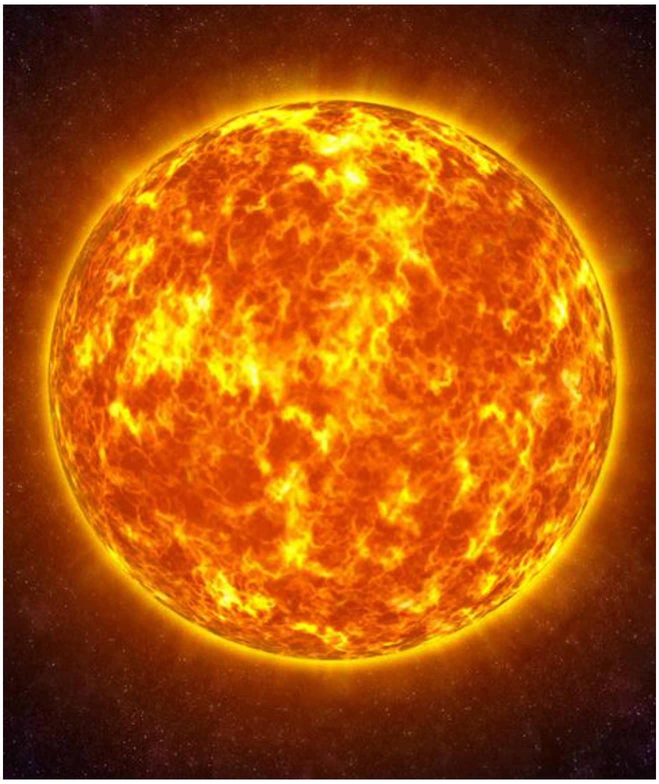

PEC versus PV-E
A Future Potential Comparison

Master Thesis

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PEC versus PV-E a future potential comparison

Abstract

The standard hydrogen production method uses methane as source. In this process the greenhouse gas CO_2 is emitted. An alternative hydrogen production method is from water with an electrochemical reaction. A technology which uses solar energy to produce hydrogen from water is a photoelectrochemical (PEC) cell. The PEC cell converts the photons into separated electrons and holes, which drives the electrochemical water splitting reaction. Unique about the PEC cell is both photon conversion and the electrochemical reaction are in one device. That should lead to cheaper hydrogen production and higher solar to hydrogen efficiencies, compared to it's direct competitor a PV-E system (a PV panel connected to an electrolyser). However, a PEC cell is still far from commercialisation, while the equipment of a PV-E system is available on the market. Therefore, the aim of this research is to compare the future potential of PEC vs PV-E. In this research are first comparable PEC and PV-E systems designed for the short term. In the second part is the future potential of both systems compared with more optimistic values. The results show that a lower future PEC system cost compared to PV-E could be possible, but that this difference is small. A lot of development and upscaling is expected needed to achieve this future lower cost for PEC, without being cost competitive in the market. Therefore, is it considered unlikely for a PEC cell to achieve a lower hydrogen cost perkg than a PV-E system.

Key words: PEC; PV-E; solar hydrogen production; potential comparison; LCOE; LCOH

Colophon

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Executive summary

Photoelectrochemical (PEC) cells are considered promising technologies to produce hydrogen. A PEC cell converts solar energy and water into hydrogen and oxygen in one device. Claims are that the hydrogen could be produced cheaply, due to high conversion efficiency and the use of cheap materials. PEC cells are however far from commercialisation, while the direct competitor (equipment) is available on the market. This direct competitor is a photovoltaic (PV) panel connected to an electrolyser(PV-E). For investments and selection of R&D subjects it is important to have insights in the potentials of PEC systems and PV-E systems. This research aims to answer: Will PEC systems be able to beat PV-E systems in costs versus performance in the medium till long term?

Therefore, two standalone systems are designed which must deal with the same environment and requirements for a fair comparison. A PEC cell design selection is done, because it is not on the market yet. The selected PEC cell design is chosen for its possibility of cheap large-scale production with realistic but high performance. The PV panels and electrolysers are already on the market, therefore only a selection of available technologies and price estimations are done. The balance of system costs of these systems is found in literature.

Results show a levelized cost of hydrogen of 10,14$/kg$H_2$ for PEC and 7,75$/kg$H_2$ for PV-E in the current/near term (2020). For both the electrolyser as the PEC cell is large scale production of the equipment assumed, despite the current lack of large scale production. This result makes clear that in the short-term PEC will not outcompete PV-E. For the long-term multiple parameters are given optimistic values to create better performance for lower cost. Potential future cost is calculated at 4,64$/kg$H_2$ for PEC and 4,99$/kg$H_2$ for PV-E. This difference is considered insignificant and therefore is concluded that PEC cells are unlikely to beat PV-E systems in costs versus performance in the medium till long term.

This difference is considered insignificant, because the PEC cell needs much development and scale up while not being competitive in a market. Therefore, this development must come mostly from scientific research. The (cost) development of PV panels and electrolyser is pushed by a commercial market besides the scientific research. PV panels and electrolysers operate also in other markets than solar hydrogen production. This ensures cost development of the PV-E system will continue even if there is no solar hydrogen market. Besides costs reduction, PV-E systems can generate other revenue streams by connection with the grid.

A second important issue this research highlights is the difficulty with selection of the right photoactive material, which seems to be a bottle neck in terms of cost versus performance for PEC cells. Compared to PV panels there are additional requirements for the photoactive material; a specific voltage and stability in a corrosive environment. Good performance on these additional requirements lead often to lower performance on other requirements as efficiency and cost of material. For instance, the additional requirement of a specific voltages prevents the use of cheap crystalline silicon, the current PV industry standard. To achieve high performance by efficiency (more) expensive materials are needed. The use of earth abundant cheap materials will not lead to the desired efficiencies that could outcompete PV-E with higher efficiencies. In terms of lab efficiency PV-E defeat currently PEC with 30% versus 16,2% solar to hydrogen efficiency. Therefore, the claim of higher potential efficiency for PEC might be never realized.

This research shows PEC cells might not be that promising as some literature describes. Therefore, it might be better to shift the focus in research to other promising subjects in solar hydrogen production. This could for instance be the development of a simple and cheap electrolyser, with decent efficiency which can be directly connected to three standard PV panels.

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List of abbreviations

A-Si - Amorphous silicon (thin film)
CAPEX - Capital expenditure
C-Si - Crystalline silicon (wafer based)
DC - Direct current
DOE - Department of energy (USA)
H_2 - Hydrogen
HER - Hydrogen evolution reaction
IRR - Internal Rate of Return
kWh - Kilo watt hour
LCOE - Levelized cost of energy
LCOH - Levelized cost of hydrogen
LHV - Lower heating value
NPV - Net Present Value
OPEX - Operational expenditure
OER - Oxygen evolution reaction
PEC (cell) - Photoelectrochemical cell
PEM - Proton exchange membrane (type of electrolyser)
PV-E - PV panel combined with electrolyser in one system
PV (panel) - Photovoltaic panel (solar panel for electricity production)
R&D - Research and development
TPD - Tonne per day
STE efficiency - Solar To Electricity efficiency
STH efficiency - Solar To Hydrogen efficiency

1. Introduction

1.1 Global warming and hydrogen economy

There is much concern about global warming caused by the use of fossil fuels. These concerns have pushed, with government support, a strong increase in renewable electricity production from photovoltaic(PV) panels and wind turbines.[1] However, these sources cannot scale up or down to match the demand as fossil based powerplants can. To enable a system with a large share of renewable power an energy buffer/storage is desired.[2] Hydrogen is often mentioned as one of the high potential energy carriers to play an important role as energy storage medium.[2]

Hydrogen(H_2) is a chemical with a high mass energy density (120MJ/kg lower heating value (LHV)). Hydrogen can react with oxygen to form water and release energy. This could be done in a combustion reaction where the energy is released as heat, which can be used to drive an engine. Or this could be done with an electrochemical reaction in a fuel cell, where the energy is released as a direct current (DC) and some heat. In the reverse electrochemical reaction hydrogen is created by splitting water molecules with a current. This reversible electrochemical reaction enables to store electricity (from renewable sources) into hydrogen. Storage of electricity in chemicals enables the reliable use of intermittent renewables at large-scale.[2] In this storage and recovery process are no direct emissions. The feedstock, water, is cheap and in most places abundant (where there is a desire for energy storage). All these elements contribute to its potential as energy storage medium.

1.2 Production methods of hydrogen

Despite its potential to be a storage medium for (renewable) electricity it is mainly used as feedstock material for other chemicals.[3] The scale of the worldwide hydrogen production was 1,3x107 tonne in 2016 and is mainly used by the chemical industry.[3] For this hydrogen is natural gas the main production source caused by its relative low costs. Hydrogen is produced from natural gas with a water-gas shift reaction. In this production process is the greenhouse gas carbon dioxide (CO_2) directly emitted. Replacement of natural gas with renewable energy will decrease the emittance of greenhouse gasses.

PEC cell

Hydrogen could be made off surplus renewable power production to store for later usage. While technologies could also be designed to generate hydrogen directly from renewable sources as a product instead of an electricity storage medium. One of these systems is named photo electrical chemical cell (PEC), which is a novel technology that produce hydrogen directly out of solar energy. An illustration of a PEC cell is given in Figure 1-1.

A photon its energy is absorbed by photoactive (semiconducting) material and creates a voltage sufficient to produce hydrogen out of water. Unique about a PEC cell compared to its main competitor is that all elements are in one system for a PEC cell.

PV-E

The main competitor for a PEC cell is a system with PV panels combined with an electrolyser (PV-E). In a PV-E system a photovoltaic module delivers electricity to a separate electrolyser to produce hydrogen.

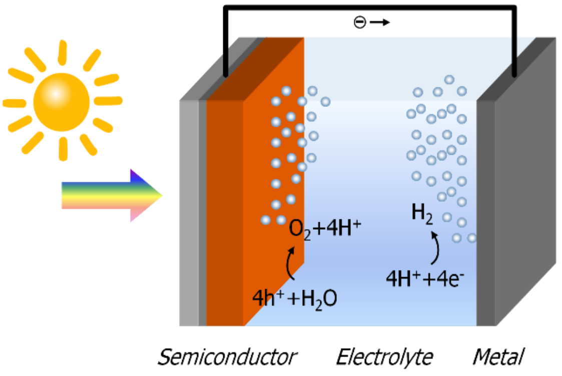


Figure 1-1An illustration of a type of PEC device, Source: https://pecdemo.epfl.ch/projectdescription

1.3 PEC versus PV-E

Both PEC and PV-E use solar energy to produce hydrogen. However, they differ at some important points. The PEC has all elements in one system, while a PV-E consist of two separate elements. The two main components of a PV-E system (PV modules and electrolyser) are commercially available. PEC cells are not commercially available yet, but are being developed (in laboratory). Some of the main advantages and disadvantages are described in Table 1-1.

Table 1-1 Advantages and disadvantages of PEC system over PV-E

Advantages PEC over PV-E

- Potentially cheaper caused by less material used
    - One encapsulation
    - No or little wiring
- Higher potential efficiency
    - Electrons must travel only a short distance, avoiding resistance in wiring and other defects
    - Low current density per area reduces resistive losses
    - Cooling of system by feedstock water

Advantages PV-E over PEC

- PV-E components are commercially available
- PV-E components are developed separately
- PV panels and electrolysers can be used for other commercially purposes as well
- Current lifetime of PEC cells is short (stable performance less than a week[4])
- Current record efficiency of PV-E is higher (30% vs 16,2%)[5,6]
- More requirements for photoactive material PEC
    - PEC panels use a corrosive electrolyte that photoactive material must withstand or be protected from
    - Current PV industry standard crystalline silicon material can't be used
        - PV-E systems can use any type of PV module, due to voltage management afterwards
        - Silicon crystalline is one of the more stable photoactive materials
    - For PEC is multi-layer photoactive material desired, which is still relative expensive
- PEC hydrogen production is spread over a large area and is outdoors
    - An outdoor environment is more aggressive to the system; solar irradiation, water(rust) & temperature(frost)
    - More piping and safety sensors required

Both PEC and PV-E modules come in different designs, depending on the design additional advantages and disadvantages appear. Many different designs and a variety of materials and technologies are therefore researched.[7–11] Most of the research focus on increase of efficiency, lifetime and the use of earth abundant cheap materials.

PEC versus PV-E in literature

Both systems can deliver the same product with the same input. Therefore, is the cost of each system the main indicator of its future potential. Cost predictions are performed in literature, for both systems.[7,10,11,4,12,13] However, almost all predictions are for PEC or for PV-E, but not together in one research. Direct comparison of the PEC and PV-E values of multiple researches is arbitrary. Because each of these calculations require a large amount of assumptions for both technical as economic parameters. Timeframe assumptions are also an important aspect which lead to different results.

Besides the use of different parameters, the main difficulty is that PEC cells are not commercially available yet. Therefore, is even more caution required for a PEC cost prediction. The main source used for cost expectations is a department of energy (DOE) report from 2009, which is an extensive cost estimation by James et al. (2009).[7] A few other sources are found that tried to estimate the cost of a PEC system.[8–10] However, these analyses are often for a large part based on the same DOE report.

In the DOE report the PEC cell is the main cost contributor of the system, while a full detailed division of a PEC cell is not given. Since PEC is not commercially available this kind of black box approach can be considered useful. Currently many researches still focus on material selection for PEC. With a black box approach change of (photoactive) materials is not an issue, as long the outcome stays the same. However, a fully operational PEC cell consists of multiple elements. Specification of material and production cost of these elements can give insight in minimal total cost and complexity of the PEC cell. A more detailed low-cost calculation for a PEC cell would emphasize the need of further development of specific components of the PEC cells.

For a PV-E system are these issues less relevant, because PV-panels and electrolysers are commercially available. Therefore, reliable data is available about cost versus performance. However, hydrogen is often not the final product in researches.[14,15] In these researches is hydrogen only a storage medium for electricity or fuel for a car. These sources can still be useful to find cost estimations about certain components for now and the future.

One research is found that compared PEC and PV-E directly.[4] In this research is a 10 tonne per day (TPD) hydrogen production compared of PEC, PV-E, PV-E with grid connection and hydrogen production from grid.[4] However, the type PEC cell used are based on PV panels integrated with a cheap electrolyser. Therefore, its arbitrary if it is a PEC or a PV-E system. Above that, a sharp decrease of PV-module costs has occurred and Shaner et al. (2009) used a low capacity factor for the electrolyser. Therefore, new research is necessary to compare PEC and PV-E directly.

1.4 Research question

There are many disadvantages of a PEC system compared to a PV-E system, together with a great uncertainty about its development. A lot more (expensive) research and development is required. Which leads to the **research question: Will PEC systems be able to beat PV-E systems in cost versus performance in the medium till long term?**

This research question leads to the following sub-research questions:

1. Which specific technologies are available and required in a PEC or PV-E system and what are their advantages and disadvantages?
2. What is the current state of technology development and what are the system costs?
3. What future developments can be expected and at what costs?
4. What are the main influencers to achieve cost reduction?
5. Is PEC expected to become better/cheaper than PV-E and will this difference be significant?

An answer to this could give insight in how useful further research and development of PEC systems could be. The analysis of the future potential also shows what elements seem to be the biggest opportunity or risk for a system. The PEC system could be completely replaced with a PV-E system with the same main input and output properties of the system. A PEC system should therefore outperform a PV-E system to become available on the market and be used on large-scale.

This research is academically important to show what is worthwhile to spend time and money on. It can help to set targets for development of specific system elements both in terms of technical properties as in cost.

Both systems produce hydrogen without direct greenhouse emissions. Insight in which system has more change to become a commercial success, could stimulate more R&D and subsidy for that system (which in general increases the chance of success). A success of solar hydrogen production would most likely decrease the carbon footprint of hydrogen production. Which is important in terms of global warming, but also for the dependency of natural gas.

2. Method

The purpose of the research is to compare two competitive technologies. To find out what their current competitive position is and what their future potential might be. This is done with a techno economic analysis. In a techno-economic analysis all technical elements to create a full working system are determined. Together with economic assumptions is the cost of the output product determined.

To answer if PEC systems will be able to beat PV-E an extensive analysis is performed. In this analysis are first comparable PV-E and PEC systems designed and cost determined for all elements in the systems. Secondly, the economic analysis is performed to calculate the current cost for hydrogen. At last, a sensitivity analysis is performed to determine the future potential of both systems.

