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# Nature versus Technology – Performance Building Skins Inspired by Nature

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## Abstract

The research will demonstrate new strategies and concepts for building envelopes based on natural systems. Smart structures and adaptive systems are standard in nature and could be the key to the next step in the evolution of intelligent building skins for architecture.

The translation of abstracted nature in mathematical terms and the application of prerequisite architectural considerations are the fundamental concepts of bio-inspired structures, materials and systems in engineering. Nature typically uses not additive, but highly integrated systems, which optimize several necessary features in one component. Energy acquired by photosynthesis or heterotrophic processes has to be diverted between growth and reproduction, and protective measures. Bionic skins are highly integrated and multifunctional and based on the compulsion to generation, self-optimize and self-adjustment.

The basis for a transfer of biological systems into technical systems requires detailed studies in combination with the crucial functional aspects within the ecological context. Thereby, the efficient use of energy is critical for survival. This present an attractive design pool for advanced technical applications.

The paper will be demonstrated new strategies and concepts for building envelopes based on natural systems. Smart structures and adaptive systems are standard in nature and could be the key to the next step in the evolution of intelligent building skins for architecture.

Natural structures and skins offer an abundance of observational material for optimization, but direct derivations in the sense of a literal imitation are not possible. The fundamental differences lie in the scale of the system, their material composition and differences of function.

**Keywords:** building envelope, intelligent building skin, bionics, morphology, new materials

## 1. Smart Materials and Smart Material Systems

A look into the future of building envelopes shows that ‘smart materials’ have a wealth of unexplored possibilities. These ‘adaptive’ materials of one or more components are able to adapt themselves to particular external requirements, for they do not have fixed properties. They actively respond to external changes such as temperature, radiation, loading or electrical current. Of particular interest is the reversibility of changes in property. These materials are similar to adaptable, self-repairing structures in nature that can identify a failure and react accordingly.

Bionic systems can be categories into *structural morphology* (Bio-inspired structures and components), *materials and material compounds* (Bio-inspired materials and surfaces) and Bio-inspired *kinetic functions and systems*. The Paper will showcase examples and possible application in these three categories.

## 2. Performance Criteria's for Building Skins

Categories for potential applications of bionic inspired concepts for performance building skins:

*Passive Systems and Strategies*

Passive strategies in architectural design take advantage of natural conditions to minimize energy use without the aid of machines or human intervention. Subcategories are: Day lighting, Natural ventilation, solar gain-/heating, natural ventilation

*Active Systems and Strategies*

Active strategies use human intervention or technology to provide for additional energy needs and improve the effectiveness of the passive strategies already designed. Subcategories are: Climate control, Solar Systems, Energy Harvesting, Water, Lighting, Control Systems, Appliances, Energy, Adaptability

*Assemblies*

The materials determine the thermal efficiency, moisture resistance, and air tightness of the building envelope. When quality materials are assembled correctly, heating and cooling loads are reduced, and air quality increases creating a healthier environment.

## 3. Case study: "Plus Energy" surfaces by naturally producing hydrogen using algae

Hydrogen[i] - Environmentally Sound Energy

Considering increasing pollution and the exploitation of fossil energy resources, new energy concepts are essential to the future of industrial society. Renewable resources have to replace fossil fuels that produce carbon dioxide upon combustion, which as a green-house gas is largely responsible for global warming. Hydrogen is the ideal means of energy storage for transportation and conversion of energy in a comprehensive clean-energy concept. Hydrogen can be produced from water using electricity, ideally produced from regenerative sources, e.g. wind, solar or water energy. Upon reconversion into energy, only water vapor is produced, leading to a closed energy cycle without harmful emissions. This natural effect can be used for "plus energy" artificial surfaces. New fuel cell technology makes it visible to develop a integrated energy+ Facade by combining $H_2$-producing green algae and energy-producing fuel cells.

## 3.1 HYDROGEN ENERGY

Hydrogen is the most abundant element in the universe, and the third most abundant on earth's surface. Consisting of only one proton and one electron, it is also the simplest. However, hydrogen does not occur naturally on earth; it always combines with other elements in nature. By combining H2 with oxygen, water results. Hydrogen is present in many organic compounds, notably the hydrocarbons of natural gas, methanol, propane, and biomass.
Applied electricity or sunlight separates the hydrogen and oxygen components of water, and applied heat removes hydrogen from hydrocarbons. Algae and bacteria produce hydrogen through photosynthesis, a natural process induced by the sun's heat.

