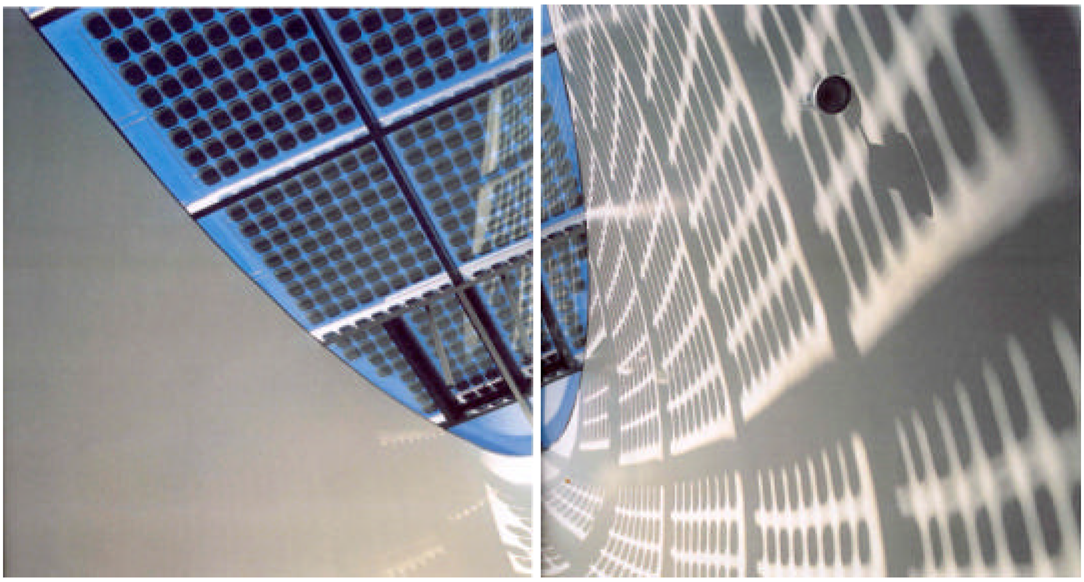
Building Integrated Photovoltaics in Smart Energy-Efficient Buildings A State-of-the-Art



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ABSTRACT

This reports summarises the State-of-the art within Building Integrated Photovoltaic (BIPV) systems and related area. The report marks the start of subtask 2.4 “Building Integrated Photovoltaics” within the project “Smart Energy Efficient Buildings” (“SmartBuild”). The aim of the SmartBuild project is to develop new knowledge, integrated solutions, and technologies that will make it possible to cover our building-related energy needs with substantially less harmful environmental emissions, while still satisfying the whole range of end-user needs such as comfort, aesthetics, costs, operability, reliability and functionality.

Future buildings will need very little thermal energy, because of well-insulating envelopes, high-performance windows, and energy-efficient ventilation. However, they will still need electricity for lights and appliances. PV is the renewable energy technology available today that is most likely to cover this need on-site. This is because it has the lowest environmental impact, and may be aesthetically integrated into the building. If BIPV is going to fulfil this vision, further research and development is needed in several areas. Within the SmartBuild Project, two areas of work seems to be of particular interest:

1. Development and optimisation BIPV elements that perform several functions, i.e. daylighting, shading, heating, cooling, and ventilation for different types of buildings and users. The multifunctional PV elements must be part of an “environmental low-energy package” that may be sold to different types of clients.
2. Integration of the BIPV elements with the building management and information system.

Both of these areas require the co-operation between architects, building engineers, HVAC engineers, electrical engineers, and sociologists.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Energy	Energy
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SELECTED BY AUTHOR	Photovoltaics	Solceller

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1 Introduction

This report marks the start of subtask 2.4 “Building Integrated Photovoltaics” within the project “Smart Energy Efficient Buildings” (“SmartBuild”). The aim of the SmartBuild project is to develop new knowledge, integrated solutions, and technologies that will make it possible to cover our building-related energy needs with substantially less harmful environmental emissions, while still satisfying the whole range of end-user needs such as comfort, aesthetics, costs, operability, reliability and functionality. To accomplish this, a 5-year multi-disciplinary project has been initiated in 2002, combining the knowledge of a wide range of experts in the field of energy use in buildings at NTNU and SINTEF, as well as the expertise of related Norwegian industry.