The method used can in general be qualified as a bottom up analysis. A bottom up analysis starts with combining the detailed components of a system to work up to a value for the complete system. In this research this value is the cost of hydrogen. One of the main purposes of this research is to find out what the main cost contributors are, if it is feasible to reduce these costs and what the effects are of certain cost reductions. A top down approach would have resulted in insight in how much every part should decrease in cost, without the necessary insight in how that should be achieved.

2.1 System design

First are the system properties determined that are the same for both systems; average daily production, output properties and location specific input parameters. Industry standards are used when possible and an optimal location is selected in terms of solar irradiance and available data. These values are important for scaling the system and its components and are taken from previous cost estimations.

Next step is the selection of elements for the PV-E system. An analysis is done for each element for the best fit from a technical and cost perspective. Current prices of PV systems where examined together with PV industry expectations. This provided a basis about cost and performance expectations for photoactive devices such as PV panels and PEC cells. With the selection of electrolysers is the suitability examined to work on current from PV panels.

The design of a PEC system started with a design of a PEC cell, because a PEC cell is not commercially available yet such as PV panels and electrolysers. This design is made by comparison of multiple designs made in literature. The selection is mainly based on the properties: efficiency, lifetime and potential producible at large-scale for low costs. Cost determination is for a large part based on cost divisions of other PEC cost predictions and cost of PV panel parts. The components that are required to create two working systems are taken from an extensive DOE report and corrected for inflation.[7]

2.2 Economic analysis

In the economic analysis the main output value is the cost of hydrogen of both systems. The system with the lowest cost is economically preferred. The sensitivity analysis adds more insight to the meaning of the cost values. This could help to create a feeling how both technologies could perform in the future, by examination of the optimistic values. Selection of parameters for the sensitivity analysis was done with the cost division made. The cost division showed which elements of the systems are the main contributors to the cost. Change of these values in the sensitivity analysis resulted in significant effects.

2.2.1 Cost of Hydrogen

Comparison of technologies with a techno-economic analysis is based on the output of economic calculations. Technologic parameters such as component lifetime and efficiency are import input parameters for the calculation of cost and benefits. The main output value is the price of a kg hydrogen that is required to receive a selected return for the investment. This outcome is referred to as the Levelized Cost of Hydrogen(LCOH) or the cost/price of hydrogen. The output values are based on the combination of some economic calculation methods. These are the Net Present Value(NPV) and the Internal Rate of Return(IRR).

Net Present Value

The Net Present Value (NPV) is a calculation method that is used to take into account the time preference of money.[16] An amount of money today is normally worth more than in the next year, because of inflation and possible interest. It is assumed that the used PEC and PV-E systems will require relative large financial investment at the start of the project, while the revenue is more evenly spread over the lifetime of the total system. The formula of the NPV is stated at Equation 1 and indicates if an investment could be worthwhile.

Equation 1 Net present value

$$NPV = \sum_{i=0}^{n} \frac{\mathrm{B}i - \mathrm{C}i}{(1+r)^{i}}$$

NPV = Net present value of the project at the beginning of the first year (t = 0)
B*i* = Benefits of the project in year i
C*i* = Costs of the project in year i (at the beginning of the project (t = 0) this could include an initial investment)
r = Discount rate
n = Lifetime of the project

Internal Rate of Return

The Internal Rate of Return(IRR) is the interest rate the investor wants for his investment. This is a value that gives an indication if it is wise to invest in this project. Therefore, the IRR must be at least higher than the interest received on a savings account. You can find the IRR by setting the NPV at zero, which will make the discount rate equal to the IRR. In this research is the desired IRR selected at 10%.

Levelized Cost of Hydrogen

The levelized cost is the cost/price of hydrogen(LCOH) that is required to enable a desired IRR. The LCOH is a fixed price for the product during the whole lifetime of the project. This is done by selection of an IRR and calculation of a NPV of zero by changing the LCOH. Since the benefits(revenue) in a year is the annual production times the LCOH. The calculation of the LCOH considers the discounted cost and benefits throughout the lifetime of the project. The formula is applicable to all kinds of energy carriers and is in literature more generally referred to as Levelized Cost of Energy (LCOE). A brief equation of the LCOE is given at Equation 2.

Equation 2 Levelized Cost of Energy

$$LCOE = \frac{\sum_{t=0}^{n} \frac{\mathrm{C}t}{(1+r)^{\wedge}t}}{\sum_{t=0}^{n} \frac{\mathrm{E}t}{(1+r)^{\wedge}t}} = \frac{Sum\ of\ all\ costs\ during\ lifetime}{Sum\ of\ all\ produced\ hydrogen\ during\ lifetime}$$

C*t* = Cost in year *t* (this includes investment, operation, maintenance costs & fuel costs)
E*t* = Energy production in year *t* (in our case kg Hydrogen)
r = Discount Rate (In this case the IRR)
n = Lifetime of project
t = Year within lifetime (with special note that it might vary)

2.2.2 Cost division of the LCOH

It is interesting to find out which components are the major contributors to the expected cost of the systems. This is done by selection of the depreciation of the investments together with the annual cost. The division of these costs is multiplied with the LCOH, to see the effect of each system part in the LCOH. This is represented in a bar diagram. Such a division and display of the cost build up can indicate which relative cost reductions have the largest effects. But it can also indicate a future minimal LCOH with a system considering no/minimal cost reductions of some components.

2.2.3 Sensitivity

The sensitivity analysis is used to show the effect in LCOH of more optimistic and pessimistic values. Especially PEC cells, but also electrolysers, have large uncertainties about the current and future costs. The pessimistic values show the result if cost decrease and desired performance are not met. While the optimistic values show what the low-cost potential could be of each system in the future. Comparison of both systems ranges can give input if PEC has the potential to beat PV-E in the future. The sensitivity analysis is performed by selection of optimistic values mentioned in other researches. While the pessimistic value is a price today or for instance a predicted value for small-scale near future component.

3. Analysis

In the analysis are all steps to compose the systems and to perform the calculations described in detail. For each parameter a value is defined. The outcome of the analysis is presented in the results chapter.

The analysis consists of the following steps:

1. Technical and economic parameters for both systems
2. Techno-economic analysis PV-E system
3. Techno-economic analysis PEC system
4. Sensitivity analysis

3.1 Technical and economic parameters for both systems

Multiple parameters are selected that are required to shape comparable systems. These values set the circumstances equal and realistic for both systems.

Scale of system

An average of 10 tonne per day (TPD) production of H_2.

This scale is selected because it is large enough for (small) industrial scale. It should be large enough to gain economies of scale advantages, to create realistic market prices. Other cost calculation reports and researches also use 10TPD or a scale in this range.[7,10,4]

Output pressure

20bar

Industrial used pressure.[7]

Purity

99.9%

Acceptable and achievable purity.[7]

Solar irradiance

6.19kWh/m^2/day on average

925W/m^2 maximal irradiance

The irradiance is an important parameter when scaling parts of the system. The daily average irradiation is used to create on average 10TPD systems. This means that the system is designed for larger scale than 10TPD peak output. The main element for the scale of all components is the maximal irradiance. This determines the maximal hydrogen output for a PEC cell, which together with efficiencies determines the scale of almost all elements in the system.

These chosen values are taken from James et al. (2009) section 3.5. In James et al. (2009) a location is selected and all the important aspects are considered (e.g. refraction, angels, hours of sun). Some other researches uses higher irradiance[10] or lower irradiance[4]. These different input values will lead to different results in LCOH, which is one of the reasons it is arbitrary to compare to outcome of different researches directly. For a direct comparison it is only important that the environment input values are the same. Selection of decent input values will only make the result more realistic.

Lifetime

20 years

Such as most researches is 20 years selected.[7,4,13,17] This term is also often seen for tenders of wind or PV parks.[18] Longer lifetimes might be interesting, since some elements have a longer lifetime expectation such as PV panels (25year).[19] However, a longer lifetime will also increase uncertainties of especially cost of other elements.

Year of start

2020 is year 1

The year 2020 is considered the near future. PEC cells are not commercially available yet, while PV panels and electrolysers cost are expected to decrease. A PEC system like this in 2020 is probably still optimistic. Because no standard design is chosen and no commercial PEC cells are found. While in this research it is assumed that the PEC cells are made in mass production. 2020 is for especially PEM electrolysers a year in which electrolyser cost should have decreased significant.[20] In year 0 (2019) the complete systems are build.

Capacity factor complete system

0,95

Capacity factor is here defined as the total work performed / the total work that theoretical could be performed. A value of 0,90 by James et al. (2009) would mean an average 36 days of no production. Victoria (2015) uses a value of 0,99, which leave little room (5 days) for defects and replacement times. For these systems much maintenance could be done after the sunset, without affecting the capacity factor. Therefore, a capacity factor of 0,95 is selected.

Inflation rate

1,9%

Labour

1,02M$ in year 1 with inflation adjustment each year.

For both systems are the same labour costs assumed. To determine if this is realistic an in-depth research should be done with a cost comparison of inspection, maintenance and operation control of all elements. The labour costs are based on an average salary of 25$/hr and 40.880hours of labour per year. The sun only shines during the day, so two 8hour shifts are assumed per position per day. Assumed that there is every day a full crew of 7 people working simultaneously of which one is a supervisor. The comparison below shows that expected labour costs might be optimistic and differ a lot in other researches.

- James et al. (2009) 21 employees for 10TPD, 50$/hr
- Victoria (2015) 10 employees for 0,5TPD, 16,5$/hr

Insurance

2% of the capital cost in year 0, inflation corrected

Alike James et al. (2009).

Taxes

24,9%

The system is expected to be in the USA. In James et al. (2009) a tax rate of 38,9% was used, of which 35% was federal and 3,9% state or other taxes. New tax laws reduce the 35% federal to 21%, which results in a total of 24,9%.

Ground cost

629$/acre (0,15$/m^2)

From James et al. (2009) is the ground price taken and adjusted for inflation.

3.2 PV-E system

A PV-E system consists of photovoltaic cells and a separate electrolyser. One of the claimed advantages is that both components can be developed individually. Although they must work together this combination still offers a variety of options to choose from. First is a PV panel selected including additional components that are required. Second the electrolyser is selected. For both components is cost compared to performance the parameter to determine the type of the component selected for the systems.

3.2.1 PV systems

The selection of a type of PV module is mainly based on a direct cost of performance analysis. The main value for a PV module is $/W. Which enables direct comparison of modules without examination of efficiency or materials used. With a note that efficiencies and other properties can have significant effect on the balance of system (BOS) costs. For a decent selection the following subjects are examined:

- Current PV market standard and competitors
- Balance of system
- Learning curves
- PV selection of type and corresponding properties

Current PV market standard and competitors

The PV market is currently dominated by crystalline silicon single-junction PV cells, with commercial efficiencies till 20%.[21] These silicon panels outperform others in total cost. Other types of PV cells are developed as well; organic, quantum dots, perovskite and dye-sensitized. Within these types there are multiple variations such as single-junction, multi-junction and thin film. The large variety of differences between the PV technologies create (niche) market opportunities.

To determine if silicon might be surpassed as market standard, an examination at the relative disadvantages of the current silicon is done.

Disadvantages of silicon base PV cells:

- Energy intensive to produce[22]
- Relative thick layer of silicon caused by bad photon absorption[22]
- Requires a (thick/strong/heavy) glass protection[22]
- Rigid (not flexible) [22]
- Needs to be produced in batches[22]
- Relative low theoretical efficiency (highest lab efficiency is around 25.3%[23] and commercial efficiency is already at 19.9%[21])

Caused by these relative disadvantages there are claims for other PV types to be potentially cheaper. Arguments for these claims are: continuous roll printing, a 1000 times less photoactive material required, less energy required in production process and higher efficiency.[22] However, most technologies are not commercially available yet or need large-scale ups. Most technologies with higher efficiencies are multi-junction and more expensive, while others have less efficiency and lack durability.[22] However, a main competitor is CdTe thin film panels by the company First Solar. Which claims highly competitive prices after realisation of new factories.[24]

The crystalline silicon PV cells are made in panels (a PV module). Besides panels other PV types based on thin film can be made as semi-transparent PV windows, PV roof tiles or a mounted PV film. These options are currently financially only interesting in the build environment where windows or roof tiles are already required. For this comparison we assume a PV park on its own, with low cost of land. Panels are desired for this PV park due to relative low cost, high efficiency, durability & scalability. It will remain uncertain if c-Si panels will stay the industry standard or that for instance CdTe panels will achieve a better cost performance ratio.

Balance of system

Total system cost is not only about the module but includes the balance of system (BOS) costs, which are all other costs made to create a working system. The BOS can be divided into a hard-BOS and a soft-BOS. The hard-BOS are the other materials required for operation, for PV is this: wiring, mounting, ground and the inverter, see Figure 3-1.[19] The soft-BOS are the non-material costs such as permitting and installation.

The costs for ground are excluded from the BOS in this research, because they are calculated separately. The inverter is used to create alternating current and could be left out or replaced by a DC/DC converter. Shaner et al. (2016) left it out, because efficiency loss caused by non-optimal operation is expected the same as caused by the DC/DC converter.[4] Leaving out the DC/DC converter decreases the electrolyser efficiency.

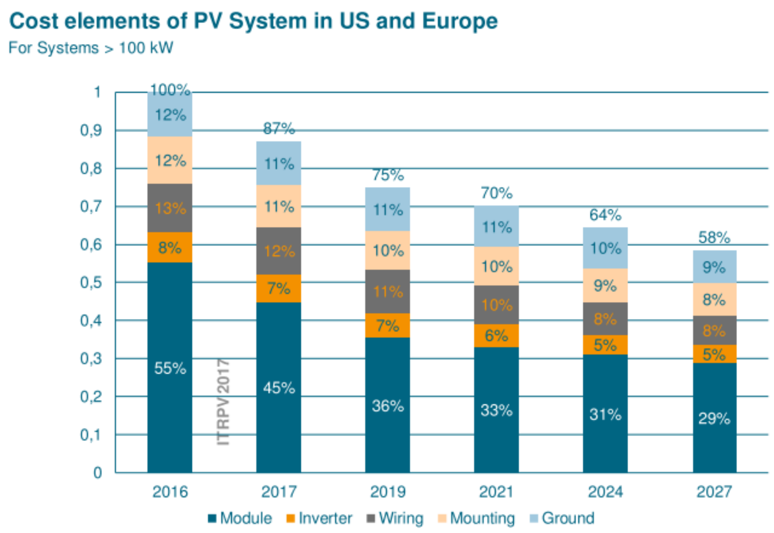


Figure 3-1 Cost reduction expectation for complete PV system, Source: ITRPV Report 2017

For large systems (>100kW) is the module about half of the expected total costs.[19] For domestic installations the PV module might only be around 20% of the costs.[25] In this research the BOS values of large systems are used. A point of attention is that a PV module can have some influence on the BOS. The amount of mounting material is directly corelated with the modules efficiency. Effects of adjustments to properties of a PV module must be calculated for BOS, although the effect tend to be minor.

Learning curves

Figure 3-2 shows the cost reduction against cumulative shipment of PV modules. Silicon panels are now the main contributor to this graph. Silicon based technology seems to be at least favoured in the short-term with a continuous learning curve.[19,22,26] Continuous improvement is expected for the silicon based modules. These improvements are mainly in terms of: less material used, less energy consumed, increased efficiency and increased durability.[19]

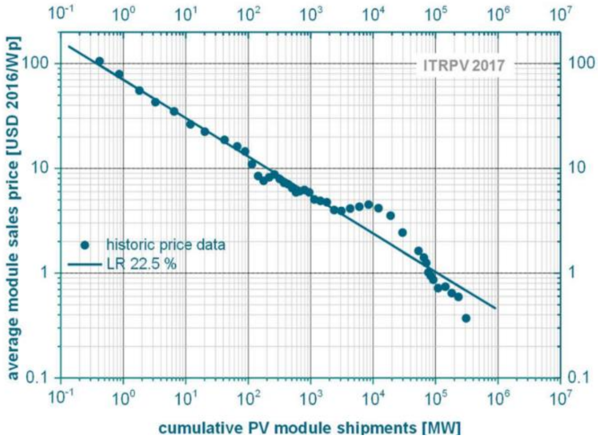


Figure 3-2 Learning curve PV modules based on cumulative shipment, source: ITRPV Report 2017

Besides module cost are BOS also expected to decrease as shown in Figure 3-1. Different materials, standardization and larger scales are the main contributors for this decrease.[19]

PV selection and expected cost

Crystalline silicon single-junction panel based; 18% efficiency;
0,30$/W module cost; 0,12$/W wiring; 0,14$/W mounting material

Silicon is the current industry standard due to its: low $/W value, relative good efficiency, good stability and durability. When silicon panels are surpassed by a competitor for instance thin film CdTe, then that competitor can be used in the PV-E system in the same way. The main parameter is the $/W value of the module and BOS together. Under the condition that stability in production for minimal 20 years is guaranteed. For current/near future 2020 is examined the properties of silicon crystalline panels.