When burned, hydrogen produces high energy, and constantly replenishes itself. Fueling an engine, hydrogen again joins with oxygen to form water. Since the 1970s, NASA (National Aeronautics and Space Administration) has been fueling rockets into orbit with liquid hydrogen, and energizing their electrical systems with hydrogen fuel cells. The crews drinkits byproduct pure water.

Furthermore, as an energy carrier, hydrogen stores, transports, and delivers energy. Hydrogen-produced energy can be stored to provide energy where and when needed.

Looking toward the future, hydrogen fuel cellsii hold great promise as our electrical energy source for buildings, vehicles, and our day-to-day technological devices. Hydrogen is the expected future of our ecology and economy. [1]

## 3.2 Green Algae

History

In 1939 a German researcher named Hans Gaffronworking at the University of Chicago observed that the algae he was studying, *Chlamydomonas reinhardtii* (a greenalgae), would sometimes switch from the production of oxygen to the production of hydrogen. Gaffron never discovered the cause for this change and for many years other scientists failed in their attempts at its discovery.


Figure 2 Natural Algae in a pond

Figure 3 "DIY Algae/Hydrogen Bioreactor", (Franceschini, 2004) [NATURE, VOL 414.15, NOVEMBER, 2001 www.nature.com]

In the late 1990s researchers[iii] at the University of California at Berkeley discovered that if the algae culture medium is deprived of sulfur it will switch from the production of oxygen (normal photosynthesis), to the production of hydrogen. They found that the enzyme responsible for this reaction is hydrogenase, but that hydrogenase loses this function in the presence of oxygen. Anastasios Melis found that depleting the amount of sulfur available to the algae interrupts its internal oxygen flow, allowing the hydrogenase an environment in which it can react, causing the algae to produce hydrogen. [2]

**3.3 Biological hydrogen production (Algae)**

Genetically changed single-cell green alga[iv] have great potential: they produce five times the volume of hydrogen made by the wild form of alga and are energy efficient up to 1.6 to 2.0 percent. Research shows that the technology could surpass the economically viable 10 percent efficiency level[v]. [5]

On a much larger scale, hydrogen can be produced in a bioreactor. Efficiency can be tremendously increased by providing competitive inhibition of photosynthetic hydrogen production by carbon dioxide for example from offices and factories etc.. To become economically feasible, energy efficiency, the conversion of sunlight into hydrogen, has to reach 7-10 percent (alga in its natural form achieves at most a meager 0.1 percent).

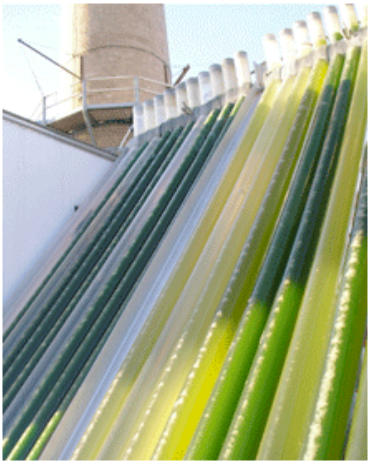

Figure 4 Smokestack emissions bubble through algae-filled tubes at MIT's Cogen plant. (Photo: Ashley Ahearn)

### 3.4 Current H2 production efficiency

From lab measurements, peak $H_2$ production is obtained 24-72 hours after sulfur depletion with 2-2.5 ml $H_2$ produced from 1 liter of culture per hour. Then the rate gradually declines (Zhang et al., 2001)

Theoretical extrapolations:

On a cloudless spring day at a moderate latitude, this translates into the delivery of 50mol photons $m^{-2}$ $day^{-1}$. Under these conditions, green algae can produce a maximum of 10 mol (20g) $H_2$ per m2 culture area per day [Melis and Happe, 2001].

In reality, lab measurements indicate that algae don't use all their photosynthetic potential – only 15 to 20%. They don't capture all the light they can – particularly under bright sunlight, they would only capture some 40%. Additionally, the optimal procedure of growing algae currently involves photosynthetic growth under normal conditions followed by sulfur deprivation – $H_2$ production is turned ON after 24-120 hours. Algae cultures have to be sealed from air to maintain anaerobic conditions. To keep cultures going, S had to be added - during which time there is no production of $H_2$. So roughly, the culture will be able to produce $H_2$ only 50% of the time during this S depletion/repletion cycle.