The aim of this report is to form the basis for further work within the SmartBuild project, and to provide information that may be used by the other project participants in order to see the possibilities for effective integration of our different fields of expertise.

2 Central Concepts

Photovoltaics (PV) are solid-state, semi-conductor type devices that produce electricity when exposed to light. The photovoltaic effect can be achieved by using many different semiconductor materials, the most commonly used is silicon.

The conventional silicon cell is constructed of very pure silicon doped with boron and phosphorous and sandwiched together to form a p-n junction, see Figure 1. When solar photons strike the silicon atoms, electrons are freed to flow from one layer to another, thus producing an electric potential (voltage). The resultant electrical current can then be harnessed through a metal grid that covers the cell and an external circuit to perform work. This effect continues as long as the cell is illuminated, and without the deterioration of any material or the consumption of additional energy.

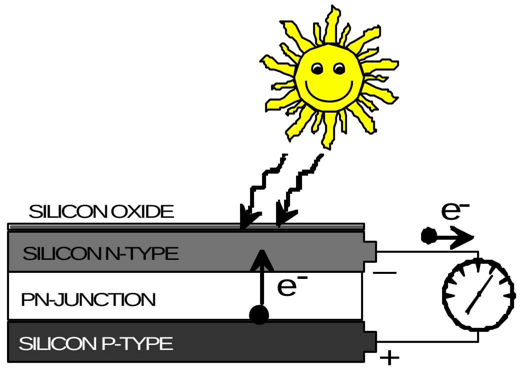

Figure 1. The silicon PV cell.

Three types of silicon materials are used for the fabrication of solar cells: mono-crystalline silicon (m-Si), poly-crystalline silicon (p-Si) and amorphous silicon (a-Si). Crystalline cells are breakable silicon wafers cut from large silicon blocks, while amorphous cells consist of a very thin layer of un-crystallized silicon which is deposited onto a carrier material (substrate). Therefore, amorphous silicon cells are often called thin-film cells. As a consequence, amorphous cells can have a variety of forms and dimensions, whereas crystalline cells have typical dimensions of 10 x 10 cm. Also, the different types of cells have quite different appearances. The mono-crystalline cells usually have an even, black or gray color, the poly-crystalline cells are most often bright blue and "shiny" because of the many small crystals, and amorphous cells are brownish or reddish-brown.

Solar cells are connected in a series and/or parallel configuration and placed in sealed units called modules. The module's top layer is purposely transparent and can be made from glass or plastics. This cover keeps out water and gaseous pollutants which could cause corrosion of a cell and protects the cells from physical damage. The next layer is an anti-reflective coating designed to reduce the amount of reflected sunlight. The cell's bottom layer is called the back contact and is a sheet of metal which together with the front contact (the metal grid) is a bridge to the external circuit. To seal the whole structure, the back is covered with a layer of tedlar or glass. A frame of aluminium gives the module the needed mechanical stability.

The amount of power produced by a photovoltaic module is mainly dependent on the intensity of sunlight and the operating temperature of the cells. The output of the PV module is directly proportional to the amount of sunlight. The effect of temperature is not so obvious; PV devices produce less and less electricity as the operating temperature increases.

The efficiency for conversion of light into electricity depends on the cell material. The conversion efficiency of modules of amorphous silicon cells varies from 3 to 8%. Modules of poly-crystalline silicon have a conversion efficiency of about 9-12%, while modules of mono-crystalline silicon cells have an efficiency of 12-16%.

For buildings that are out of reach of the utility grid or for some other reason are independent of the grid, a storage or back-up system is required to ensure electricity production during cloudy periods or at night. Today, the only practical available storage options for PV systems are lead-acid or nickel/cadmium batteries. These two types of batteries are well known and available to the consumer. There are, however, limitations with respect to energy density, cycle life, temperature of operation and toxicity associated with both of these options. Alternative energy storage options are being developed that include other kinds of battery technology and hydrogen.