Selection of properties

For the cost of PV panel there is a website (https://pv.energytrend.com/pricequotes.html) that gives current factory prices of modules. Most sources used in this research have taken the prices of this website when they refer to crystalline silicon PV cost.[4,19] With a scale of 10TPD an order can directly be done at the factory for these costs. Besides current price, the price other research took and their hard-BOS cost were examined. An overview of this is displayed in Table 3-1.

Table 3-1 Properties in terms of efficiency and cost of PV modules, mounting material and wiring from multiple sources

Properties in terms of efficiency and cost of PV modules, mounting material and wiring
Source: Pv.energytrend.com[21] (11-10-2017) Module cost in $/W at 11-10-2017 per low/average/high efficiency - Multi-Si: Low 0,32 / Average 0,368 / high 0,40 - Mono-Si: Low 0,36 / Average 0,384 / high 0,42 - Highest commercial efficiencies silicon PV-cell till 20.8% - 280-285W/module is standard output for mono-Si panels which lead to 17,4% module efficiency, with the assumption of 1,64m2 surface per panel - (26-1-2018) Average price is 0,358$/W(Multi) and 0,367$/W(Mono) a decrease of 0,010$ and 0,014$ in about three/four months
Source: ITRPV Report 2017[19] (1-1-2017) [2016$] - PV module: efficiency 17,5%, 0,37$/W, 64,75$/m^2 - See Figure 3-1: In 2017 is the PV module 45/87 of total system cost, wiring 12/87 and mounting 11/87. o Mounting: 0,09$/W, 15,83$/m^2 o Wiring: 0,10$/W, 17,27$/m^2
Source: Shaner et al. (2016)[4] [2014$] (Their source: pv.energytrend.com, 2015) - PV module: efficiency 16%, 0,60$/W, 96$/m^2 - Mounting: 29$/$m^2$, 0,18$/W - Wiring: 16$/$m^2$, 0,10$/W
Source: Fu et al. (2017)[27] [2017$] - PV module: efficiency 17,5%, 0,35$/W, 59,50$/m^2 - Mounting: 17,50$/$m^2$, 0,10$/W - Wiring: 17,50$/$m^2$, 0,10$/W

Cost is expected to decrease for both modules and BOS, as shown in Figure 3-1.[19] The ITRPV report 2017 predicts a 20% decrease of module cost in two years, from 2017 to 2019. This would mean a price of ~0,30$/W in 2019. First Solar a CdTe thin film producers aims for 0,20$/W in 2019.[24]
0,30$/W is selected for the PV system in this research, which is a significant cost reduction but modest compared to ambition of First Solar. The commercial efficiency is set at 18%, a slight increase compared to current standard.
0,08$/W is set as cost for mounting material; a decrease that is in line with the ITRPV report 2017.
0,09$/W is set as cost for wiring; a value slightly lower than Shaner et al. (2016) and the ITRPV report 2017. 20years lifetime is assumed for these three components, which is for the current products no issue.

3.2.2 Electrolyser systems

Multiple types of electrolysers are available, first a short analysis of their properties is done. Based on their specific properties in relation with PV panels a selection is made. Next, the specific technical and cost parameters are determined.

Types of electrolysers

The market of PV is large and grows rapidly, while the market for electrolyser is relative small and moves more slowly. Within the electrolyser market the Alkaline electrolyser could be considered the market standard. With a decent efficiency and a relative low price, it is favoured in most industries. However, it is still expensive and no learning curve is discovered by Schoots et al. (2008).[28] Still the predictions are that cost of these electrolysers will decrease by an increase in scale, automatization and further development.[17] Many research has been done to determine the optimal electrolyser in general.[29,2]

Besides Alkaline, is the Proton Exchange Membrane (PEM) often mentioned as promising electrolyser. The PEM is also commercially available but currently more expensive and available on a smaller unit scale. For both electrolysers are system analysis done in combination with PV; PEM[5,12,17,30] & Alkaline[15]. The main advantages and disadvantages of Alkaline and PEM are described in Electrolyser. In Appendix A are other types of novel electrolysers mentioned. These novel electrolysers are not further considered in this research, due to their current state of development. However, they indicate that in the long-term other electrolyser design are possible which perform better and are cheaper.

In a PV-E system PV-panels can deliver a strong fluctuating current as shown in Figure 3-3. An electrolyser should be tolerant for strong fluctuations. Other important electrolyser criteria are cost, durability and purity of products. The PEM electrolyser is selected in most researches to combine with PV-panels, because of its flexibility to handle strong fluctuating current.[12,17,30] In terms of costs are large reductions expected[17,20], which should make them also cost competitive with Alkaline. Therefore, PEM is selected in this research as electrolyser.

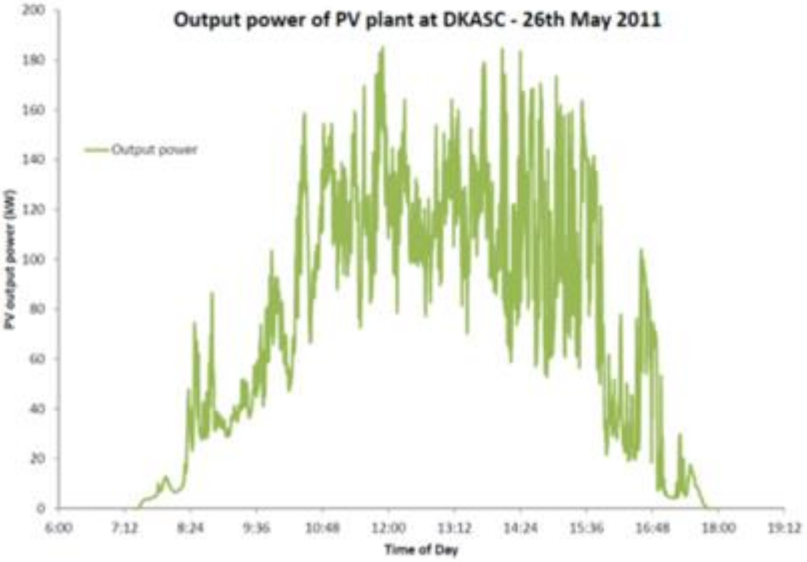


Figure 3-3 PV daily power output Source: (Sayeef et al. (2012))

PEM stack and balance of system

Design

A fully operational PEM system requires more than the electrolyser(stack) as illustrated in Figure 3-4. Thermal management is not in Figure 3-4, but could be added to this.[17] The PEM cell elements besides the stacks are referred to as hard-BOS. For the PV-E system in this research the 'Power Electronics' and 'Oxygen Gas Management System' are excluded. No transformer and rectifier are required since the PV panels deliver direct current. As mentioned in the PV selection no DC/DC inverter is used either. The Oxygen produced is vented to the air in the PV-E system.

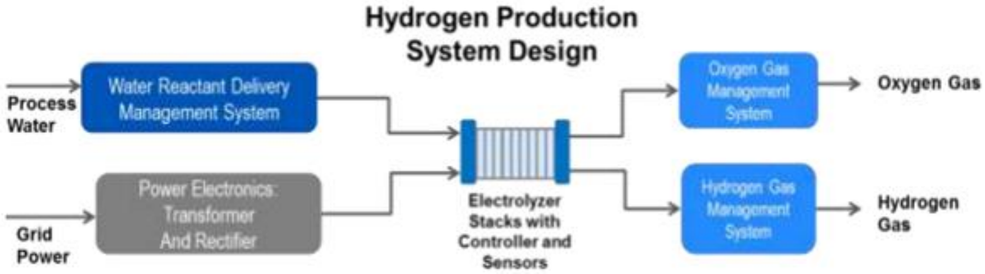


Figure 3-4 Simplified overview of elements required for a working PEM system, source: (Ainscough et al. (2014)

The main component of a PEM system are the electrolyser stacks, where the actual hydrogen production take place. The stacks consist of Multiple PEM cells. In Figure 3-5 is an illustration given of the working principle of ad PEM cell.

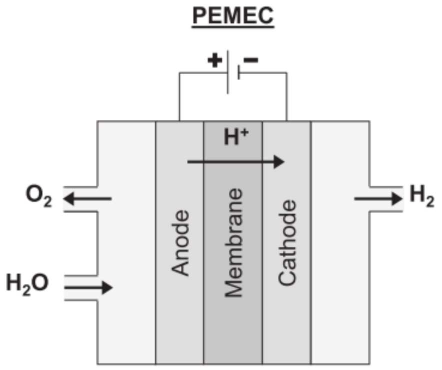


Figure 3-5 Illustration of working principle PEM electrolyse, Source: (Schmidt et al. (2017))

A short overview of main components is given for a PEM cell.

- Membranes (only let through the protons H^+)
- Catalysts (donators of electrons and holes to enable the electrochemical reaction)
- Bipolar plates (Separate cells, give support for the system)
- Gas diffusion layer (regulates level of reactants and products for catalyst)
- Gasket (seals the edges to prevent leakage and mixing of chemicals)

Claims of PEM system properties

The market scale of electrolysers and especially PEM is much smaller than for PV systems. Therefore, only limited data is found. The main properties of PEM systems are efficiency, cost and lifetime, see Table 3-2. It is important to distinguish between stack and system costs, since that is not always clear.

Table 3-2 PEM system properties

Source	Efficiency	Cost currency/kW,el input	Lifetime
Shaner et al. (2016)	61% for system* 68% for stack	400$/kW stack [2014$] 375$/kW BOS [2014$]	7 years*
Bertuccioli et al. (2014)	For system: 60%(2015) 64%(2020) 67%(2030)	For system: 950-1600€/kW(2015) 600-1000€/kW(2020) 600-800€/kW(2030) Stack cost: 60% of system costs in 2015	

*This system also excludes DC/DC inverter, transformer and rectifier, but assumes a decrease from max efficiency caused by non-optimal current from PV and electricity use by other components.

Properties of PEM system used in this research:

All selected properties are based on Shaner et al. (2016). These values are already in dollars and in the range of the values expected by Bertuccioli et al. (2014). Shaner et al. (2016) system had the same system requires, such as no inverter.

- 61% efficiency for system (electrolyte pressure pump included)
- 400$/kW stack
- 375$/kW BOS (power electronics/inverter excluded)

3.2.3 PV-E complete system

An overview is given of all components selected for the PV-E system in Table 3-3

Table 3-3 Overview PV-E elements

PV-E element	Assumed cost in 2020 [2017$]	Properties
PV module	0,30$/W (54$/m^{2}solarpanel)	18% efficiency, 20y lifetime
Wiring	0,09$/W (16,5$/m^{2}solarpanel)	20 years
Mounting material(/racking)	0,08$/W (15$/m^{2}solarpanel)	20 years
PEM electrolyser stack	400$/kW	61% BOS losses included, lifetime 7years
Water/electrolyte supply (pump included)	Included in hard-BOS of 375$/kW*	20 years
Hydrogen gas processing (collection piping system)	Included in hard-BOS of 375$/kW*	20 years
Thermal management system	Included in hard-BOS of 375$/kW*	20 years
Sensors	Included in hard-BOS of 375$/kW*	20 years
Control system	Included in hard-BOS of 375$/kW**	20 years

*James et al. (2009) did an extensive calculation for a 10 TPD PEC system that is used as the main source for the system cost PEC system. The water reactant system had a price of ~2$/m2, which is insignificant when other costs are exanimated.

** James et al. (2009) had for PEC a Control system cost of ~7/m^2 (4M$ for 10TPD). Main contributors were Water Level Controllers and Hydrogen Area Sensors (46% &49%). Both are in the PV-E used on way smaller area due to large hydrogen production capacity per electrolyser compared to a PEC cell. The water processing, gas processing and other additional equipment are assumed to be accounted in the BOS of the electrolyser.

3.2.4 PV-E Soft Balance of System

Soft Balance of System costs

There are other costs that are non-material based and are made in year zero. These are referred to as soft Balance of System (soft-BOS) costs. These cost can vary per country significantly, due differences in: maturity of technology, labour rates, laws and other variables.[19] Often are some cost left out the soft-BOS, such as installation cost.[10] A few main costs of soft-BOS are listed below, together with expectations of the difference for PEC compared to PV-E. These expectations and findings in literature are the basis of the soft-BOS cost selection of both systems.

- Installation: Almost same amount of area. PEC requires more piping and compression. PV-E requires more cabling and installation of PEM electrolysers. The expected costs are similar.
- Contingency: PEC is a less mature technology. In a PV-E system both parts can be replaced separately. PV-E system will most likely require a smaller contingency factor.
- Engineering & design: Relative similar designs could be made, therefore no large differences expected.
- Permitting cost: The processes are almost identical; they have same in and output. No difference is assumed.
- Site preparation: Both systems require mostly that they can place the panels. No difference is assumed.

Literature findings about BOS. (Values in \$/m^2 is about m^2 of panels.)

Shaner et al. (2016)	56\$/m^2 soft-BOS for PV [2014\$], installation not included. Electrolyser no soft-BOS in PV-E system. Installation cost 29\$/m^2 for PV. Installation cost electrolyser 19\$/m2 → 117\$/KW electrolyser. Total of →104\$/m 56\$/m^2 for PEC [2014\$], installation not included
James et al. (2009)	No soft-BOS mentioned, but costs of elements are separately taken in account as percentage of the direct capital costs Engineering & design 7% Contingency 20% Up-front Permitting Costs 0.5% Site preparation 1% *(minus unique excavation costs)* Total 28% of "direct capital cost". → 58\$/m^2 excluding installation Installation cost ~30\$/m^2 of which 20\$/m^2 for panel installation [2005\$]. → 84\$/m^2 with installation
Victoria (2015)	Engineering, Construction general expenses, Contractors fee, Contingency, Up-front R&D, Up-front License are all taken together as soft-BOS. Installation is not mentioned separately and therefore in the soft-BOS. The cost accounted are 20% of "fixed capital investment". → 21\$/m^2

Selection of soft-BOS costs

The main contributors: installation, contingency and engineering & design are depended on the cost and maturity of the technologies. Therefore, are factors assumed for these values. A small BOS factor is considered for the rest.

Installation	20% of uninstalled costs
Contingency	20% of uninstalled costs
Engineering and design	5% of uninstalled costs
Soft-BOS other	5\$/m^2

3.2.5 Optimization of PV versus Electrolysers

In Shaner et al. (2016) the electrolysers equipment is scaled to the maximum output of the PV panels. In Figure 3-6 is shown that a small amount of time the max irradiation of 925W/m² happens. Scaling the electrolysers to the max PV output result in a low capacity factor for the electrolyser. An optimisation is performed between the number of electrolysers and PV panels to reduce total system costs. The detailed calculation is given in the Optimisation PV panels versus electrolysers.

In short, the following steps are performed:

1. A load duration curve is made to give insight in the number of hours of each level of irradiation in a year, see Figure 3-7.
2. For different irradiation caps is calculated the additional PV panels that are required.
3. The reduction in electrolyser capacity per irradiation cap is calculated.
4. The cost of the electrolyser part and PV panel part are combined and displayed in Figure 3-8. From this graph is concluded that 700 W/m² is the optimal cap for incoming irradiation to scale the electrolyser to in terms of system costs. 8% of the electricity produced with this cap is not used. This lead to a 9,1% increase of PV panels and 17,5% less electrolyser required.

