
SUMMARY

[FeFe]Hydrogenase Mimics for Proton Reduction Catalysis

As the use of fossil fuels unambiguously leads to global warming, the need for an alternative and sustainable fuel is growing. Hydrogen (H_2) is an energy carrier with interesting properties, in that it can be produced from the splitting of water, giving only oxygen (O_2) as a side product. When needed, this fuel can release the energy stored in the H-H bond by reaction with atmospheric oxygen to reform water. As such, no toxic or otherwise harmful substances are released in the atmosphere. However, hydrogen can only be regarded a sustainable fuel when the water splitting reaction is driven by a sustainable energy source. Considering the size of the earth's population, sunlight is the most obvious choice, because the sun provides us with an almost infinite amount of energy. To put it into numbers: in one hour, the sun delivers more energy to the earth's surface than the human population uses in a year. This sets the outline of the task to be solved: how can sunlight and water be reacted to produce hydrogen at a competitive price?

The overall photolysis of water to produce hydrogen is already feasible, e.g. by connecting photovoltaic cells to an electrolysis cell. In such a set-up, solar energy is first converted to electrical energy, which is in turn converted to chemical energy. Unfortunately, these additional conversions come at a cost, and the catalytic materials currently used in electrolyzers (platinum and iridium) are expensive. For these reasons, the BioSolar Cells research consortium of the Netherlands was founded with the aim of producing solar fuels directly from sunlight and water, without the need for the conversion to and from electricity. One part of the consortium focuses on photosynthetic fuel production using algae, bacteria and plants. The other part focuses on artificial photosynthesis: non-natural systems that perform similar functions as found in photosynthetic organisms, but are catered to the production of hydrogen or related fuels.

The natural photosynthetic chain is initiated with the oxidation of water. In the so-called oxygen evolution complex, two molecules of water are oxidized in an overall four-electron process to form one molecule of oxygen and four protons according to: $2 \text{H}_2\text{O} \leftrightarrow \text{O}_2 + 4 \text{H}^+ + 4 \text{e}^-$. The released (low-energy) electrons are transferred

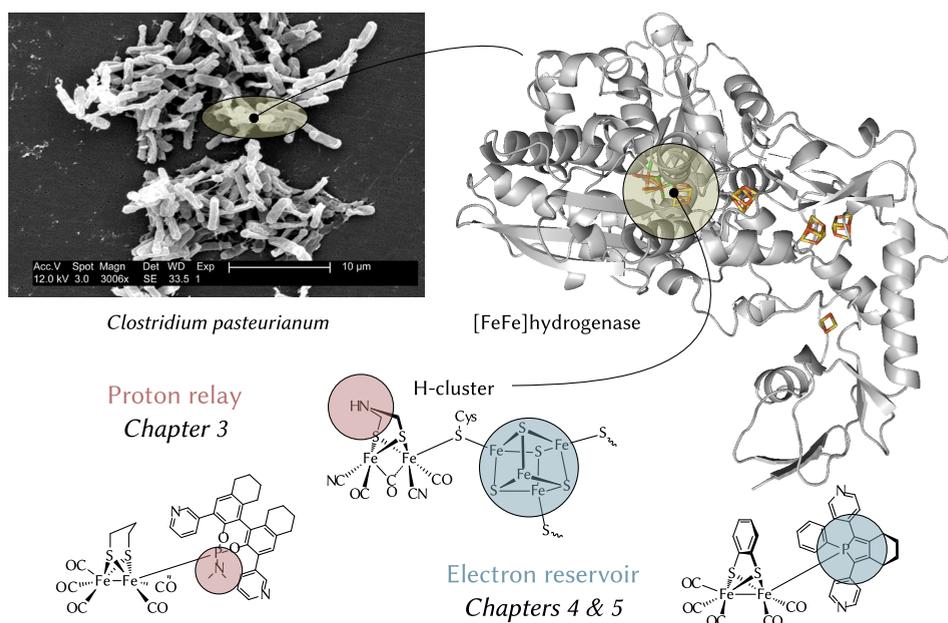


Figure 1. The [FeFe]hydrogenase enzyme as found in *C. pasteurianum* and the synthetic mimics studied in this thesis.

to a photosystem which increases the energy of the electrons by incident photons. In nature, the (high-energy) electrons produced as such are used to synthesize NADPH, which serves as an energy carrier ('fuel') to perform work. In artificial photosynthesis the process is similar, although in this case the part that produces NADPH is replaced with a part that produces H_2 . Although in principle we could isolate all the useful parts out of the photosynthetic membranes and use them to construct an 'artificial leaf', in practice this process is too expensive. However, we can still take a look at how nature has solved this problem, and identify the molecular structures and architectures that have proven to work over the course of evolution. Such molecular imitations of nature are generally called 'synthetic mimics', and are classified as either or both *functional* or *structural*, meaning that they mimic either or both the function or the structure of its natural counterpart. Apart from being less expensive to make or isolate, synthetic mimics offer the advantage of being tuned rationally, e.g. so they can function outside the protective environment found in photosynthetic organisms.

In this thesis, we focus only on the proton reduction (hydrogen generation) half-reaction of the overall water splitting reaction. To drive this reaction with light, we make use of zinc porphyrins as synthetic photosystem mimics, because they resemble the chlorophylls in the natural photosystem. As proton reduction catalysts we use mimics of all-iron hydrogenase, $[FeFe]H_2$ ase, a naturally occurring enzyme that generates hydrogen at a rate and overpotential comparable to platinum (the best proton reduction catalyst currently known). To connect the chromophores with the catalysts, we make use of supramolecular chemistry by creating 'plug-and-play' building blocks for the construction of photosystem-like molecular architectures. The $[2Fe-2S]$ clusters studied in Chapter 3 and 4 are equipped with pyridine moieties that can coordinate to the central zinc atoms of the porphyrins, e.g. in the porphyrinic metal-organic frameworks (MOF) presented in Chapter 6. Using this strategy, we show how an artificial leaf could be constructed from earth-abundant materials.