For PV applications in buildings, the inverter is a key component. The inverter is an electronic device that converts direct current to alternating current. In grid-connected applications PV electricity is fed into the utility network by means of an inverter. In stand-alone systems power inverters are needed to operate common appliances with electricity from the batteries charged directly by the solar generator.

Due to their modular layout, lightweight and simple assembling, there are many possibilities for integration of photovoltaic panels into roof or facade elements. PV panels may replace or assist other necessary functions, such as weather skin or solar shading. In this way, it is possible to identify three main principles for PV integration into buildings:

1) Weather skin: roof and facade integration
2) Solar shading elements
3) Daylighting elements

The traditional PV modules are often not very suitable for integration into the building envelope. However, in the last few years, we have seen an increasing number of PV modules that are specially designed for building integration. These modules can fit into conventional roof and facade structures, such as for example glazing frames. Also, specially designed facade systems are available that ease the integration of PV modules into the building envelope. Some companies have specialised in supplying PV facade or roof systems, and offer PV panels as well as special structural components that go together with their modules. PV panels can be mounted as fixed shading elements over the windows, on awnings or venetian blinds. Using movable or semi-transparent PV elements, the combined function of shading and daylighting can be achieved. As shading elements, the PV modules are oriented towards the sun for maximum energy output, while blocking the direct radiation from entering into the building. Semi-transparent PV elements block most or all of the direct radiation, while allowing diffuse light to enter the room.

Building facades represent a dominant architectural feature, and are often designed to express the company's profile. Facade integrated PV modules can add exciting and elegant features to the building envelope. Figure 2 shows PV integrated into window and cladding systems.

Figure 2. Left: Crystalline silicon PV cells between glass panes in a German building (Pilkington Solar AG). Right: PV modules as a patchwork on a building in Switzerland (Solution AG).

For the rest of this report, building integrated photovoltaics will be referred to as BIPV, which is a commonly used abbreviation. BIPV means that photovoltaics are used as part of building elements.

3 Technology and Market

Watt (2001) summarises the key barriers to wide-spread use of PV:

- High production cost and electricity prices relative to conventional energy sources.
- Lack of familiarity with and procedures for financial analyses, compounded by limited financing options.
- Lack of consideration of environmental externalities in the energy sector
- Lack of procedures for project assessment, approvals and installation, leading to delays and higher costs.
- Lack of standard designs and optimised PV products and systems.
- Poor back-up service delivery in many areas
- Restructuring in the electricity industry, with impacts on PV programmes, electricity prices and network access.
- Lack of long-term energy policy guidelines regarding the transition to sustainable options, which would provide confidence for investors.
- Lack of information for customers and investors.
- Lack of standards and certification.

Although the costs of PV energy generation have become significantly lower in recent years, PV is still considered to be an (economically) expensive method of electricity production. Depending on the system lifetime, the interest rate and other constraints, the costs quoted today vary between 4-8 NOK/kWh, if no subsidies for market introduction are available.

However, if the BIPV is regarded as building elements, their cost compete with that of the more expensive conventional façade elements, such as natural stone and coloured glass.

"The interesting thing to note is that many of these premium exterior cladding systems cost nearly as much or even more than a solar electric skin, and none of them ever undergoes a return-on-investment analysis prior to being specified – whereas, in the past, solar electricity has been subjected to unrealistic short-term payback demands. The irony is that when a solar electric building skin is incorporated, a cash flow stream is provided for decades to come, whereas a granite façade will deliver only prestige."

- Steven Strong, Architect, Harvard, Massachusetts, in (Strong, 2002).

A further reduction in the price is very much dependent on establishing a wide-spread market with production of scale. Although the PV market is steadily growing, it is still small. The grid-connected building BIPV sector has grown with over 50% per year the recent years. The PV market in general increased by 36% in 2001, in total 390 MW of PV modules was produced in 2001. The Japanese market increased by 31 % to 171 MW, the European production increased by 42% to 86 MW, while the production in the United States increased by 34% to 100 MW. PV modules from single and polycrystalline silicon make up 80% of the total production.