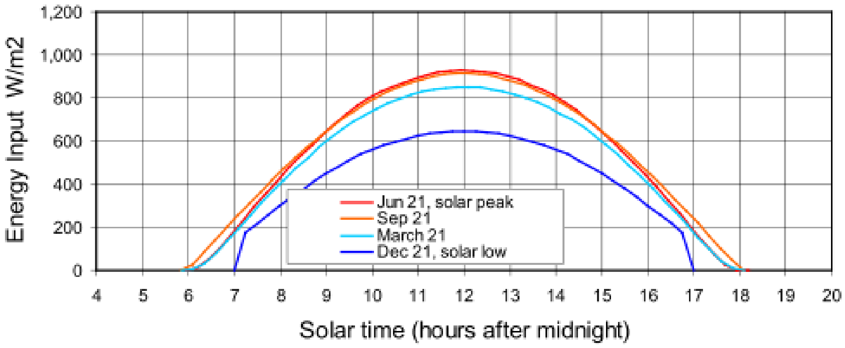


Figure 3-6 Max irradiation per hour, source: James et al. (2009

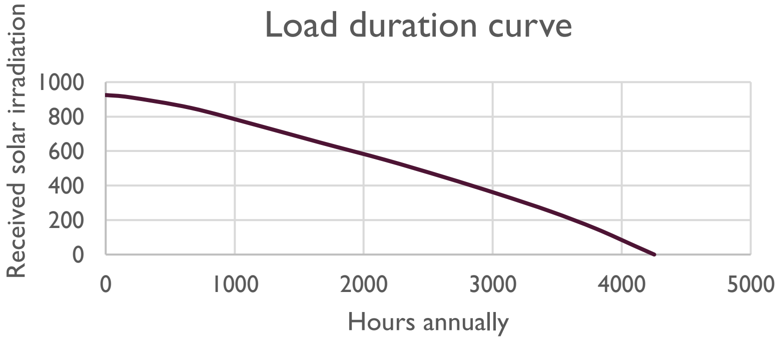


Figure 3-7 Load duration curve solar irradiation

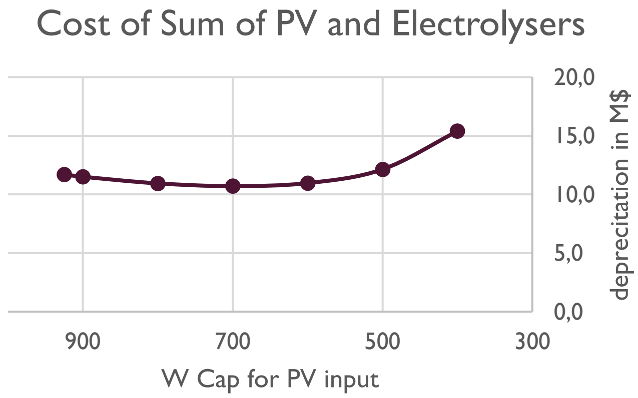


Figure 3-8 Optimisation of PV versus Electrolysers

3.3 PEC system

PEC cells are not on the market and therefore a PEC cell design is made first. After the design materials and the other system equipment are determined.

The three steps taken for the PEC cell are:

1. Design PEC cell
2. Material and cost of PEC cell
3. PEC balance of system

3.3.1 Design PEC cell

Types of PEC design and selection of research design

PEC systems are not commercially available and therefore only an estimated guess could be made what a future commercial design would look like. Multiple designs are created that classify as PEC. Victoria has made a good overview of the multiple designs available.[10] This overview is shown in the PEC cell configurations. In this chapter the large differences are explained and a selection is made between;

- Nano and panel based PEC
- Concentrated and unconcentrated
- Number of solid liquid-junctions (0,1 or 2)
- Compressed or uncompressed PEC systems

After all selections is a summary paragraph with an illustration of the chosen design, see Summary of selection PEC cell design and illustration.

Nano and panel based PEC designs

Nano based designs

The Nano based designs (also named slurry based or photoactive particle based) use suspension of photo active nanoparticles in an (KOH) electrolyte. The nanoparticle consists of a conductive substrate on which anodic and cathodic photoactive particles/layer is added. Catalyst such as gold could be added to improve reaction kinetics. An illustration of a nanoparticle is given in Figure 3-9. Cell designs could use plastic bags and depending on design hydrogen and oxygen are produced separately (Type 2, Figure 3-10) or in one space combined (Type 1, Figure 3-10).

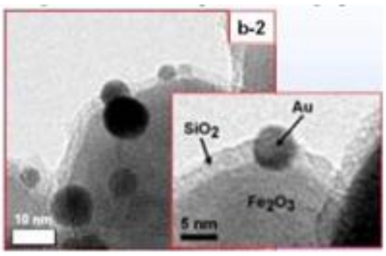


Figure 3-9 Nanoparticle Fe2O3 Core, SiO_2 layer & gold catalyst, Source: James et al. (2009)

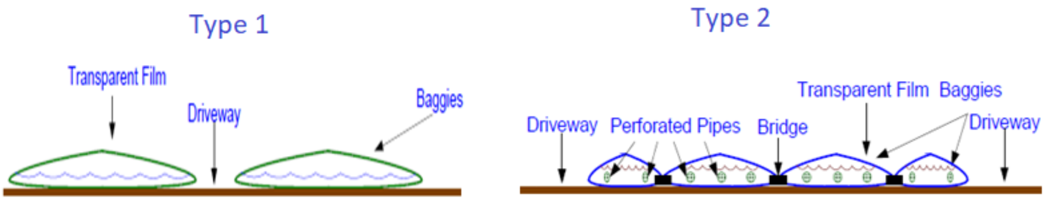


Figure 3-10 Type 1 with Bag system nanoparticles hydrogen & oxygen mixed. Source, Type 2 Bag system nanoparticles with oxygen and hydrogen separated, Source: James et al. (2009)[7]

Panel based design

The panel based design contains a panel, alike a PV-panel that supplies electrons and holes for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). These panels consist most likely of a multi-junction photon absorber to create enough voltage to drive the reactions. A good conducting anode, cathode (and catalysts) are often added to improve the reaction kinetics.

Selection of panel based design

In the report by James et al. (2009) nano based designs tend to be much cheaper.[7] However, in type I an extremely explosive gas mixture will be created. Which is considered too risky for large commercial scale. The assumptions made by James et al. (2009) about durability are for all systems optimistic, when current standards are considere.[7,31] The development of panel based designs is relative far ahead of Nano based designs in terms of: TRL, efficiency and durability.[10,31] Most research seems to focus on panel based designs, which has more possibilities for different configurations and material use. The panel based design is therefore selected in this research.

Concentrated versus non-concentrated

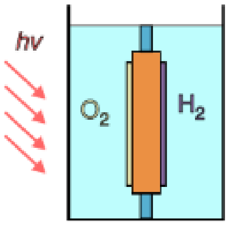
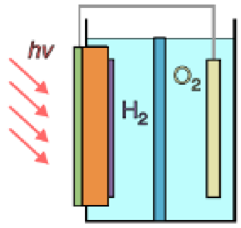
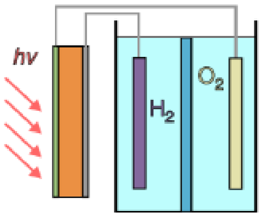
In the PV industry concentrated PV was one of the promising options.[32] However, it has small role in the market. For PEC additional advantages could be expected as proposed by James et al. (2009). However, for simplicity reasons a non-concentrated PEC sell is selected.

Number of liquid-solid-junctions (0-1-2)

Two liquid-solid-junctions design

One of the main design choices between panel based designs is the number of liquid-solid-junctions. The designs with two liquid-solid-junctions has the photoactive materials and additional anode and cathode submerged into the electrolyte, see Table 3-4. Therefore, the HER will be on one side on the surface of the panel and the OER on the other side. This design is used by James for type 3 and would require in theory the least amount of material.[7] For the side that receive solar irradiation a transparent conductive oxide is required as electrode, to enable photons to reach the photoactive material.

Table 3-4 Illustration of design with varying number of liquid-solid-junctions, Source: Turan et al. (2016)

Two liquid-solid-junctions	**One liquid-solid-junction**	**Zero liquid-solid-junctions**
		

One liquid-solid-junctions design

The design with one liquid-solid-junction has one side that is connected by a wire to a separate electrode. Current and previous PEC efficiency records are set by this design.[31] Also (more) ion-exchange membrane should be added. The negative effects of these extra materials are compensated due that only on side of the panel must withstand electrochemical reactions and corrosion. This improves durability and with more material choice it can also improve efficiency and cost of the system.

Zero liquid-solid-junctions design

Configurations with zero liquid-solid-junctions could be named PEC and PV-E. This is because the system consists of photoactive part that is wired with an electrochemical part. The electrolyte and hydrogen are not in the same space as the photoactive part. The advantages of this compared to other PEC systems are no corrosive environment for the photoactive part and possibilities to use conventional PV panels. The downside is more wires, most likely more housing materials and lower possible efficiencies. It can be considered an PV-E system as well despite this configuration could work independent and all component are completely attached to each other. This PEC design is in this research considered a PV-E system, without a DC-DC converter and an advanced electrolyser.

Selection of one liquid-solid-junction for research

Current STH efficiency record is made by the one liquid-solid-junction design (16,2%).[31] There are higher values for the zero liquid-solid-junction design, but it is arbitrary to call the zero liquid-solid-junctions designs PEC cells. Therefore, this is excluded in this research. The two liquid-solid-junctions design compared to the one liquid-solid-junctions design has more challenges to overcome. The two liquid-solid-junctions design requires a TCO that has additionally good properties to enhance the chemical reactions while simultaneously not being so much affected by corrosion caused by the electrolyte. These additional properties, besides transparency and conductivity create the major material challenge for the two liquid-solid-junction design. The one liquid-solid-junction will require additional wiring, a counter electrode and protective/catalyst layer which does not have to be transparent. Comparison of the systems advantages and disadvantages give the one liquid-solid-junction design an expected higher chance of a stable low-cost system.[8,10] Therefore, the one liquid-solid-junction design is selected.

Compressed or uncompressed systems

In the report of James et al. (2009) there are two panel based designs; compressed and non-compressed. In the compressed system the input of water is pressurized, which removes the need of hydrogen compressors afterwards. To withstand this pressure the PEC cell will require thicker glass. A calculation indicated that the compressed version will cost 81$/m^2 more than the uncompressed version, see Compressed versus uncompressed PEC. To put this in perspective the total cost assumption for a PEC system is around 150$/m2. Therefore, the non-compressed design is selected in this research.

Summary of selection PEC cell design and illustration

In the complete PEC system is the PEC cell the most uncertain factor in terms of design and costs. There are two technical properties that determine for a large part its market potential: efficiency & lifetime. An efficient system uses less (costly) material and lifetime is required to produce enough revenue to make an investment worthwhile. Therefore, a design is desired that has potential for cheap mass production and good performance in terms of efficiency and lifetime.

The outcome is a panel based PEC cell design with one solid-liquid-junction. In Figure 3-11 is an illustration given of this design.

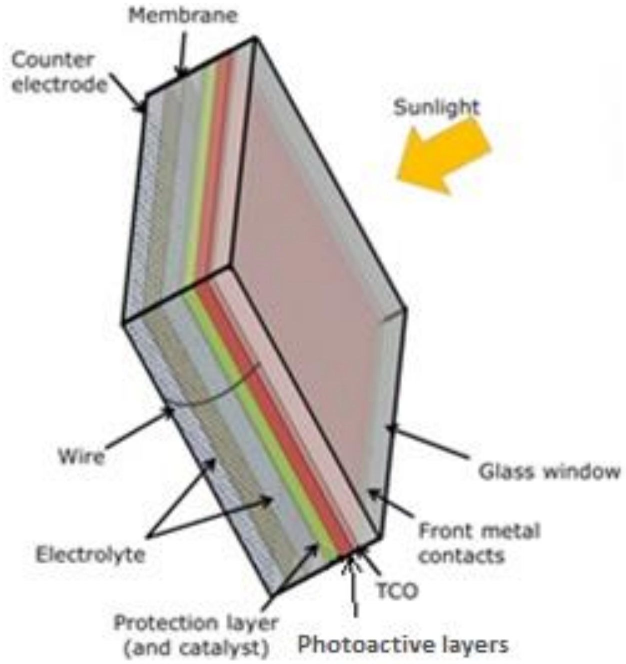


Figure 3-11 Illustration PEC design for Research, Image Source: Victoria (2015) (slightly modified)

This design is selected because:

- Panel based design such as this have the highest efficiency and can be produced for a large part such as PV panels.

- A one solid-liquid-junction with a protective layer (and catalyst) enables to protect components from the corrosive environment that electrolyte and the electrochemical reactions create. This decreases the number of requirements per component like the photoactive material. Less requirements increases the amount of materials that can be selected for a component and therefore its performance compared to its costs. Especially the lifetime of the photoactive material is a current issue in the PEC development and is expected to increase significant without contact with the electrolyte.[4,10]

- The valence and conduction band of the photoactive material do not have to match the band edge requirement of the water splitting reaction. Now the protective layer, which act as electrode, and the counter electrode should have good properties regarding the energy level band gap. Therefore, a wider range of photoactive materials can be used.

3.3.2 PEC cell material and cost

A variety of materials are chosen by different researches. Material selection is for a large part about photoactive material, but also about membranes, (transparent) conductors, catalysts and supporting component. An extensive analysis is done for the photoactive material. The other components are more briefly discussed. Most other components are commercially available, or the assumption of other researchers are expected to be valid.

Photoactive materials

Selection of the right photoactive material is one of the main challenges. The photoactive layer has often the biggest influence on the efficiency, while multiple types are not so stable and have relative low lifetime even in non-corrosive environment.[33] The photoactive layer also seems to be one of the main contributors of the cost of the system. Therefore, other elements in the design are used to reduce the number of requirements the photoactive material needs to fulfil. The selection of photoactive material focusses on: the efficiency, lifetime in a less corrosive environment, a right band gap and most of all the cost of the material. In literature these photoactive materials are discussed in the PEC and PV sector.

Photoactive materials in PEC literature

Photoactive materials are doped semiconductors that generate a charge separation due to the absorbance of photons. This research is not the first one to come up with a design and a choice in photoactive material. In some reports is an extensive analysis done on selection of materials, for example by Victoria (2015). In Table 3-5 is a short list of photoactive materials given that is used by cost estimations and other research for PEC cells.

Table 3-5 Photoactive material used in PEC cost estimations

Photoactive material used in PEC research	Source	STH efficiency
p-i-n amorphous silicon (a-Si) (3layer)	Victoria (2015)[10]	15% (chosen value)
GaInP/GaInAs	Young et al. (2017) (record efficiency)[31]	16.2% (achieved in lab)
CIGS/Ge	James et al. (2009) (Type 3)	10% (chosen value)
GaAs/Ge	James et al. (2009) (Type 4)	10% (chosen value)
p-i-n a-Si (3-layer)	Turan et al. (2016)	9,5% (potential value)
p-i-n a-Si (3-layer)	Rodriguez et al. (2014)	10% (potential value)
p-i-n a-Si (3-layer)	Xu (2014)	10% (chosen value)

All photoactive material used in these researches is based on thin film technology, which is considered necessary to be cheap enough for these photoactive materials to compete. Besides the desire for thin film, most used photoactive components are multi-junction to ensure enough voltage for the chemical reaction. Table 3-5 makes clear that triple-junction a-Si (thin film) is often selected as photoactive material. The main reason behind this is the potential for low cost production.

Learnings from PV sector

Current PV industry standard is single-junction crystalline silicon (c-Si) with ~90% market share, despite it uses more photoactive material than thin film cells.[19] Which type of solar panel will be the industry standard in the near, mid-term and long-term future is an ongoing discussion for the last decades. This is also briefly discussed in selection of PV panels in PV-E systems. Some elements of this discussion are pointed out to give some handhelds by selection of photoactive material for the PEC cell.

While multiple forecast indicated large increases in thin film production, the production market share actual decreased the last 7 years.[34,35] The bright forecasts were mostly based on less material cost compared to crystalline silicon and cheap production methods such as roll printing. However, their relative disadvantages seem to be overlooked and the (cost)development of crystalline silicon underestimated.

Commercial efficiency, life time and cost reduction of production methods were lacking behind crystalline silicon solar cells. The high cost of silicon was considered a large advantage for thin-film, but the silicon material cost decreased with ~80% from 2011 to ~0.09$/W in 2016.[19] This cost reduction is expected to continue for coming years for crystalline silicon.[19] The current market shows that single-junction thin-film technologies has much difficulty competing with crystalline silicon solar cells.

