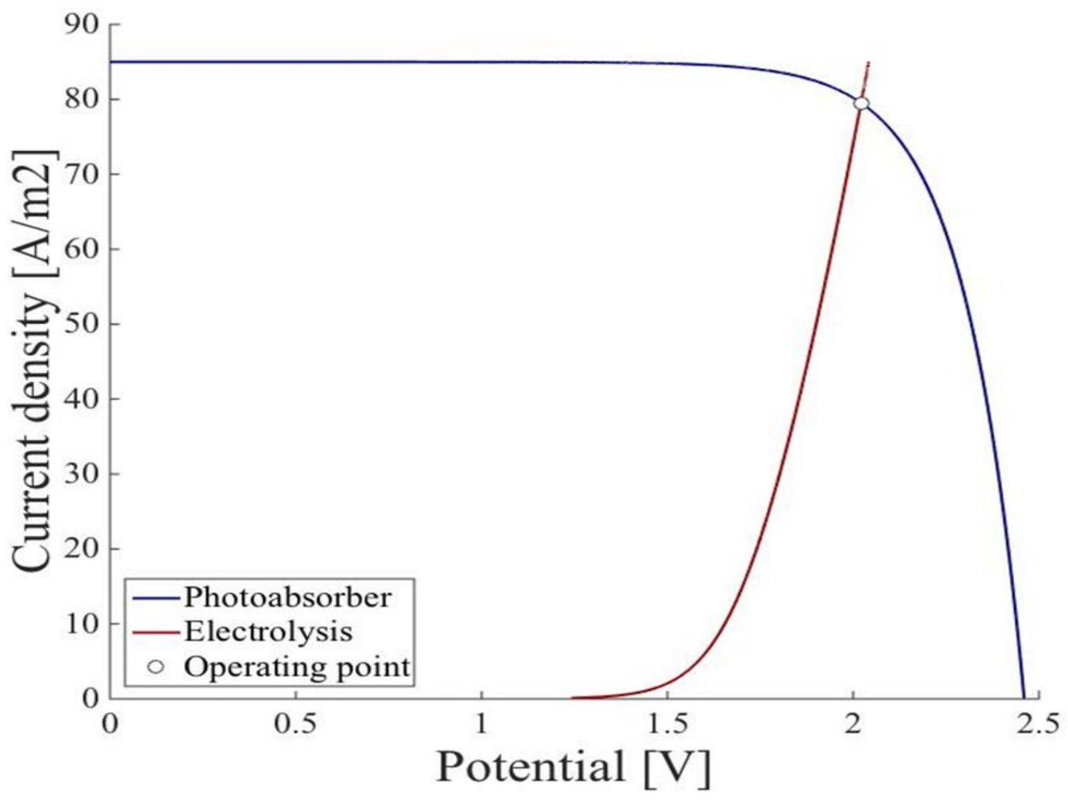
Correction factor : $n = 2.375$

Catalysts :

Tafel Slope : $\begin{cases} b_{Pt,HER} = 0.03\ [V/dec] \\ b_{Pt,OER} = 0.12\ [V/dec] \end{cases}$

Ex. Cur. Density : $\begin{cases} J_{Pt,HER} = 1\ [A/m^2] \\ J_{Pt,OER} = 0.186\ [A/m^2] \end{cases}$

❑ **Design 2:** Four c-Si PV cells connected in series with a NiB catalyst-layer for the OER and a NiMoZn catalyst-layer for the HER.



Ex. Cur. Density : $J_0 = 1.82 \cdot 10^{-5}\ [A/m^2]$

Short Current Density : $J_{SC} = 85\ [A/m^2]$

Correction factor : $n = 6.19725$

Catalysts :

Tafel Slope : $\begin{cases} b_{NiMoZn} = 0.13625\ [V/dec] \\ b_{NiB} = 0.05727\ [V/dec] \end{cases}$

Ex. Cur. Density : $\begin{cases} J_{0,NiMoZn} = 11.114\ [A/m^2] \\ J_{0,NiB} = 9.279 \cdot 10^{-7}\ [A/m^2] \end{cases}$

- ❑ The graphs give the current density (J) versus potential (V) curves of the cells.
  - blue curves expresses the photocurrent density by the diode equation :

$$J = J_{sc} - J_0 \cdot \left[exp\left(\tfrac{q \cdot V}{n \cdot k \cdot T}\right) - 1\right] \quad [A/m^2]$$

  - red curves are computed with the following equation:

$$\Phi_J = \Delta\Phi + \eta_a + \eta_c + 1.23 \quad [V]$$

  - The crossing of the red and the blue curve gives us the operating point, from which we can compute the STH efficiency:

$$\eta_{STH} = \frac{J_{op} \cdot 1.23}{S_{AM1.5}} \rightarrow \begin{cases} \eta_{STH,design1} = 16.47\ \% \\ \eta_{STH,design2} = 9.7\ \% \end{cases}$$

- ❑ The production of hydrogen in a PEC cell, based on the solar irradiance of Lausanne ($S = 3.42\ [\mathrm{kWh/day \cdot m^2}]$) is given by the equation:

$$M_{H_2} = \frac{S_{Lausanne} \cdot A_{panels} \cdot \eta_{STH}}{LHV_{H_2}} \rightarrow \begin{cases} M_{H_2,design1} = 0.816\ [kg/day] \\ M_{H_2,design2} = 0.513\ [kg/day] \end{cases}$$

CONCLUSIONS

- ❑ Based on our calculations, it is possible to cover the energy consumption per year for electricity and sanitary water heating of a Swiss household with the Design 1, whereas the Design 2 only covers ~70% off the mentioned consumptions.
- ❑ In order to be cost competitive with more traditional energy resources, the hydrogen should be produced at a price between 2.00 [CHF/kg] and 4.00 [CHF/kg][1]. The main drawbacks are the short life time of the PEC cells (10 years), and their still low efficiencies. Moreover, regions with more solar irradiance would produce more hydrogen.

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[1] Blaise A. Pinaud et al. ,Technical and economic feasibility of centralized facilities for solar hydrogen production via photocatalysis and photoelectrochemistry, Energy Environ. Sci., 2013, **6**, 1983-2002