The global photovoltaic market could hit the $10-billion mark by 2010, according to a new report by Allied Business Intelligence, Oyster Bay, N.Y. ABI states that the industry has gotten the prices down far enough and the production quantities high enough so price is no longer a problem for manufacturers. Now, production capacity is the major issue. Worldwide production is expected to be 800 MW by 2005. Demand, however, may exceed 900 MW by 2005 and approach 5 GW per year by 2010.

4 Interactions with other SmartBuild strategies and technologies

4.1 BIPV and User Needs

The following list is a summary of what the author thinks about the different stakeholders attitudes towards and experiences with PV:

- *Architects* are rather positive about BIPV. This may be because they see it as an exciting building element that may be used to give their project a special profile – to stand out.
- *Engineers* do not know much about BIPV (at least in Norway). They have no education in this field. Therefore, they are reluctant to have anything to do with PV.
- *Contractors* don't know anything about BIPV. Therefore, they are reluctant to include PV. They don't want to take the risk.
- Most *building owners* and investors don't know much about BIPV. Some may be interested in having BIPV because they want to advertise a "green" image. Several utility companies in Europe have BIPV on their headquarters. For most building owners, BIPV appear expensive.
  Investors or real-estate companies are interested in buildings that are easy to let, and buildings that will bring high incomes when let or sold. In general, they are not interested in adding to their investment, if they are not sure it will give a quick pay-back.
  Building owners that occupy their buildings, will be concerned with the robustness of their building; they don't want to hassle with a lot of repairs that disturb their work. Worker productivity is a main concern. Liability in power supply may also be important, especially if their operations are vulnerable to power outages.
- Most *building occupants* are not concerned about BIPV. Their main interest is to have a comfortable working/living environment, and they are not interested in how this is accomplished.
- *Governments* – societal concerns such as employment, industry and economic growth, environmental concerns, and the country's dependence on imports.

Figure 3. A PV façade at the Headquarters of Gøteborg Energi Utility Company.

Watt (2001) has summarized studies on stakeholders' values with respect to PV:

Table 1. Value of PV for different stakeholders, from (Watt, 2001).

Stakeholder	PV value
Governments and Policy Makers	• Net energy benefits and greenhouse gas emissions. • Clean air targets • Energy supply security • Industry development and employment growth
Utilities	• Reduced infrastructure costs and network losses • Reduced financial risk • Capacity credit and peak lopping • New business opportunities • Image
Architects and building developers	• Environmental design feature • Combined effect of insulation, heating, ventilation, shading and sound proofing.
Customers	• Visual appeal • Green image • Reduced power bills • Increased self-reliance and reliability of supply • Enhanced property value

4.2 BIPV and Environmental Criteria

PV systems have a number of environmental and social benefits. Few power-generation technologies have as little impact on the environment as PV. During operation, PV produces no air pollution, hazardous waste, or noise, and it requires no transportable fuels. Because the energy source (sunlight) is free and abundant, PV systems can provide guaranteed access to electrical power while reducing the nation's trade deficit and avoiding the cost of maintaining energy supply routes in politically volatile regions such as the Middle East.

In 1996, a major international study was conducted that summarised the environmental aspects of four major solar cell technologies with special attention to future expected technology developments and market increase (Alsema, 1996). Cell technologies investigated were multicrystalline silicon (m-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS). The following aspects were considered: energy requirements and energy pay-back time, material requirements and resource depletion, environmental emissions, waste handling, possibilities for recycling of modules, occupational health and safety and external safety.

The study found that energy pay-back times of the present day m-Si and a-Si modules were around 4 - 4.5 years for frameless modules under Dutch irradiation conditions. This pay-back time is considerably shorter than the expected technical lime time of the module (15-30 years). Moreover, the study also concluded that very good prospects exist for reducing the energy requirements by future technology developments, resulting in pay-back times well below 1.5 years for all module types.