All photoactive materials considered for PEC are multi-junction. That is more complex to make and is still too expensive to compete in the PV-market. Current c-Si competitors are also single-junction such as CdTe.[24] Most single-junction photoactive materials do not have the right output voltage for hydrogen production. While the materials that can generate enough voltage can only use a small part of the solar spectrum. Therefore, multi-junction photoactive material is desired for PEC. In Table 3-6 are important limits for efficiency stated for PEC. Especially the realistic limits of PEC single-junction indicate the need for multi-junction photoactive material.

Table 3-6 Efficiencies of PEC, source Fountaine et al. (2016)

	Theoretical	**Realistic limit, high efficient materials**	**Realistic, earth abundant material**
Single-junction	30,6% (1,59eV)	15,1% (2,05eV)	5,4% (2,53eV)
Dual-junction	40,0% (1,40eV & 0,52eV)	28,3% (1,59eV & 0,92eV)	16,2% (1,93eV & 1,38eV)
Triple-junction	-	25,4%	17,3% (1,91eV & 1,36eV & 0,93eV)

A limit for PV-E systems are not given, but there is an achieved record PV-E efficiency that beats all PEC realistic efficiencies.[5] This record efficiency of 30%STH is achieved in lab. InGaP (1,895eV), GaAs (1,414eV) & GaInNAs(Sb)(0,965eV) is the used as photoactive material combined with a PEM electrolysis. Concentrated sunlight is used (42sun), which resulted in 39% solar to electricity (STE) efficiency. They also mentioned that one sun gave 33% STE efficiency. 33% STE efficiency with the same conversion factor result in a STH efficiency of 25%. This shows together with Table 3-6 that the claimed higher potential efficiency for PEC will be difficult to become a reality.

A-Si is proposed in multiple PEC researches as high potential material, however it was also one of the promising thin film PV materials.[34] The efficiencies in Table 3-7 shows that high STH efficiencies as proposed by Victoria (2015) (15%) are not even achieved by a-Si PV. Xu (2014) mentioned that STH efficiency could be 75-80% of STE efficiency. A second important issue is the fast degradation of this top lab efficiency for a-Si, by the Staebler-Wronski effect.[8] Commercial a-Si has therefore a lower stable efficiency of 9.5% STE compared to record efficiencies.[35] This makes even 10% STH efficiently currently optimistic for a-Si.

Table 3-7 Efficiencies PV

Efficiency limits of PV cells, Source: Green et al. (2017)[36]			
	Theoretical (SQ-limits)	**Lab**	**Commercial**
Single-junction	33,7% (1,34eV) (1sun)	28,8% non-concentrated 29,3% concentrated	24-20%
Dual-junction	42% (1sun)	32,8% non-concentrated 35,5% concentrated	
Triple-junction	49% (1sun)	35,9% non-concentrated 44,4% concentrated	
Efficiency limits of a-Si cells, Source: Green et al. (2017)[36]			
Single-junction		10,2%	
Dual-junction		12,7%	
Triple-junction		14%	

Selection of photoactive material and cost

The selected material by most recent and multiple researchers is triple-junction amorphous silicon. Promises of low production cost are available, such as for most thin film technologies.[8] However, the production technology need to scale up to reach the desired low costs. Despite challenges around efficiency is in this research chosen for a-Si. The efficiency is set at 10% which is optimistic according to the PV values and confirmed by Urbain (2016).

It is complicated to determine decent values for cost of the photoactive component. Multiple cost estimations for PEC photoactive material is based on PV cost expectation of Zweibel (2000).[7,10] Zweibel his cost estimation is 15\$/m^2 (5\$/µ m thickness * 3µ m). Victoria (2015) justify a choice of 15\$/m^2 by examination of commercial CdTe production. With a (2015) thin-film prices of 0.45\$/W per module, these 15\$/m^2 are in the same range as the cost of commercial (CdTe) thin film productions. The commercial productions are single-junction CdTe and the design of Victoria is a triple-junction a-Si. 15\$/m^2 is in this research as current price for 10% efficient a-Si considered optimistic.

Besides a-Si other materials can be used as shown at the current record cell efficiency of 16,2% STH.[6] They used GaAs/GaInP (with silicon handle) as photoactive layer. For PV there is a research done to investigate the combinations GaAs/Si and GaInP/Si, with potential commercial solar to electricity efficiencies (STE) of 30% till 35%.[6] In this PV research a current PV-cell price is assumed of 4,85\$/W (GaInP/c-Si, 30% STE) and 7,15\$/W (GaAs/c-Si, 30% STE). With upscaling these costs could go down to 0,66\$/W (GaInP/Si, 35% STE) and 0,85\$/W (GaAs/Si, 35% STE).

A quick cost analysis is done for GaInP and GaAs is done with these values:
0,66\$/W & 350W/m^2 → 231\$/m^2 (current c-Si cell cost is 68\$/m^2 (0,34\$/W for 20%STE efficiency[21]))
GaInP addition to c-Si will cost 163\$/m^2 (70% of photoactive material cost)
GaAs addition to c-Si will cost 230\$/m^2 (78% of photoactive material cost)
This calculation might be oversimplified, but still shows the use of GaInP and GaAs in a multi-junction PEC cell will give a large increase in cost of the photoactive material.

In the same PV research is an efficiency mentioned of a PV cell of GaAs/GaInP (35,9% STE efficiency), which uses the same photoactive material as the record PEC cell. The record efficiency of PEC is only (16,2/35,9=)45% of the PV efficiency, which is remarkable. (The PV efficiency is cell efficiency and not module efficiency.) For this PEC material configuration current record will most likely be broken, because it is still far away from the max limits. These max limits are the realistic limits in Table 3-6 of the high efficient material of dual-junction. A second claim about max PEC limits is that STH efficiency can be about 75-80% of STE efficiency.[11] Even with high efficiencies will the cost be relative high when high-performance material are used, therefore a-Si is used for PEC in this research

The cost of 15\$/m^2 by Victoria (2015) is assumed optimistic for 2020. A value for CdTe is used while commercial CdTe is single-junction based and a-Si seem to have even more problems to compete in the PV market.[37] Therefore, a less optimistic value production cost of 45\$/m^2 (3 times 15\$/m^2) is chosen.

Non-photoactive elements of PEC cell

In cost estimations such as James et al. (2009) not every element of the PEC cell is taken apart for a cost analysis. Therefore, it is harder to check if total PEC cell costs are reasonable in other cost predictions. The following items are discussed: Glass, TCO, front contacts, cathode, anode, membrane wiring, housing and assembly costs.

Glass - Glass is required at the front and should have a high permeability for photons and form the support structure of TCO and photoactive layers. In the chosen design it has ideally no connection with the reactants and products. Compared to a PV panel it need to be stiffer to give structure, because it does not have a full surface solid connection with the back of the housing. Because, the electrolyte is in between.

In literature we find price estimates for glass for PV and PEC. Glass prices of PV show a constant value and value for PEC also, see Table 3-8. It is expected that the glass used by PEC cells is thicker than for PV cells and therefore more expensive. A glass front is selected at a price of 10$/m^2. The assumption is made that the inflation was at a lower rate compared to the cost decrease caused by developments in production. It is further assumed that the prices in literature uses a (TCO) coating. Therefore, is 1$/m^2 deducted as will mentioned by the TCO part.

Table 3-8 Glass price estimations

$/m^2	PEC or PV	Source
11	PEC (glass + TCO)	Victoria (2015)
12,30	PEC (plexiglass)	James, 2009
5	PV	Shaner,2014
5,1	PV	Horowitz,2017

Transparent Conductive Oxide (TCO) - Used for thin film PV to conduct electrons to the contacts, while simultaneously enables most photons to pass through to the photoactive material. Crystalline silicon cells are not mentioned when searching for TCO and vice versa. For current collection and conduction a silver grid is used in crystalline silicon PV.[19] TCO layers are favoured for thin film PV such as amorphous silicon and Cadmium Telluride.[38] A TCO can also play a role as anti-reflective coating. No specific cost for TCO were found in other PEC design researches. Victoria (2015) assumes a price of glass and TCO combined. Two main TCO are often mentioned: Indium Tin Oxide (ITO), Fluor Tin Oxide (FTO) and Zinc Oxide (ZnO). ZnO is mentioned to be cheap[38], while tin oxides are used for competitive CdTe production[39].

The cost of TCO is expected to be relative low for the PEC cell. However, it does require some material and additional production steps. A cost of 1$/m^2 is assumed and discounted from the 11$/m^2 Victoria (2015) uses for the glass.

Front contacts - Victoria (2015) incorporates a metal grid at the front together with TCO. The metal grid gives connection points for the wires to the anode. Good conducting (metals) materials such as silver are used to collect the electrons from the TCO. A trade of is made between conductive capacity, amount of occupied surface and material cost. Silver is the most used material for this in the PV-industry.[19]

Victoria assumes as price of 0,20$/m^2. ITRPV 2017 report show a median of 100mg silver per PV cell and a 2017 silver price of 548$/kg. This result in 2$/m^2 material cost for silver. Silver is the main non-silicon material cost of crystalline silicon PV cells and the amount used is expected to decline or even be replaced. A value in between the two sources is selected of 1$/m^2.

Cathode/protective layer - One of the crucial elements is the layer which promotes the hydrogen formation reaction, while simultaneously prevent contact between the photoactive material with the electrolyte and hydrogen. While this element is considered desired, since it improves the lifetime, it is not used in all the designs. For the current record PEC cell efficiency is not a protective/catalyst layer used, but they use PtRu catalyst for promotion of the reactions.[31] Victoria (2015) uses nickel mesh (Ni-mo) at 5$/m^2, which is also used in this research.

Anode/counter electrode - This promotes the oxygen formation reaction and can be directly attached to the housing of the PEC cell for structure. Stainless steel[11], Nickel[10], RuO_x with Pt gauze[31] are named as possible options. Only Victoria (2015) design has a counter electrode for which a cost estimation is done. 0,10$/m² is assumed by Victoria (2015). This is purely done based on material cost (thickness, surface area, price per kg). However, some production cost and material left overs are assumed in this research for the anode. 0,50$/m² is taken for a Nickel anode/counter electrode.

Membrane - Membranes are one of the main cost contributors for PEM stack cells and are expected to decrease strong in cost when produced on large-scale.[17] James et al. (2009) didn't use membrane separation for the panel based system. For a Nano particle based system they did use a membrane with $5,71/m². Shaner et al. (2016) uses a cost 50$/m² and Victoria (2015) uses 18,18$/m². Both use forecasts of future prices.
The estimation 50$/m² by Shaner et al. (2016) is used for the membrane.

Wiring - The used copper wires are insulated to prevent contact with the electrolyte. The distance from front to counter electrode is expected to be less than one cm in the chosen design. Material cost are expected to be low. Cost efficient design and fabrication might be more difficult at first. Large-scale production of PEC cells is assumed for this research. Therefore, an effective and cheap design for wiring will be applied. This might be done by incorporation of the wiring in the housing. No direct cost estimates are found in literature. Victoria (2015) combines it with housing cost. 1$/m² is selected.

Housing - Victoria (2015) set the cost at 21,21$/m² wiring included. This is based on cost expectations of PEM housing (bipolar plates and gasket). James et al. (2009) assumes a material cost of 14$/m². For c-Si PV panels there is a cost difference of ~15$/m² between cell and module cost[21]; which contain-junction box, housing, glass and mark up. Based on this is assumed that cost of PV housing is around 5$/m². However, the PEC cell requires probably a more expensive housing. Additional costs are made to make it resistant to the electrolyte, give the membrane a stable structure and make it gas tight. Therefore, 20$/m² is selected.

Assembly - The cost described above are material cost and production cost of the specific elements. Within the sources found there are some remarkable choices made, see Table 3-9. Since it has large impact on the total module cost it is important to see where the values come from. James et al. (2009) cited Zweibel (2000) with a value of 56$/m². However, Zweibel (2000) did only claim this value for a thin film of First Solar (CdTe), when the total sum of cost is 100$/m² (44$ m² is by material costs).[40] This stated cost can decrease by half with mature production scenarios. James, 2009 stated 56$/m² (100$-44$) for both panel designs. First solar module price in 2011 was 87$/m² (11,6% eff. 0,75$/W) and forecast of 2019 is 36$/m² (18% eff. 0,20$/W).[24] It is unfortunately not clear if mark-up was included in Zweibel (2000). Even without knowledge about mark-up there is a cost decrease found.

While two sources refer to same CdTe production. Victoria (2015) does not mentioned assembly as a specific cost element. Of the ~15$/m² difference between c-Si cell and module is some part assembly costs. In this research is assumed for costs of elements such as glass, that the assembly/production part is included. TCO is for example directly produced on the glass or on the photoactive layer (depends on direction of production). Therefore, are assembly cost only about combining different elements into one module.
Assembly cost are set on 20$/m², with the assumption it is still more complex with the sealing compared to a PV panel and it includes mark-up for the assembly.

Table 3-9 Assembly costs of PEC cell

$/m²	Photoactive material	Source
56$	CdTe/CdS	Zweibel,2000 (2000 prediction)
28$	CdTe/CdS	Zweibel,2000 (2010 prediction)
56$	CIGS/Ge	James et al. (2009) (Type 3)
56$	GaAs/Ge	James et al. (2009) (Type 4)
0$	a-Si	Victoria (2015)

Mark-up - When real market prices are available then mark-up is already included in the price. James et al. (2009) added a 50% mark up above the calculated cost of the PEC cell. For this research is assumed that all elements costs are market prices and no additional mark-up is account for.

3.3.3 PEC complete system

A working PEC system consist of the following elements.

- Gas processing system
- Water/electrolyte management system
- Control system

For these elements is the extensive work of James et al. (2009) used. There has been a correction for inflation and the cost are kept similar per m^2 of PEC cell. The results used in this research are put in Table 3-10.

Table 3-10 PEC system BOS element costs

PEC system BOS element	***M$***
Gas processing system total	**11,5**
Compressors	9,5
Condensers	0,2
Intercoolers	0,5
Piping	1,3
Water management total	**1,3**
Water pump	0,003
Piping	1,3
Control system total	**3,8**
Controller	1,7
Sensors	1,8
Other equipment	0,3

3.3.4 Soft balance of System PEC

The cost estimates for the soft-BOS are done simultaneously for both PEC and PV-E system. Analysis on how it is done is therefore described at

3.2.4 PV-E Soft Balance of System . Here are the values presented which are used for the PEC system.

Installation	20% of uninstalled costs
Contingency	30% of uninstalled costs
Engineering and design	5% of uninstalled costs
Soft-BOS other	5$/m^2

Replacements

PEC cell replacement is expected needed every 7 years. The PEC cell price is expected in this analysis to decrease to 75% in 7 years and 60% in 14, alike the electrolysers. Replacement cost in labour are kept at 20% of the uninstalled equipment cost.

3.4 Sensitivity analysis

PEC cells cost estimations have high uncertainty caused by lack of commercialization. In the cost calculations many assumptions are made. With this sensitivity analysis is the effect of some of the main assumptions on the total costs examined. Both low and high values are assumed.

This sensitivity of the cost of PEC is compared to cost expectations for PV-E parts and systems. This comparison gives an indication of future potentials with the chosen designs of both systems. A significant lower potential cost is desired for PEC since it needs to be cheaper to become commercially viable. Besides a look at the potential low end, there is a high end as well. This tries to show the effect of a less optimistic parameters and the together a range of uncertainty around the cost predictions of PEC cells. This can be compared to expected decreases in cost for PV and electrolysers.

3.4.1 Cost of PEC cell elements

The first basis cost analysis shows the large impact of the photoactive layers and the membrane on the cost of a PEC model. In the sensitivity analysis is the effect shown of more optimistic and pessimistic cost assumptions.

Photoactive material

The choice of photoactive material is discussed in 3.3.2 PEC cell material and cost. The selected value is 45$/m^2. For the pessimistic scenario a material of GaAs/GaInP is required to achieve a commercial production of PEC cell with 10% STH efficiency. Even for this pessimistic scenario the cost of upscaled production are used. The added cost of both materials is combined for a total cost. (These costs were calculated in section 3.2.2.) GaInP cost 163$/m^2 & GaAs cost 230$/m^2 → 393$/m^2
The optimistic case is set at 15$/m^2, the value Victoria (2015) assumes. (James et al. (2009) assumes 20$/m2 and Xu,2015 assumes a value of 30$/m^2 catalysts included.)