The naturally occurring $[FeFe]H_2$ ase enzyme produces hydrogen efficiently because of two main functionalities present near the catalytically active $[2Fe-2S]$ cluster. One is a *proton relay* to pre-organize protons close to the active site – the other is an *electron reservoir* to mediate electron transfer from the enzyme's surroundings to the active site. Chapter 3 shows how the dimethylamino group of a phosphoramidite ligand (when attached to an $[2Fe-2S]$ cluster) pre-organizes protons in a similar way as the natural enzyme, leading to a higher catalytic reaction order in protons as opposed to similar catalysts lacking this functionality. This result exemplifies

how a natural enzymatic function can be mimicked through the use of a radically different structural motif. We used this insight to mimic the enzyme's electron reservoir in the following chapters.

In Chapter 4 we present a catalyst equipped with a redox-active dipyritylphosphole ligand, resembling the electron reservoir present in the $[\text{FeFe}]\text{H}_2$ ase enzyme. By electrochemical analysis, time-resolved infrared spectroscopy, density functional theory and spectroelectrochemistry we elucidate the peculiar behavior of the catalyst and show that the redox-active ligand partakes in catalysis, i.e. it donates an electron into the active site when needed. Moreover, in the presence of acid the dipyritylphosphole ligand mediates electron transfer to the $[\text{2Fe-2S}]$ cluster by protonation of one of its side-arms via a proton-coupled electron transfer (PCET) process. Additionally, the attached pyridyl moieties make the complex soluble in acidic water, leading to fast proton reduction catalysis in dilute sulfuric acid. The catalyst tolerates the presence of oxygen in the reaction medium – a useful property considering that in an ultimate application, trace amounts of oxygen might be expensive to remove.

Chapter 5 elaborates on the redox and protonation chemistry of phosphole-appended $[\text{FeFe}]\text{H}_2$ ase mimics. Electrochemical analysis combined with density functional theory shows how the incorporation of redox-active phosphole ligands into an $[\text{2Fe-2S}]$ cluster leads to structural integrity of the complexes after one-electron reduction, whereas the reference phosphine-appended complexes show a cleaved Fe-S bond after mono-reduction. This structural difference leads to distinct reactivity, where the mono-anions of the phosphole-based complexes are basic enough to be protonated, even though the phosphole ligands effectively remove electron density from the active site. Although the overall efficiency for electrocatalytic proton reduction does not change appreciably, the catalytic mechanisms change drastically. An implication of this finding could be that the mechanism for electrocatalytic hydrogen formation can be changed at will without paying a penalty in terms of overpotential or rate. This feature is crucial in the design of photocatalytic architectures, where the potentials and rates of the steps in the catalytic cycle have to be matched to excited state potentials and lifetimes of photosensitizers.

Porphyritic architectures for the design of an artificial leaf are presented in Chapter 6. Based on the geometry of the phosphole-appended catalyst studied in Chapter 4, we impose design constraints on such macromolecular materials, which throughout the chapter turn out to be too rigid, leading to the conclusion that catalyst inclusion into a porous material might be severely sterically or kinetically re-

stricted. Since an artificial leaf is most practically constructed on a solid electrode, the last part of Chapter 6 is devoted to metal-organic frameworks (MOFs) grown on a transparent electrode. Solvothermal synthesis of known MOF-545-Zn on a fluoride-doped tin oxide coated glass slide yields a uniform red film which turns out to be fully electrochemically addressable. This MOF features the largest pore size of any porphyrinic MOF known at the time of writing, which should allow for facile catalyst inclusion. However, preliminary experiments suggest that the investigated catalysts were not encapsulated into the porous structure under the applied conditions. As a possible starting point in the design of an artificial leaf, we elaborate on alternative strategies for the (covalent) anchoring of small molecules in this particular framework, which might ultimately lead to a stable and efficient proton reduction photocathode.

In this thesis we have shown how relatively small modifications in the coordination sphere of a proton reduction catalyst can lead to drastic changes in the catalytic mechanism and therefore in the overall thermodynamic and kinetic properties of a catalytic system. The most pronounced effects can be ascribed to proton pre-organization, electron pre-organization and the geometry of intermediate species – all key factors in the efficient operation of the [FeFe]hydrogenase enzyme. However, both for the mimics studied in this thesis as for mimics reported in literature, the overpotential for proton reduction is in most cases around 0.6 V. We envision that lowering this overpotential can only be attained by opening up PCET events to circumvent high kinetic barriers or to include very electron-rich ligands (i.e. cyanide) that are held in place by a second coordination sphere.

Regarding the design of an artificial leaf, we consider metal-organic frameworks as a key component due to their high stability, tunability, porosity and ease of handling. The modes of catalyst inclusion are manifold: simple soaking, supramolecular coordination, ship-in-a-bottle, covalent attachment, post-synthetic linker exchange, etc. As such, these molecular frameworks can be regarded the *LEGO*[®] of chemistry. One aspect, however, is largely preventing chemists from unleashing the enormous potential that MOFs harbor: the need for heterogeneous characterization techniques. We suspect that once MOFs can be analyzed in a straightforward manner by the (in)organic chemist, systems chemistry will flourish, and the artificial leaf will slowly populate our rooftops.