Recently however, a mutant strain of *Chlamydomonas*, *Stm6* was found to have an increased $H_2$ production rate, typically ~540 ml $H_2$ liter-1 over 10-14 days, with a maximum rate of 4 ml/h-1. These figures are 5-13 better than that of the wild type [Kruse et al., 22005].

### 3.5 Principle of a Fuel Cell

The principle is based on the electrochemical reaction between hydrogen and oxygen to water [Figure 6]. The key feature of a fuel cell is the electrolyte, which separates hydrogen and oxygen. The hydrogen atoms "see" the oxygen atoms on the other side, but hydrogen can only penetrate the electrolyte if the electron is left behind. The electron has to take the long way over the electric cords before it can "reunify" with the hydrogen or water ions, respectively, on the other side. This electric current can be utilized, e.g. for lighting, HVSC systems, electric motors etc. [3,4]

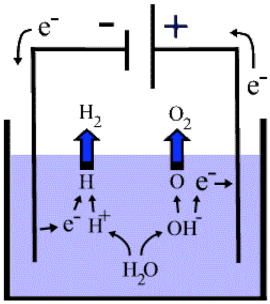



Figure 6 Electrolysis: Splitting water with electricity to produce hydrogen and oxygen [ThinkQuest New York City]

Figure 5 Hydrogen compressed fuel cell development at ORNL

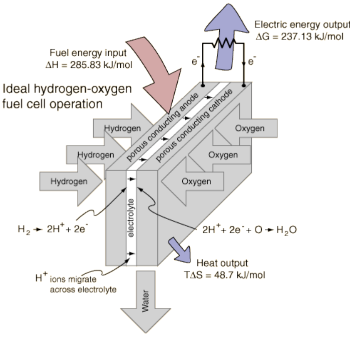


Figure 7 The diagram shows the chemical reaction that produces the electric current. [ThinkQuest New York City]

Figure 8 Fuel cell installations at ORNL

### 3.6 Fuel cell research at ORNL

The National Transportation Research Center (NTRC) [6] has just begun operation of a UTC phosphoric acid fuel cell to provide heating, cooling, and electricity to the building. It is currently supplying up to half of the building's power supply. Hydrogen is generated from an on-site natural gas steam reformer, and a SEMCO desiccant wheel recovers energy (heating or cooling) and controls humidity from exhaust air.

- The cell produces 200kW, or1/3 of the building’s electricity.
- The cell produces 450,000 Btu/hr to heat water to 250°F, which is then used to heat the building. The cell increases resource efficiency from 33% to 59% by combining space conditioning and power.

## 4. Hydrogen Façade

Green algae produce hydrogen naturally. This natural effect can be used for “plus energy” artificial surfaces. Hydrogen, manufactured locally using water, wind and sun, is a secure, inexhaustible, emission-free fuel for consumer electronics, heat and electricity production, and the next generation of highway vehicles. It is recognized that green algae produce hydrogen naturally by dividing water into hydrogen and oxygen. This process is not just $CO_2$ neutral, comparing the $CO_2$ – $O_2$ ratio shows it is actually CO2 negative. That means a surface applied with these microorganisms will produce hydrogen by dividing water and produce oxygen as a natural organism like trees.

Without energy input, the organisms produce hydrogen, which results in a positive energy ratio – “plus energy” surface. They do so using a cell protein, the enzyme hydrogenase. The energy necessary for this process is provided by photosynthesis. Producing hydrogen is a loss of energy for green algae, so they must be forced to produce hydrogen through the deprivation of sulfur. Sulfur is one of the nutrients that enable plants to grow – without sulfur there is no growth, but photosynthesis continues anyway. Because of photosynthesis green algae produce masses of energy – the hydrogen. The hydrogen escapes as a gas and can be stored without problems as a gas in tanks.

This hydrogen façade consists of modules including green algae and fuel cells. The green algae are in tubes between two glass sections. The tubes are perforated and the hydrogen can thus escape into the space between the two pieces of glass. At the top of each façade module is a fuel cell that converts the hydrogen into electricity and heat.