Membrane

A value of 50$/m^2 is chosen for the membrane based on Shaner et al. (2016). Victoria assumes a cost of 18,18$/m^2. Therefore, is an optimistic value of 15$/m^2 chosen for the sensitivity analysis. That values of 20$/m^2 or less are possible is stated in Houchins et al. (2012).[41] For the pessimistic options is examined the commercial Nafion prices on the internet [636$/m^2].[42] For large-scale a pessimistic value of 300$/m^2 is assumed.

3.4.2 Technical PEC cell parameters

The main performance indicators besides cost are cell lifetime and STH efficiency.

Lifetime of the PEC cell is set at 7 years, which corresponds with lifetime expectation of a PEM electrolysers. Stable performance of PEC cell for more than a week is not found.[4] Therefore, is lifetime often mentioned as issue which requires more research.[43] But most cost estimations use even more optimistic values than used in this research. James et al. (2009) 10years; Victoria (2015) 15years & Xu (2015) 10years. For the optimistic is a value of 12 years chosen and pessimistic 3 years.

Efficiency is set at 10% which might already be optimistic considering the use of a-Si.[33] Nevertheless a 15% efficiency is chosen as optimistic value and 5% as pessimistic.

3.4.3 PV and electrolysers

PV

PV modules are produced on large-scale, therefore is the chosen value realistic. A pessimistic value is expected unlikely to occur in the future. In this part of the sensitivity analysis are therefore two cost reductions considered. The first one is the cost prediction by the ITRPV report of ~50% in 10 years of the module and hard-BOS. The other one is a more moderate assumption of 35% decrease, with the expectation hard-BOS will decrease with 20%.

Electrolyser

For the electrolyser a stack value of 400$/kW and hard-BOS value of 375$/kW was chosen. For the optimistic case a stack cost of 148$/kW is used, this is based on predictions of Colella et al. (2014). The hard-BOS is set in the optimistic case set at 200$/kW. For the pessimistic case a stack cost of 1000$/KW is assumed and hard-BOS of 750$/kW. This pessimistic value is in line with stated cost in 2014.[20]

4. Results

The results are a current system costs of both systems, which are divided in the main cost elements per system. A division of the PEC cell cost is given. Followed by the result of the sensitivity analysis, which ends with a future potential prediction of both systems.

4.1 Current systems costs

The calculated cost for the two systems build in near term (2020) are:

PEC 10,14$/kg H_2
PV-E 7,75$/kg H_2

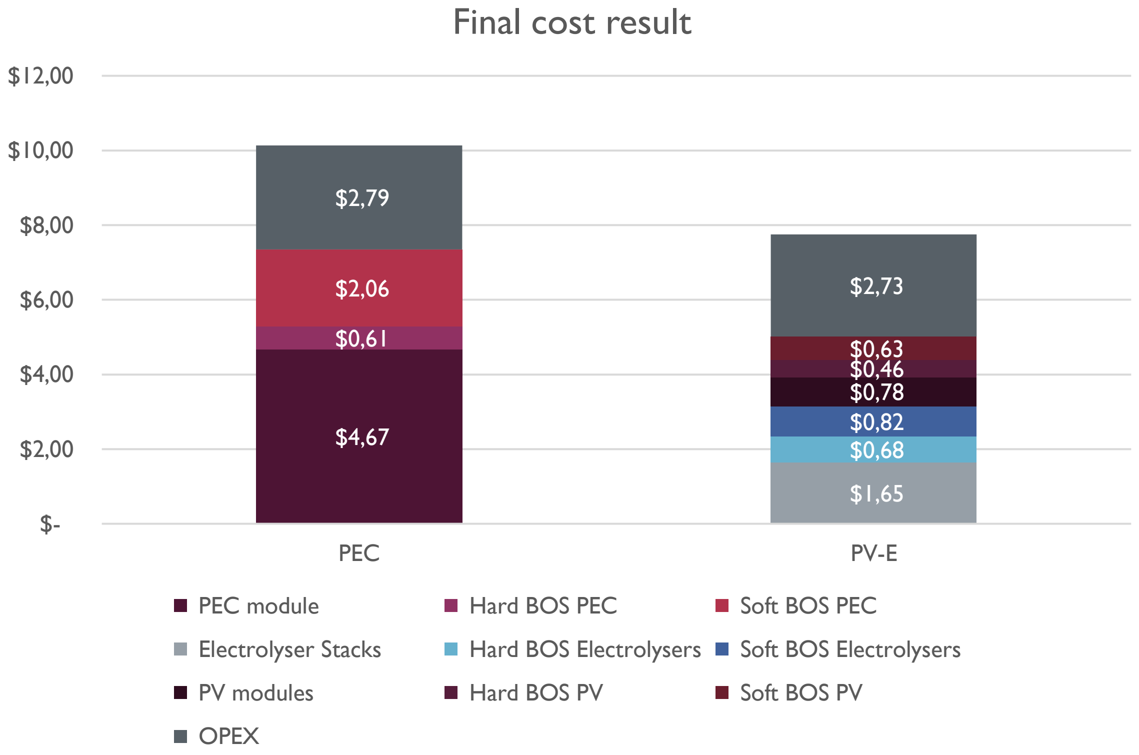


Figure 4-1 Calculated cost totals of PEC and PV-E systems in the near-term future (2020)

PEC

Figure 4-1 shows that the PEC cell cost is the main contributor of the PEC system. (In Figure 8-3 is the detailed version presented.) The second cost contributor are the OPEX costs, which are mainly made by “property tax & insurance”. For these cost is assumed that they are 2% of the initial investment cost, therefore they are directly depended on the other costs. The other cost are soft-BOS and hard-BOS, which have a lighter correlation with the PEC cell cost. Therefore, reductions of these BOS costs will not necessary occur with a decrease in the cost of PEC cells. The labour costs and the BOS costs are expected to set the minimal cost of a PEC system.

PV-E

The PV-E system in Figure 4-1 is divided in more core components, since it is approached in this research as two individual systems that are connected. The electrolyser system(3,15$/kg) is more expensive than the PV system(1,87$/kg). This difference was even larger before the optimisation. The optimisation added more PV panels to decrease the number of electrolyser required, by improvement of the electrolysers capacity factor. This emphasize that the biggest influence is caused by the electrolyser. The soft-BOS of PV is not expected to decrease at the same pace as the hardware. Soft-BOS and hard-BOS of electrolysers are still uncertain and scale up of production lines could lead to large reductions in stack and BOS costs.

PEC versus PV-E

In this near-term future comparison, the current PV-E cost are expected to be lower than for a PEC system. Three elements of this comparison are highlighted.

- The cost of PV panels is significantly smaller than the cost of a PEC cell. Which is expected due to their different properties: the additional elements put in, shorter lifetime and more requirements for photoactive material.
- The OPEX cost are similar despite the final cost in $\$/kg\ H_2$ are lower for PV-E. This is caused by a higher initial investment cost of the PV-E system which is balanced by higher replacements cost of the PEC system.
- The lifetime and complementary replacement cost make the main difference between the electrolyser stack cost and the electrolyser hard-BOS. Both electrolyser stack and PEC cell are due to their relative short lifetime (7years) large cost contributors.

Division of PEC cell cost

The sensitivity analysis shows that selection of other values could turn this comparison in favour of each desired system. The PEC cell is the largest contributor to the complete PEC system. Therefore, a cost division is presented of the proposed PEC cell, see Figure 4-2. With an assumed cost of $50\$/m^2$ and $45\$/m^2$ are the membrane and the photoactive material the most expensive parts. These two elements present a relative cost of $1{,}51\$/kg\ H_2$ and $1{,}36\$/kg\ H_2$. Therefore, the membrane and photoactive material are taken for the sensitivity analysis. Almost all other elements in the PEC cell have a high uncertainty as well since such PEC cells are not commercially build yet. Therefore, it is for instance possible that the protective/cathode layer will have more impact than expected.

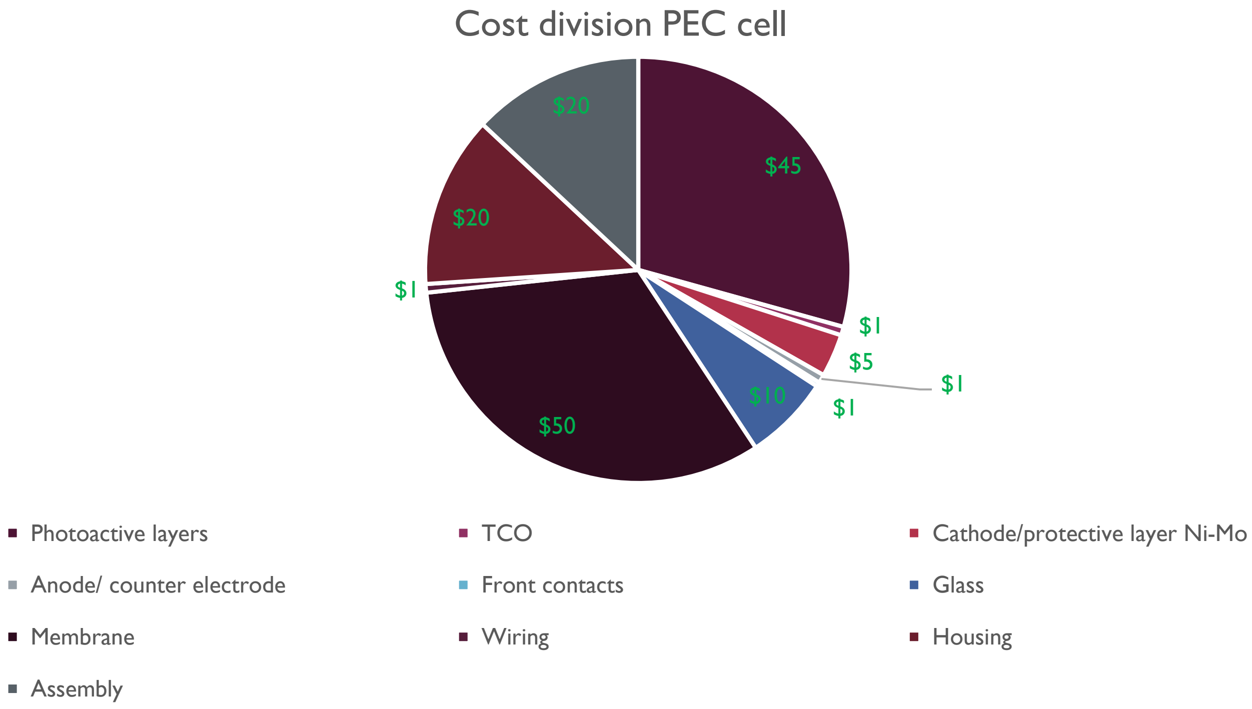


Figure 4-2 Division of PEC cell cost, [$154\$/m^2$, 10% STH efficiency, 2020)

4.2 Sensitivity analysis

The sensitivity analysis is done to show the large effect different parameters have on the outcome of the costs. The optimistic values give insight in what future potential might be. For a far future scenario all optimistic values are used of both systems to give some indication of the potential PEC has compared to PV-E.

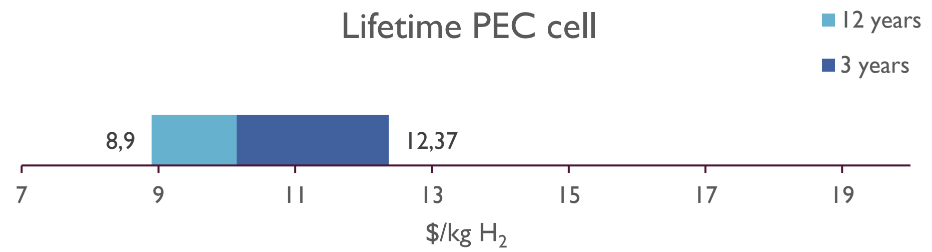


Figure 4-3 Sensitivity to lifetime of PEC cell.
Optimistic value 12 year, 8,9$/kg; start value 7 year, 10,14$/kg; pessimistic value 4years, 12,37$/kg.

Lifetime of the PEC cell is an uncertain factor, which needs a lot of improvement. Degradation of PEC cell by the corrosive electrolyte and the chemical reactions caused the selection of a protective layer for the photoactive material. Still only 7 years lifetime is assumed for the base case. This corresponds with the stack lifetime of PEM electrolysers, that works in similar conditions. The results show short lifetime has a negative impact on the hydrogen cost. This proves lifetime of the PEC cell is important for commercial success. The effect of PEC cell lifetime has relative little effect on the complete PEC system cost, since it only affects the PEC cell. Cheap refurbishment is an option that could reduce the impact of lifetime, but is considered unlikely in terms of labour and process costs. If cheap refurbishment will be possible, then it will be most likely possible for electrolysers stacks as well.

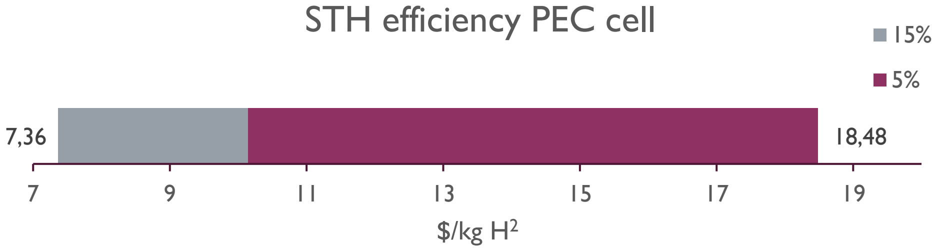


Figure 4-4 Sensitivity to STH efficiency PEC cell.
Optimistic value 15%, 7,36$/kg; start value 10%, 10,14$/kg; pessimistic value 5%, 18,48$/kg.

Most elements of a PEC system are directly correlated with the STH efficiency. A 50% reduction in efficiency will lead to almost twice as high cost compared to the base case of 10%. While a 50% increase to a value near the current record efficiency leads to a decrease of ~25%, see Figure 4-4. Therefore, high efficiencies are crucial for PEC systems. However, high values combined with cheap photoactive materials seem to be difficult to realize as explained in 3.3.2 PEC cell material and cost.

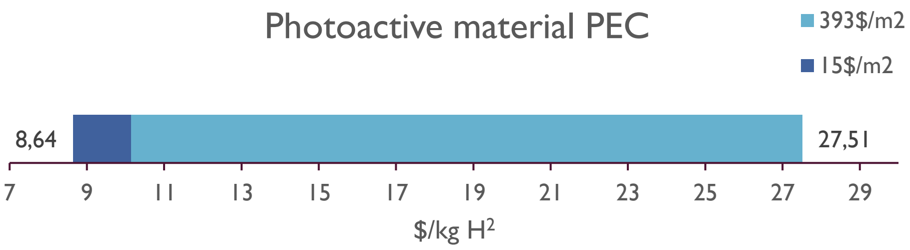


Figure 4-5 Sensitivity photoactive material PEC cell.
Optimistic value 15$/m², 8,46$/kg; start value 45$/m², 10,14$/kg; pessimistic value 395$/m², 27,51$/kg.

The pessimistic value in Figure 4-5 is based on the use of GaInP/GaAS, which is used for the current record PEC efficiency of 16,2% STH.[6] This illustrates it will be difficult for high performance materials from the lab to become competitive in the market. Even with a STH efficiency of 25% the $/kg cost will be more expensive. Earth abundant materials such as a-Si are therefore preferred. In Table 3-6 are expected limits in STH efficiency given for PEC cells. This table shows a choice for earth abundant materials will result in limited efficiencies.

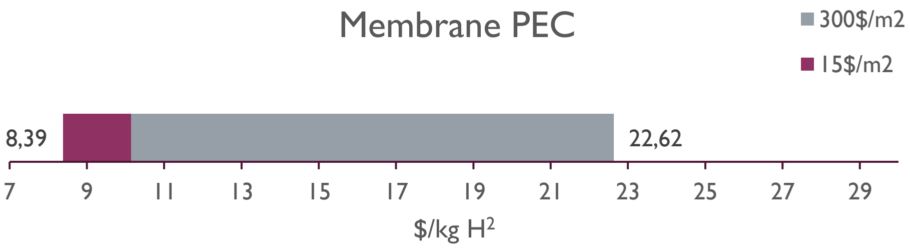


Figure 4-6 Sensitivity Membrane PEC.
Optimistic value 15$/m², 8,39$/kg; start value 50$/m², 10,14$/kg; pessimistic value 300$/m², 22,62$/kg.