The study also concluded that for the immediate future there are no reasons for concern regarding the material requirements and emissions of solar cell modules. Only with large scale deployment of modules – with annual production levels of several GW's – some points may need closer attention:

- resource depletion of silver (m-Si modules)

- resource depletion of indium (CIS modules)
- waste management and recycling possibilities for decommissioned modules (m-Si, CdTe, CIS)
- cumulative fire-induced emissions from CdTe and CIS modules

Regarding occupational health and safety and external safety, the only significant risks were found in the storage and handling of explosive and/or toxic gases, i.e. silane in a-Si production and H_2Se in a certain CIS deposition process.

Watt (2001) states that the avoided CO_2-emissions for grid-connected PV systems vary by country, but the world average figure is 0.6 kg CO_2 per kWh output. Lifetime CO_2-emissions with current PV technologies are 85-95% less than those from coal fired power stations. The key results from the EPIA/Greenpeace study (Cameron et al. 2002) show that, even from a relatively low baseline, solar electricity has the potential to make a major contribution to both the future global electricity supply and the mitigation of climate change. It is estimated that the cumulative carbon savings by 2020 will be more than 700 million tonnes of CO_2.

4.3 BIPV and Indoor Environment

During operation, PV produces no air pollution, hazardous waste, or noise. Thus, PV has no direct impact on the indoor environment. However, if PV cells are integrated into glazing or solar shading elements, they will influence the indoor environment. PV is being used in glazing to produce interesting light patterns in the room (figure 4). Used in this way, one also has to take into account glare, contrast and solar heat gains caused by the PV glazing. Lien and Hestnes (2000) have studied the glare, contrast and light modelling of PV glazing in an office façade. Figure 5 shows examples of computer modelling, the work also involved studies of a scale model.

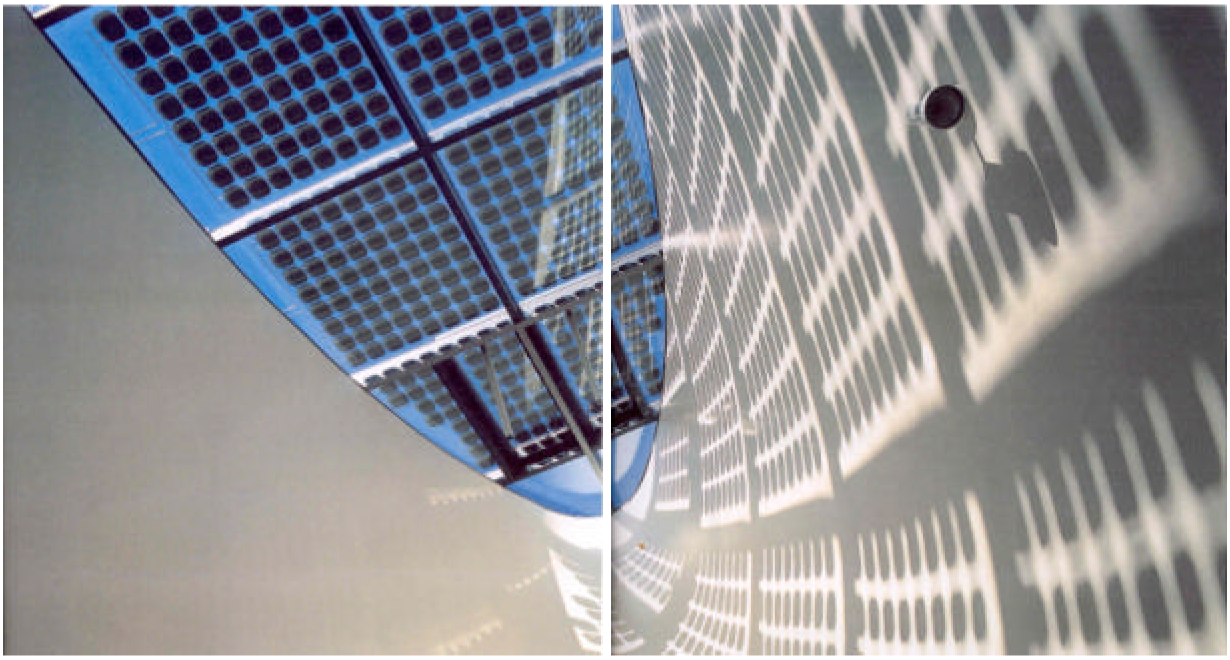

Figure 4. A PV skylight creates a play of light and shadows at Lærkelængen School, Denmark.