At present, the overall energy conversion efficiency of the process - photons absorbed and converted into hydrogen product - is only about 10%. With optimization, it could come close to or be about the same as photosynthesis itself, between 85 and 90%, possibly as high as 95% by optimized light exposure. [Melis Berkeley/NREL]

**What is the benefit to the nation?**

• Energy efficient buildings: housing, offices …
• Energy producing surfaces at buildings
• Hydrogen production
• $CO_2$ elimination
• Sulfur elimination
• Decreased greenhouse gas emissions

**4.1 Project Description**

The Oak Ridge National Laboratory and UT have already established research in the fields of energy, $H_2$ production, fuel cell technology and building technology. The "Plus Energy" facade project combines these research fields to develop a completely integrated, energy producing new facade system. The project goal is to use a natural organism (e.g. green algae) for the generation of hydrogen on façade surfaces and the production of energy. The added bonus of using algae in this way is that they could consume Carbon Dioxide ($CO_2$) in the atmosphere and thus possibly slow down Global Warming.

An important benchmark is to develop hydrogen cells with an economically viable 10 percent efficiency level. This can be achieved by shortening the chlorophyll stacks in the photosynthetic organelles.

**Issues and Approaches:** The focus will be on successful application of organisms on surfaces and the capturing of hydrogen. Hydrogen cells can be incorporated into the façade of a building, complementing or replacing traditional materials like roofing tiles, batten-seam metal roofing component or semi-transparent glazing. Often, these installations are vertical, reducing access to available solar resources, but the large surface area of buildings can help compensate for the reduced power output.

One possible application of hydrogen façades in buildings is the full integration of algae-filled glass tubes into glazed curtain walls. Low-emissive glass screened by algae-filled glass tubes will reduce the building's cooling loads and at the same time produce hydrogen as an energy resource. Thin horizontal glass tubes placed on a steel framework in front of the glass will screen and shade the full height glass wall around the building and diffuse light through them from different angles. The hydrogen produced can be coupled with a fuel cell to generate heating or cooling energy for the building.

**4.2 Key study: Glass tubes as shading devices**
One possible application for the hydrogen façade appears in Renzo Piano's new Times

The proposal is to use exactly the same façade detail but replace the ceramic rods with glass tubes filled with green algae. The goal is to compare energy data from the existing building with computational simulations using the green algae façade. The $H_2$ producing glass tubes will shade the façade by allowing diffuse lighting. At the same time energy will be generating in combination with a fuel cell.

**The energy peak-shaving value of a hydrogen façade**

The cost of peak electric power for the top 50-150 hours a year is $600- 900/MWh, typically 30 to 40 times the cost of base load power (~$20/MWh). The hydrogen façade provides energy for peak capacity. Using hydrogen for peak storage will be worthwhile, particularly in cities with transmission constraints (such as Los Angeles, San Francisco, Chicago, New York City, and Long Island). Globally hydrogen storage can also save power-plant fuel by permitting more flexible operation of the utility system.

Figure 15 shows a Detail from the window curtain walls as a high-tech synergy curtain wall with integrated hydrogen façade. The complete profile systems are aluminum. All façade types, including twin wall, curtain walls and window units are possible with the proposed façade. The $H_2$ tubes are a part of the passive and active solar shading systems. [Drawing by author based on Schuko standard profiles].

The horizontal orientation of the glass tubes generated a larger surface and more efficient light absorption compared to flat surface panels. Important in this respect are the spacing of the tubes, which influences internal lighting. By increasing or decreasing the tube spacing, the $H_2$ output will change.

**Economic considerations**

The question of the commercial viability prospects of the green algal hydrogen production process depends on two different sets of parameters, i.e. the productivity/yield of microalgae and the operational photobioreactor cost for the scale-up of the process. Hydrogen delivered "at the gate" would need to be produced at a cost that favorably compares with some other "benchmark" fuel, normally natural gas or gasoline. [Melis 2006]

Assuming average solar (photosynthetically active radiation, PAR) insolation of about 50 mol photons (PAR) $m^{-2}$ $day^{-1}$, 82% absorbed photon utilization, and requiring four photons to produce 1 mol of $H_2$, the calculated theoretical maximum yield of $H_2$ production by green algae would be equal to about 10 mol $H_2$ $m^{-2}$ $day^{-1}$; (20 g $H_2$ $m^{-2}$ $day^{-1}$or 80 kg $H_2$ $acre^{-1}$ $day^{-1}$) [Melis and Happe *2001*].