Cost of membranes are expected to decrease strongly with factory scale ups.[17] Current online found cost have a huge negative effect on the cost, but are considered pessimistic for industrial use. Still the membrane is a large and uncertain contributor in the PEC cell. PEC cells could also be made without membrane or not over the full surface, this is expected to have influence on efficiency and purity. In this research the effect of no or less membrane is not examined.

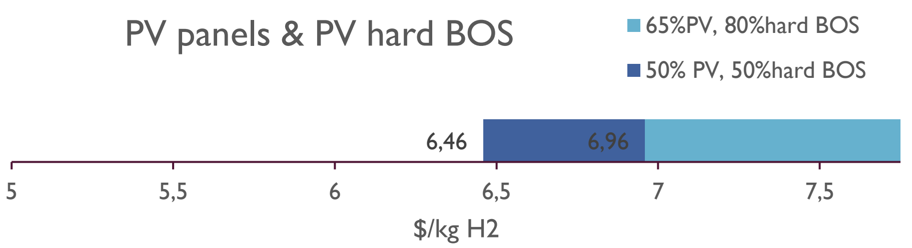


Figure 4-7 Sensitivity PV part.
Optimistic (Green), 6,46$/kg; less optimistic (Blue), 6,96$/kg; start value, 7,75$/kg.

The cost of the PV elements are the most certain values of both systems. Therefore, are two cost reductions scenarios displayed in Figure 4-7. The most optimistic one is based on the learning curve of Figure 3-1 for the year 2027. When examining the long-term future this value might even be conservative. The other scenario (blue) could considered a little pessimistic for the long-term future. The results are significant but also show the PV material cost are of relative low influence compared to other costs of the system.

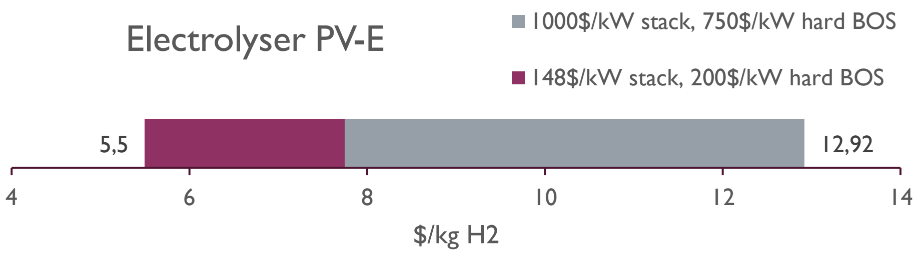


Figure 4-8 Sensitivity Electrolyser.
Optimistic value (Orange), 5,5$/kg; start value, 7,75$/kg; pessimistic value (Yellow), 12,92$/kg.

Contrary to the PV costs are the electrolyser costs not so certain. The cost development of this PV-E part plays the biggest role in hydrogen cost decrease of the PV-E system. However, lack of development will have a negative impact on the cost development of the membrane as well.

Sum of all optimistic values for future potential

All sensitivity parameters for both systems were set at the optimistic values combined. This gave a PEC cell cost of 88,50$/m^2 with 15% STH efficiency and 12year lifetime. Which made the total PEC system a bit cheaper than the PV-E system.

Future potential cost of both systems:
PEC system 4,64$/kg H_2
PV-E system 4,99$/kg H_2

5. Conclusion

Available and desired technologies

Design and material selection of the PEC cell made clear there is a difficult trade-off between desired properties and realistic properties. Ideally there is only (cheap) photoactive material, electrolyte and encapsulation required. However, to reach acceptable efficiencies and lifetime additional elements are desired. These additional elements can often be found in electrolysers, such as membrane and catalysts. High efficiencies are only possible with multi-junction photoactive material which is not the industry standard for PV panels, caused by a lower cost performance ratio. Most multi-junction photoactive material is expected to be relatively too expensive, as shown with GaInP/GaAs. While the used a-Si multi-junction has difficulties to obtain a stable high efficiency. The balance of system(BOS) cost in the complete PEC system are well known and form the basis of the minimal cost of the system.

The PV market is a large-scale market, only the cost in \$/W is examined for this research. It is assumed that other types of panels could easily be used as substitution. The electrolyser market is less mature and besides costs are advantages as flexibility are important. A PEM electrolyser is chosen because its flexibility, promises in reduction of cost, high efficiency and it is already available on the market. The BOS of the PV part is well known, while the electrolyser BOS has the same uncertainty as the electrolyser itself.

Current state and cost of systems

A current/near future (2020) cost analysis of the chosen PEC system is optimistic and arbitrary to start with. A working prototype is not found yet which has: 10% STH efficiency, stability over 7 years of operation and use cheap photoactive material such as a-Si. From the current point in development multiple steps are still to be taken, see Figure 5-1.

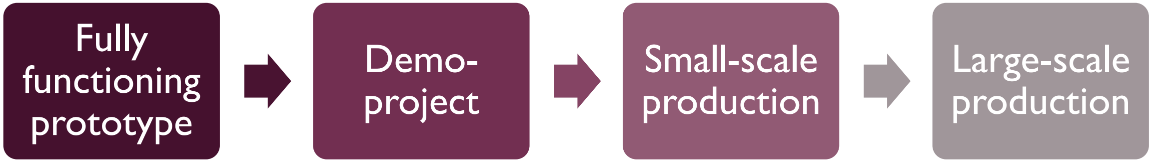


Figure 5-1 Steps required to be taken for PEC cell to achieve the assumed commercial production costs

The PV parts are already in the last step and the electrolysers are in the small-scale production step. In terms of lab efficiency current PV-E outperforms PEC with 30% versus 16,2% STH efficiency. The promises of PEC to beat PV-E with high efficiency are further toned when (earth abundant) cheap materials are required, see Table 3-6. The calculated costs of **current systems are *10,14\$/kgH_2 for PEC*** and ***7,75\$/kgH_2 for PV-E***. This difference makes it unlikely that such a PEC cell and system could outcompete a PV-E system in the short term.

Main influencers of systems cost

The biggest part of the PEC system cost comes from the PEC cell. Reduction of this cost is essential for cost competitiveness and decreases related costs as well. Within the PEC cell are membrane and photoactive material the biggest cost contributors. In the sensitivity analysis it is shown they have significant effect on total cost depending on optimistic or pessimistic values. The pessimistic value shows that cost of high performance photoactive material has a large negative impact on the total cost. Therefore, it is considered necessary to use cheap earth abundant material of PEC cells. These cheap earth abundant materials will limit the maximum efficiency.

This efficiency of the PEC cells is an important parameter as shown in the sensitivity analysis. A 50% decrease to 5% STH efficiency result in almost doubling of the total system costs. A stable 10% STH efficiency is difficult to achieve for the selected a-Si, which could be a deal breaker. Another important parameter is lifetime, which is one of the difficulties often mentioned in research. The relative effect of this is however smaller than for efficiency, because it does not affect the BOS of the system and each replacement PEC cell is assumed to become cheaper in time.

The electrolyser part is the largest cost contributor to the PV-E system. Even after optimisation it is has a low capacity factor. The electrolyser hard-BOS are expected to decrease together with the stack cost, while the soft-BOS of the electrolysers are expected to decrease with further scale up by standardization. The electrolyser part is the largest uncertainty in the PV-E system. The PV module has a history of fast decrease in cost and the expectations are that this will keep decreasing. The BOS of PV and especially the soft-BOS are not expected to decrease with the same pace, since there is already a large amount of standardization for these elements. The effect of further cost reduction of the PV part is minimal compared to cost the effect the electrolyser has. When the pessimistic 2014 market value is used for electrolysers, then the PEC system outperforms the PV-E system. If that would be the case, cheap membrane cost of a PEC cell is also more unlikely. A change in cost of the PV part or Electrolyser part should always be followed be a new optimisation. An optimisation between the amount of PV panels versus electrolysers used, will have positive effect on the total system costs.

Future potential of PEC versus PV-E

All optimistic values in the sensitivity analysis are used to calculate future potentials of both systems. A ***future potential value of 4,46$/kgH$_2$ for PEC*** and ***4,99$/kgH$_2$ for PV-E*** are calculated. This small advantage for the PEC system is however not significant. While PV panels and electrolyser already have an existing market, while the PEC cell does. Therefore, cost development of a PV-E system will be pushed even without a solar hydrogen market. To enable a PEC system at this future cost level much development must be done. This development will not be facilitated by a commercial market, since there is no market yet and the competitive PV-E system is currently cheaper. A second factor that reduce the relative potential of PEC is that a PV-E system could be connected to the grid, which enables additional revenue streams.

It is unlikely that this PEC system will become much cheaper than a PV-E system in the long term, when comparing PEC cells with PV panels. PEC cells are expected to always be more expensive than PV panels. Because; more elements are required, less lifetime caused by corrosive environment, more requirements for used photoactive material and a smaller possible market.

The answer to the research question is therefor: it is considered unlikely for a PEC system to beat a PV-E system in cost versus performance in the medium till long-term.

6. Discussion

This research contributes to the scientific discussion about the potential of PEC systems by showing that it is unlikely for the chosen type of PEC cell to become commercial on a large scale. The role of the right photoactive material is highlighted in this research. This material needs to fulfil multiple additional requirements that are not required in PV panels. Current materials do not have all desired properties, including the chosen a-Si. The current/near-term cost based a-Si in this research are therefore considered optimistic.

The key element of this research is the comparison of a future PEC system with a future PV-E system. Most cost estimations provide a cost estimation of only one of the systems. Comparison of cost values of different researches is arbitrary, since many underlying parameters are often different. Different parameters such as location, labour rates, IRR and exclusion of tax can have large impact on the cost result. In this comparison all standard conditions are set equal. This research is not meant to predict what the exact cost of a system are expected to be, but it is meant to compare two systems under the same conditions which each other.

One other relative similar comparison is done by Shaner et al. (2016). However, their research had some shortcomings. The first shortcoming is regarding the used PEC cell. This has no soli-liquid-junctions and could as easily be described as a PV-E system, with a simple electrolyser for three standard silicon PV panels in series. A second shortcoming is that the electrolysers in the PV-E system are scaled to the maximum PV output. Therefore, a PEC design is chosen with a liquid-solid junction in this research. Also, an optimisation between PV and electrolyser is done which had significant effect on the reduction of total costs.

Societal benefits of this research are more indirect, by helping researchers to select research topics that will end up in real contribution to the hydrogen economy. It gives direction for investments (subsidy) in technologies for hydrogen production by solar energy.

This research has some limitations. First limitation is the uncertainty around large scale production cost of a PEC cell. PV panels and other cost estimations as Victoria (2015) has provided guidance in this process. Another is issue of concern is the dependency of cost elements to each other. This occurs in other cost estimations as well. For instance, installation cost is often taken as a percentage of uninstalled cost. The PV sector shows these costs will not necessary go down at the same pace as the hardware costs. To cope with this, an additional analysis has been performed to see which related elements of the sensitivity analysis per optimistic value were affected. If they were expected not to be affected at the same pace, these values were kept the same as with the current cost values.

An extensive analysis is done for selection of a PEC cell design. However, the relative cost of the PEC cell results might support different PEC cell designs for future research. The membrane is expected to be a relative expensive part, therefore design with less or without membrane could be considered. This will affect purity and probably efficiency, but might lead to better cost performance ratio.

A second interesting design could be the PEC system used by Shaner et al. (2016), which is earlier classified as PV-E. It uses standard PV panels that deliver the current directly to a simple electrolyser. Many research of electrolysers seem to focus on achieving the highest efficiency possible, because in most cases is electricity feedstock the main cost.[44] The second aim in these electrolyser research is reduction of the stack and BOS costs. However, electricity feedstock can be cheap for a part of the time, especially with the continuous expected cost reduction of PV panels and other intermittent electricity sources. Use of intermittent sources lead to a low capacity factor of the electrolysers, with electrolyser hardware as biggest cost driver as result in our PV-E system. Development of cheap durable electrolysers with decent efficiency could have high potential. A modular design could be used with for instance a good fit with three PV panels. This enables: mass production, racking systems that hold both the PV panel and electrolyser, no external wiring and easy replacement of the electrolysers.

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8. Appendix

A. Electrolyser

List with advantages and disadvantages of the commercial available electrolysers Alkaline and PEM in Table 8-1. In Table 8-2 are new promising electrolyser technologies mentioned that could in the long-term play a role as cheap electrolyser. These new technologies are currently far from large scale production, but show there are novel designs for the electrolyser as well.

Table 8-1 Main advantages and disadvantages Alkaline and PEM electrolysers

Technology	**Advantages**	**Disadvantages**
Alkaline	Commercial available MW scale[29] Cheapest[29] No noble catalyst (Ni/Fe)[29] Long term durability (10y stack /20y system)[12] Efficiency 70%[29]	Low current density (result in larger systems) Lower purity Electrolyte is corrosive Low dynamic operation Load range is low for partial load Lower operational pressure
PEM	Good partial load range Higher current density Higher gas purity High dynamic operation Rapid system response time	Commercial available below MW scale High cost of components: Noble catalyst, Nafion Membrane Electrolyte is acidic and corrosive Less durable

Table 8-2 New conceptual electrolysers

Technology	**Concept**	**Main advantages & disadvantages**
Rotolyzer[45]	A rotating alkaline electrolyser Strong increase in reaction rate, caused by centrifugal forces which help to remove reaction gasses from reaction site.	Increasing the availability of active area. Should lead to large reduction in size and materials. Downside is oxygen and hydrogen are fully mixed.
Battolyser[46]	A Ni-Fe battery and electrolyser in one. After overcharging a Ni-Fe battery it starts producing hydrogen such as an alkaline electrolyser.	Electricity can be stored and delivered back, delivering additional value. It is expected to be more flexible and efficient at lower loads. Downside is it will probably be a larger system.
Membrane less electrolyser[47]	It separates product gases by controlling the delicate balance between fluid mechanic forces.	No expensive membrane, variety of electrolytes are possible that enable use of non-noble catalyst. Downsides are max 40% efficiency found and less pure hydrogen product.

B. Optimisation PV panels versus electrolysers

The optimisation consists of 5 steps:
1 Production of a load duration curve
2 Calculation of non-utilized irradiation per cap
3 Calculation of additional PV panels required per cap
4 Calculation of reduction in required electrolyser capacity per cap
5 Calculation of the cost per cap of both the PV panels and the electrolyser (Including all cost that scale directly with one of these elements.)

1 Load duration curve
In Figure 3-6 is for four days in the year the hourly irradiation given at the panels. (Note: the panels are placed at a specific angle.) The irradiation received is kept as unit, since this is independent of PV panel efficiency and is assumed to be linear with PV output.
The max irradiation is 925W.

Irradiations caps are made: 925W-900W-800W-700W-600W-500W-400W-300W-200W-100W. The idea is that the irradiation energy received above this cap will not be fed into the electrolysers. For the four dates are the hours estimated for each cap by looking at the graph. These values are put in Table 8-3.. The average value per cap is multiplied with 365 to calculate total hours in a year of a specific irradiation. A load duration curve is made by using the cap values on the y-axis and the hours yearly on the x-axis, see Figure 3-7 for the graph.

Table 8-3 Hours of irradiation per cap

W	Jun	Sep	Dec	Mar	Yearly
925	0,0	0,0	0,0	0,0	0
900	2	2	0	0	365
800	4	4	0	2,5	958
700	5,5	5,4	0	4,5	1405
600	6,4	6,4	2,4	6	1935
500	7,3	7,4	4,5	7	2391
400	8,2	8,4	6,6	8	2847
300	9,1	9,4	8,1	9	3249
200	10	10,4	9,6	10	3650
100	11	11,4	9,8	11,1	3951
0	12	12,4	10	12,2	4252

2 Calculation of non-utilized irradiation per cap
First is the amount of Wh incoming irradiation per cap slice per year determined.
Example: 900W till 800W cap slice → (365h+958h)/2=661,5h times the watt gap of 100W(=900-800) → 66,6kWh/year
Next is the percentage calculated that each slice contributes to the total irradiation.
For each cap is calculated the amount of irradiation that will not be used.
Example: a cap of 800W will not use the contributions of the slices 800-900W and 900-925W → 3,1%

3 Calculation of additional PV panels required per irradiation gap
Important to realize is that the added PV panels are also affected by the cap.
Therefore, is the additional PV capacity installed to compensate the cap calculated with [1/(percentage of irradiation received under the cap)-1].
Example: 800W cap → 1/(100%-3,1%)-1=3,2%

4 Calculation of reduced electrolyser capacity

Electrolyser are scaled at the start to the 925W of max incoming irradiation. More PV leads to a relative higher W input than the cap for electrolysers. At 800W cap, there are 3,2% more PV panels therefore is the relative max input 826W.