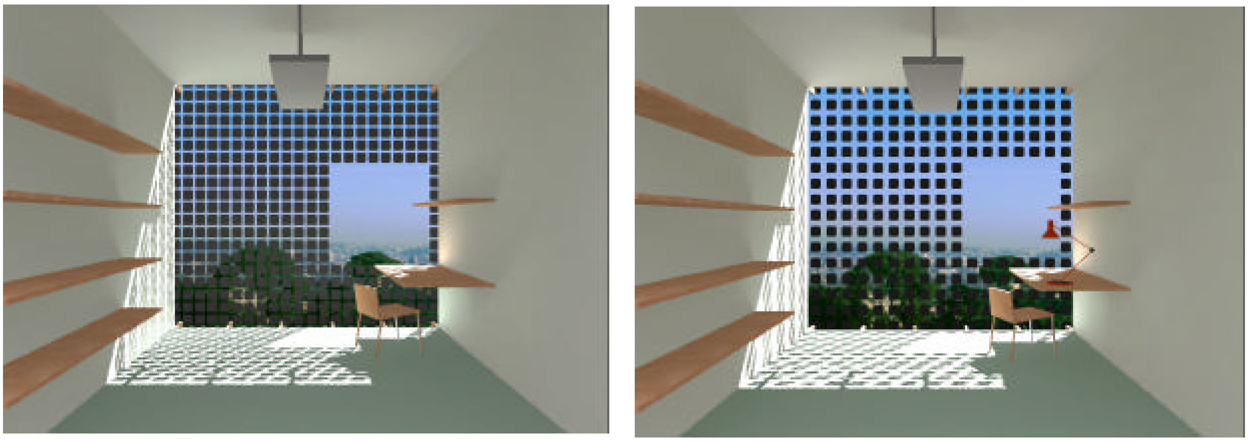

Figure 5. Visual amenity studies of PV in glazing (Lien and Hestnes, 2000).

PV in glazing may provide shading and reduce overheating, but there is little documentation of the exact influences this may have. While PV glazing will reduce the direct solar transmission, the surface temperature will increase, compared to standard glazing.

If PV is used as a thermal collector to preheat ventilation air (ref. PV/Thermal systems, section 4.8), the PV system may indirectly influence the indoor air quality.

4.4 BIPV and Implementation Strategies

A recent US survey of architects indicated that assembling and presenting technical and financial analyses to clients was a major barrier to implementation (Eiffert, 200).

Watt (2001) states that "Significant effort is needed to raise levels of awareness and credibility. Information on PV must be made readily available to the general public, for household applications and for trades, professions, investors, insurers and planning agencies. Certification procedures and standards must be developed to enhance credibility and performance. For BIPV, enhanced market acceptance would be assisted by a holistic approach to the design of the entire PV building, including overall energy efficiency and sustainability of building materials used…… Market acceptance by property developers, utilities, development and financing agencies is also required. Added values, other than avoided electricity costs, should be made clear to potential customers in these sectors."

Haas (2002) has identified a set of actions that are necessary in order to achieve successful market deployment of PV:

1. Address the customers:
   - For private households: Increase the willingness to pay (WTP) by providing proof of environmental benignity; personal identification with the technology, credible labelling of green power, simple purchase conditions, simple technical installation, affordable systems at reasonable prices.
   - For architects and housing companies: Introduce targeted education programmes.
   - For commercial companies: Provide financing programmes.
2. Solve technical problems:
   - Ensure standardised system optimisation and performance.
   - Increase compactness/standardisation and simplicity with respect to system installation.
   - Enhance and standardise safety.
   - Simplify and standardise utility interface.