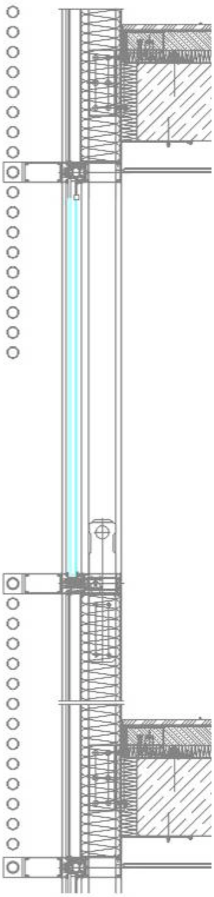

Figure 15
1. hydrogen façade glass tubes
2. curtain wall window inside
3. integrated $H_2$ piping system in suspension fitting
4. Box façade column with integrated piping
5. Window frame and light: extruded aluminum section, with thermal brake.

Materials for the scale-up facility and operational costs of a photobioreactor (photobioreactor materials, fertilizer, personnel, etc.) can be as low as \$1.67 $m^{-2}$, recurring every 2 months of continuous operation (\$0.0274 $m^{-2}$ $day^{-1}$ for the 2-month period [Melis *2002*].

Assuming a technical ability to continuously grow and produce with the green algae for a 2-month period, at the maximum of absorbed photon-to-hydrogen conversion efficiency the cost of production would be 0.0274/20 = \$0.00137 $g^{-1}H_2$(or 1.37 $kg^{-1}$ $H_2$). This \$1.37 $kg^{-1}$ $H_2$ would be the cost of production and does not include storage, distribution, and/or retail marketing of the product. For transportation purposes, 1 kg $H_2$ is the equivalent of 1 gallon of gasoline, which is equivalent to 40 kWh of free energy [Melis 2006].

The above preliminary and rough calculations clearly show that (1) substantial improvements are needed in the $H_2$ photoproduction characteristics of the green microalgae, and (2) development of photobioreactor facilities is needed for the mass cultivation of the microalgae that have the lowest possible cost of assembly and operation.

The average retail price of electricity to end-users in New York was 16.5cent/kWh. [August 2007, Energy Information Administration www.eia.doe.gov]. This is significantly higher than the 3.4cent/kWh for $H_2$ production. It is predictable that the price for electricity as well as fossil fuel will continue to rise, but at the same time the cost for $H_2$ will fall due to improved technology and higher demand. Much research needs to be done to bring down the costs for installing, operating and maintaining the hydrogen façade.

## 5. Conclusion

Buildings account for roughly 45% of the energy consumption in the world and therefore a major part of the $CO_2$ emission.

The objective of this research is to design, fabricate, and operate an innovative photo bioreactor to study the technical and economic feasibility of using a novel $H_2$-producing system as a commercial process for production of renewable energy. In comparison to vacuum tub collectors or photovoltaic cells the green algae $H_2$ production technology is not yet on the same technical level and probably 5-10 years behind. But $H_2$ technology has the advantage in comparison to thermal energy or electricity because of the way in which energy can be stored without any losses when not needed.

With an efficiency ratio of 65%, fuel cell technology is already fairly advanced.

Global warming will require more energy for periodic cooling in the future. The building skin of the future will be designed to generate energy and to actively change the building environment. The need to save energy will lead to the development of different strategies to use solar energy. Hydrogen energy will be one of them. Based on a wide range of parameters (location, availability, local technology etc.) a pluralistic energy concept will develop.

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i Hydrogen is a chemical element represented by the symbol H and an atomic number of 1. At standard temperature and pressure it is a colorless, odorless, nonmetallic, tasteless, highly flammable diatomic gas ($H_2$). With an atomic mass of 1.00794 g/mol, hydrogen is the lightest element. Hydrogen is the most abundant of the chemical elements, constituting roughly 75% of the universe's elemental mass. [http://en.wikipedia.org/wiki/Hydrogen]

[ii] A fuel cell is an electrochemical energy conversion device. It produces electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). These react in the presence of an electrolyte. Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell. Fuel cells can operate virtually continuously as long as the necessary flows are maintained. Since the conversion of the fuel to energy takes place via an electrochemical process, not combustion, the process is clean, quiet and highly efficient – two to three times more efficient than fuel burning. [www.en.wikipedia.org/ wiki/Fuel_cell]

[iii] Anastasios Melis is a biologist at the University of Berkeley in California, who is researching the possibility of creating hydrogen from algae.

[iv] Researchers from the University of Bielefeld and the University of Queensland genetically modified the algae *Chlamydomonas reinhardtii* in such a way that it produces an especially large amount of hydrogen.[1]

[v] University of California at Berkeley

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