This relative max can be calculated as percentage of the max input 89%(=826/925). This is done for all caps.

Example: 800W cap lead to 3,2% more PV panels and 11% less electrolyser required.

5 Calculation of the cost per cap of both the PV panels and the electrolyser

Per cap is the cost reduction for electrolysers and the cost increase for PV calculated. To do this right all related costs are used. To account for the difference in lifetime of components is the average depreciation over the system lifetime taken as costs.

This lead to the graph in Figure 3-8. From Figure 3-8 is concluded that 700 W/m^2 is the optimal cap for incoming irradiation to scale the electrolyser to in terms of system costs. 8% of the electricity produced with this cap is not used. This lead to a 9,1% increase of PV panels and 17,5% less electrolyser required.

C. PEC cell configurations

Overview of different kinds of PEC cell designs (by Victoria)
Victoria (2015) describes per PEC cell configuration (Figure 8-1) the advantages and disadvantages in her research. The faced electrodes version is divided into six sub designs, see Figure 8-2. This shows the large amount of possible variety within PEC cell configurations. The illustrations of Victoria (2015) are considered the best found basic principles of PEC configurations drawn. A second overview of possible PEC configurations by Minggu et al. (2010) could be interesting to investigate as well.[48]

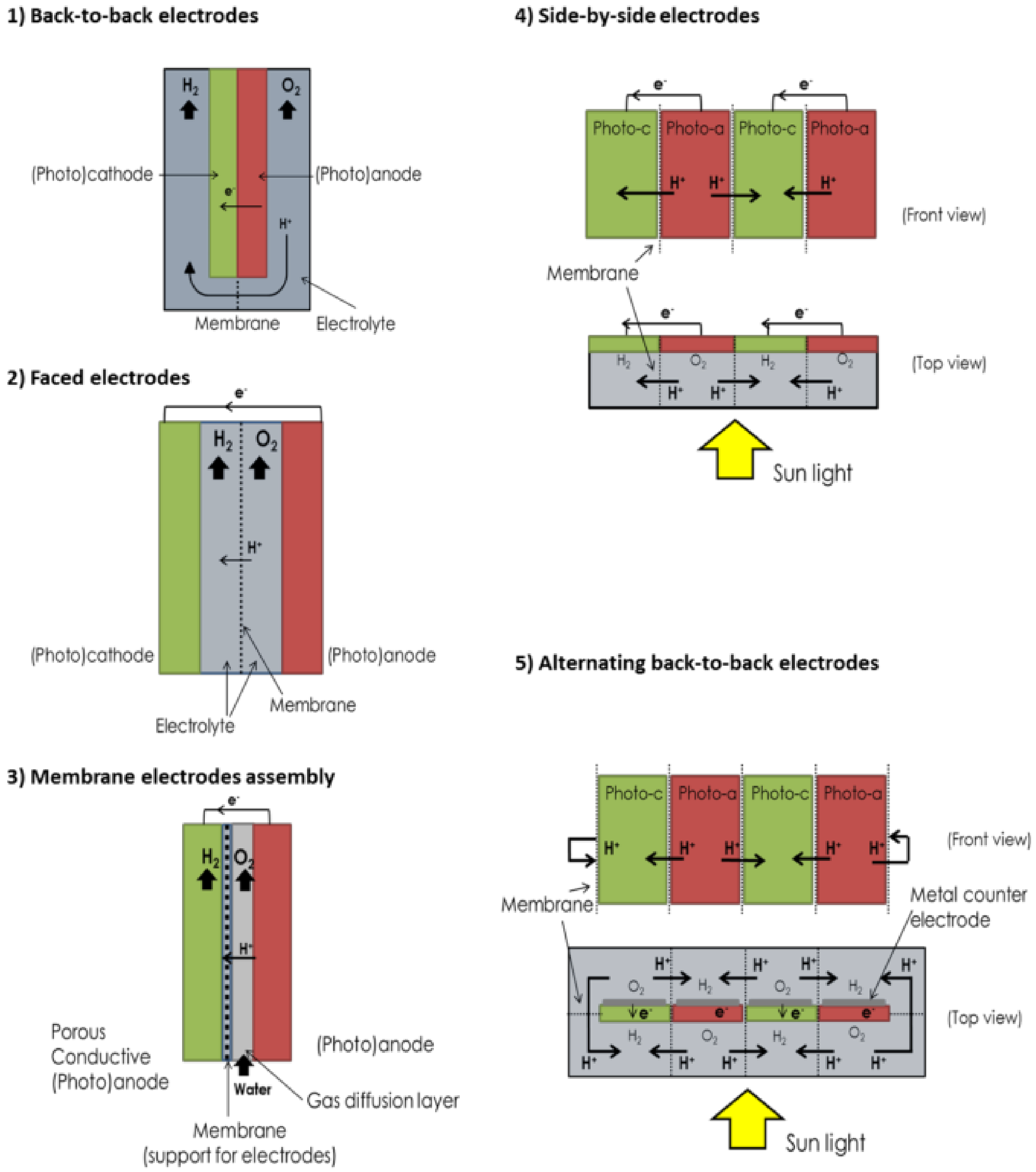

Figure 8-1 Overview of different PEC configurations, source: Victoria (2015)

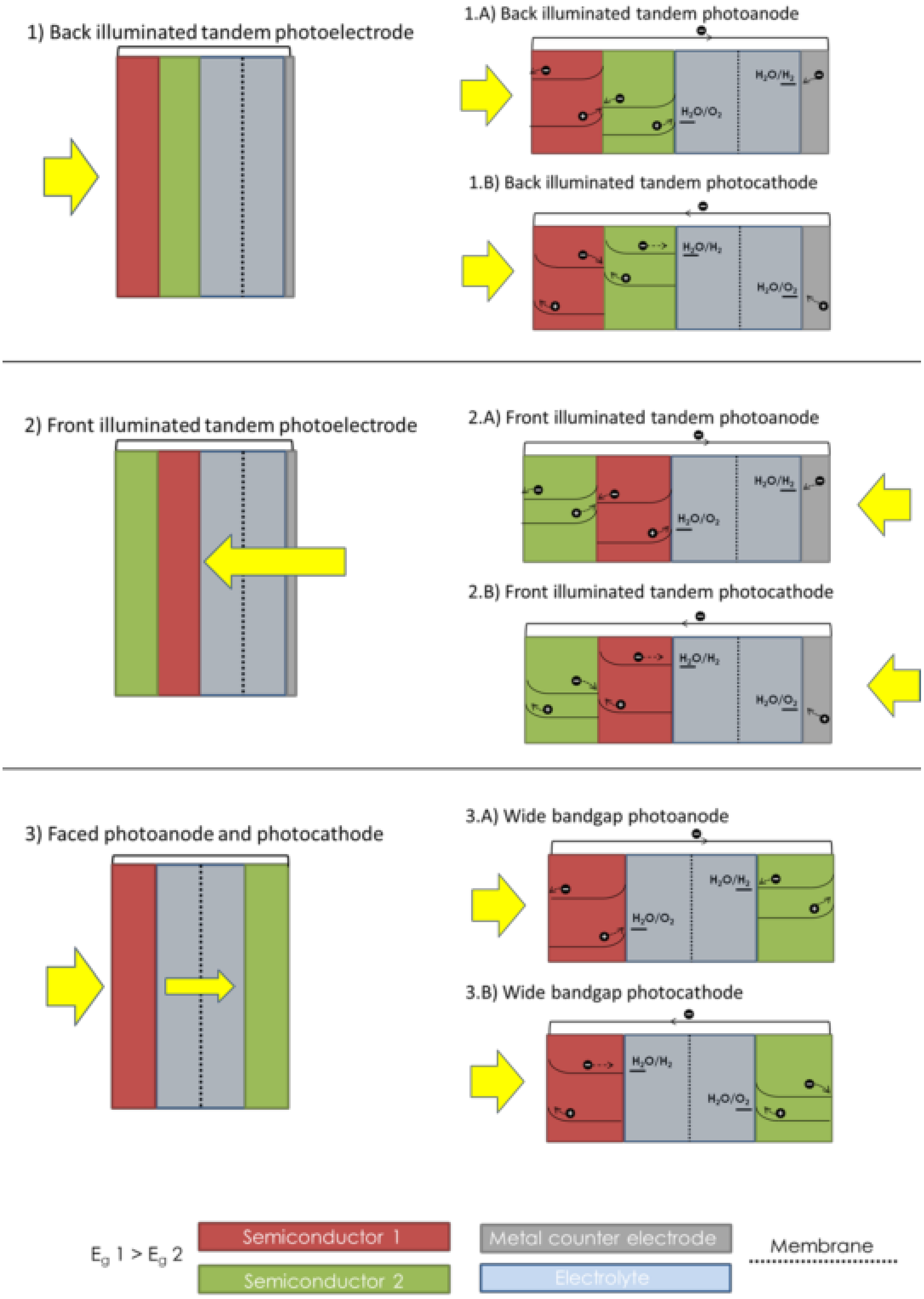

Figure 8-2 Subdivision of faced electrodes configuration

D. Compressed versus uncompressed PEC

Thicker plexiglass must be used when a PEC cell is under pressure. This is significantly more expensive according to the 2009 DOE report.[7] The relative cost per m^2 of solar area are for the compressor in Type 3 is about 14\$/m^2, while thicker plexiglass will cost an additional 81\$/m^2. For this calculation the cost difference of glass per m^2 of Type 3 and Type 4 are taken. The total compressor cost of Type 3 is taken and divided by the total surface of panels of the system.

E. CAPEX values PEC and PV-E systems

The CAPEX values are mentioned in Table 8-4 & Table 8-5 for the PV-E and PEC systems. For some elements are the original values in \$/m^2 (black colour) and for other elements this cost is calculated by division through the surface of the panels.

Table 8-4 List of CAPEX of PV-E in year 0

CAPEX PV-E in year 0 with 534.621m2 of PV panels			
Main part	**Subpart**	**$/m2**	**Total M$**
PV part	PV panels	$54,00	28,9
	Mounting material	$15,00	8,0
	Wiring	$16,50	8,8
	Total	$85,50	45,71
Electrolyser part	Electrolyser stack	$50,40	26,9
	Hard-BOS	$47,30	25,3
	Total	$97,70	52,2
Soft-BOS	PV installation	$17,10	9,1
	PV Contingency	$17,10	9,1
	PV Engineering and design	$4,28	2,3
	Installation stacks electrolyser	$10,08	5,4
	Installation hard-BOS electrolyser	$9,46	5,1
	Contingency electrolyser	$19,54	10,4
	Engineering and design electrolysers	$4,88	2,6
	Other soft-BOS costs	$5,00	2,7
	Total	$87,44	46,7469
Other	Land cost	$0,63	0,3
Total		$541,91	289,72

Table 8-5 List of CAPEX of PEC system in year 0

CAPEX PEC in year 0 with 538.450m2 of PEC panels			
Main part	**Subpart**	**$/m2**	**Total M$**
PEC cell	Photoactive layers	$45,0	24,2
	TCO	$1,0	0,5
	Cathode/protective layer Ni-Mo	$5,0	2,7
	Anode/ counter electrode Ni mesh	$1,0	0,5
	Front contacts	$0,5	0,3
	Glass	$10,0	5,4
	Membrane	$50,0	26,9
	Wiring	$1,0	0,5
	Housing	$20,0	10,8
	Assembly	$20,0	10,8
	Total	**$ 153,5**	**82,7**
Hard-BOS	Mounting materials	$15,27	8,2
	Water pump	$0,003	0,003
	Water piping	$2,45	1,3
	Gas compressor	$17,73	9,5
	Condenser	$0,39	0,2
	Intercoolers	$0,85	0,5
	Gas piping	$2,45	1,3
	Water level controllers	$3,14	1,7
	Hydrogen sensors	$3,34	1,8
	Other control equipment	$0,34	0,2
	Total	**$45,96**	**24,7**
Soft-BOS	Installation BOS	$9,14	4,9
	Contingency	$59,76	32,2
	Engineering and design	$9,96	5,4
	PEC cell installation	$30,70	16,5
	Other soft-BOS costs	$5,00	2,7
	Total	**$114,56**	**61,7**
Other	Land cost	$0,63	0,3
Total		**$314,65**	**169**

F. Detailed display of cost division result

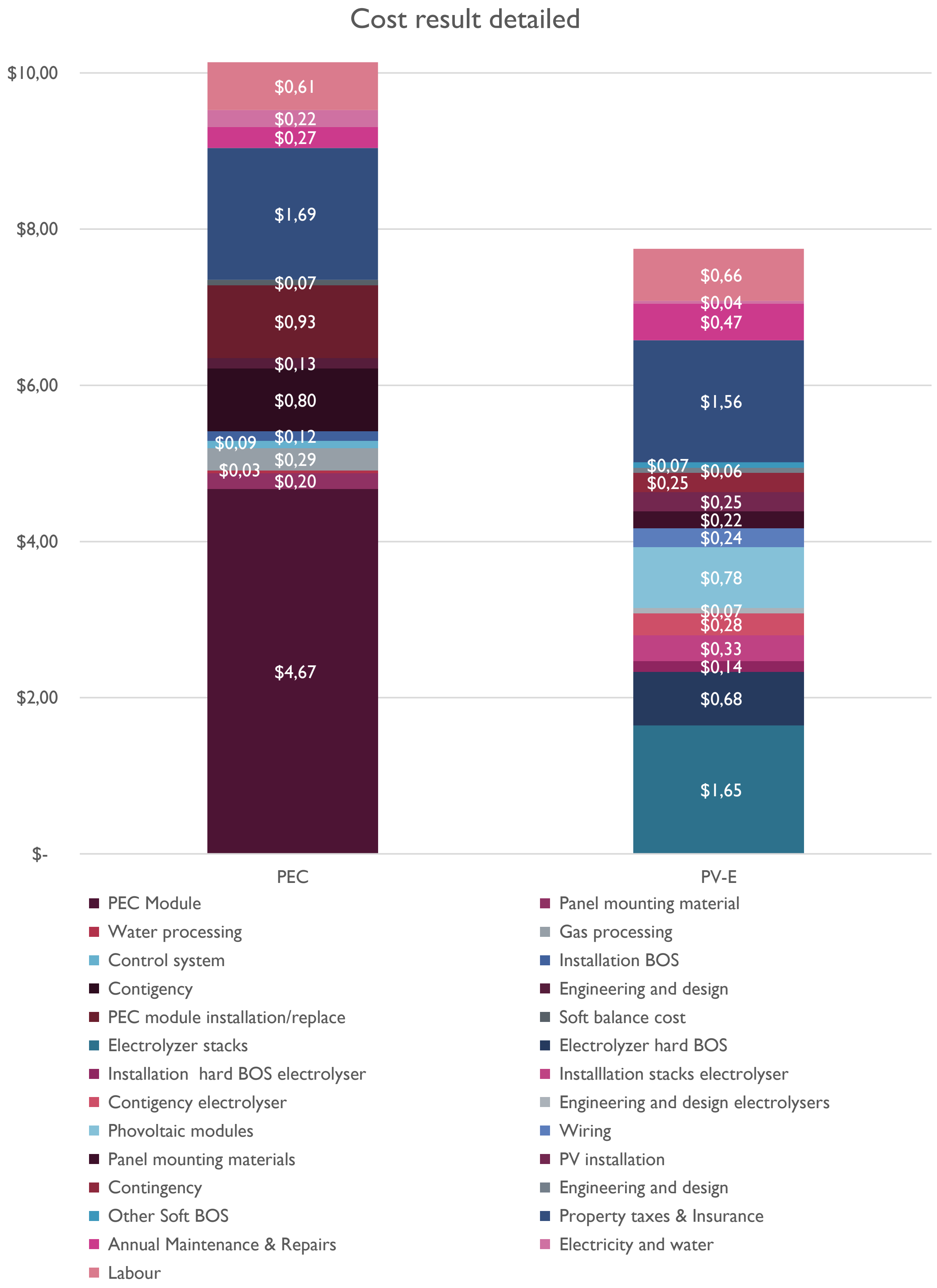

Figure 8-3 Detailed result of current cost estimation