3. Improve the markets:
   - Use the internet to increase transparency and competition
   - Provide an infrastructure network
   - Continue the development of the technology by improving efficiencies, increasing production levels, and providing reliable, easy to install and aesthetically pleasing products.
   - Form partnership and/or pool resources between the industry groups, governments, electricity suppliers and installation, operation and maintenance services.
4. Inform the society:
   - National and local governments must be convinced that PV bring about societal benefit by means of mitigating the environmental burden, increasing local employment, and enhancing supply security
   - Set up a range of education programmes, aiming at customers, planners, regulators, electricity suppliers and the building industry,
   - Encourage and support NGO marketing activities.

4.5 BIPV and Integrated Design

BIPV needs to be viewed as an architectural element as well as an integral part of the building's energy system. In particular, if PV elements are used in glazing or shading devices, their impact on the cooling and heating demands must be evaluated. In order to achieve a successful and cost-effective integration of the PV system, it has to be taken into consideration from the beginning of the design. Experts on electrical integration, HVAC, and building engineers have to work together with the architect from the concept design stage, to consider trade-offs between different issues such as daylighting, heating, cooling, comfort and aesthetics.

4.6 BIPV and Building Integrated Energy Systems

BIPV may be an integral part of many types of building integrated energy systems. For example, PV integrated into a transparent façade element may be used as a shading element, a thermal solar collector for preheating ventilation air, or as part of a thermal solar collector for water heating (see section 4.8). In this way, the PV façade may be a part of the building's heating, cooling and ventilation concept.

In addition, research is being done to develop PV-powered “smart” windows that can change colour and light transmissivity according to the need for reducing solar gains, and thereby lowering the cooling needs. The research in this area is focused on two different technologies; one is *photovoltaic-powered electrochromic devices*, the other is *photoelectrochromic cells*.

Photovoltaic-Powered Electrochromic Devices or *PV-EC* devices mount a thin-film photovoltaic device onto the ion storage layer of the electrochromic device. The photovoltaic layer generates a voltage which causes the electrochromic layer to darken. With an additional middle contact layer inserted between the photovoltaic and electrochromic devices, the voltage generated by the photovoltaic layer could also be used to charge an external battery. The battery could then be used to lighten the electrochromic layer.

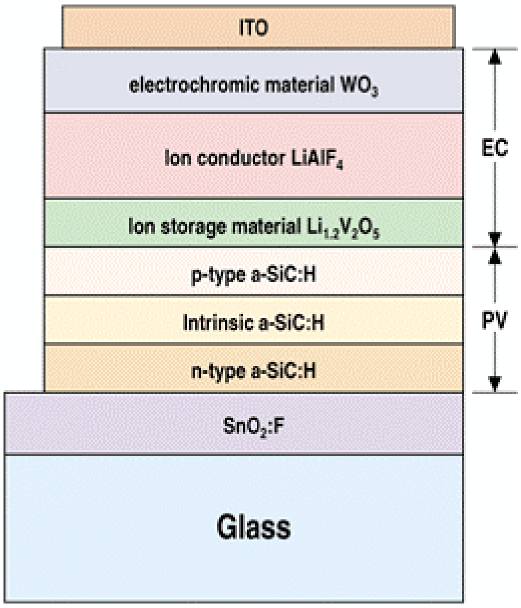

Figure 6. PV-EC devices combine a thin-film PV device with an electrochromic device. The configuration depicted above is a working PV-EC device built at NREL.

Photoelectrochromic Cells (PEC) harness a photochromic layer, which changes colour by absorbing light, with an electrochromic layer, which changes colour under the influence of an electric field, to make a self-powered smart window. On a sunny day the one layer supplies the photovoltage needed by the other layer to darken the window, letting in less light and thus lowering air-conditioning costs. PEC devices use a dye-sensitised electrode to generate electrons, thereby creating the voltage necessary to drive lithium ions into the electrochromic layer and colour it. The essential aspect of PEC devices is the use of a dye-impregnated layer of titanium dioxide. A low concentration of dye is used to maximise the transparency of the window. Between the titanium dioxide and the electrochromic layer is a layer of either lithium iodide solution or a solid polymer containing lithium iodide. This entire device is sandwiched between two layers of transparent conducting oxide material.

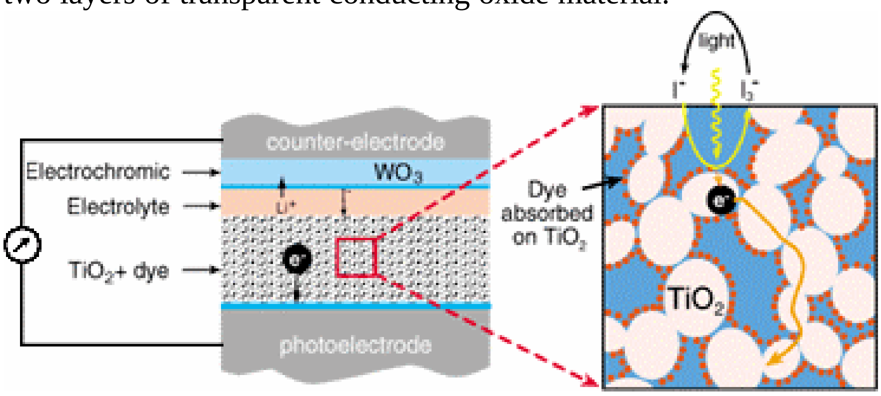

Figure 7. A photoelectrochromic device uses a dye-impregnated layer of titanium dioxide (TiO_2) to generate electrons, which create the voltage necessary to colour the electrochromic layer (NREL).

When sunlight strikes this device, the dye absorbs some of the sunlight and releases electrons, which are injected into the titanium dioxide. The electrons are then conducted to the adjacent conducting oxide layer, and pass through an external circuit to the conducting layer adjacent to the electrochromic layer, on the other side of the device. This electron flow, in turn, causes iodide ions to migrate through the solution or solid polymer toward the titanium dioxide, and causes lithium ions to migrate into the electrochromic layer. As in a standard electrochromic device, the injection of lithium ions into the electrochromic layer causes it to colour.

When sunlight stops hitting the device, the charge stored in the electrochromic layer drives the process in reverse, ejecting lithium ions from the electrochromic layer and causing it to bleach. Thus, with no external controls, the window will colour in sunlight and bleach in its absence. The external circuit can also be used as a control device: The disconnection of the circuit will cause the window to remain in its current state regardless of the presence or absence of sunlight. In addition, an external voltage can be applied to the device through this circuit to drive the device to either the bleached or coloured state.

4.7 BIPV and Lighting Systems

There exist a number of stand-alone PV-lighting products on the market. These have found a niche market, since in many cases, PV systems can provide lighting for a fraction of what it would cost to extend the utility line. The most efficient systems use fluorescent lamps, but other types of lamps, such as halogen or low-pressure sodium have also been used in conjunction with PV. Batteries are always a component of these PV-powered lighting systems.

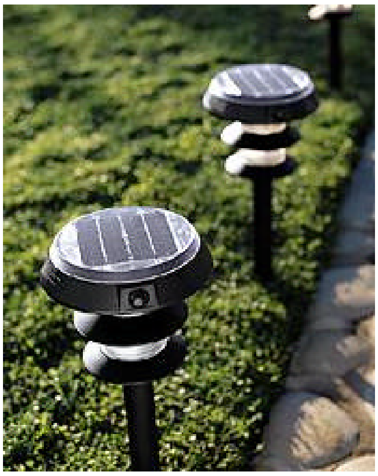

Figure 8. Pagoda sensor lights powered by PV. An infrared motion sensor turns on a bright 10 Watt halogen light when a warm body moves in its vicinity. Price: $99 (Real Goods).

PV integrated into glazing or semi-transparent shading elements will influence the daylight availability in the room. As discussed in section 4.3, the placement of the PV cells must be carefully considered in order to avoid glare and to get the desired daylight distribution. Also, the portion of the opaque PV area to the transparent area need to be optimised with respect to total energy needs, including energy for heating, cooling, ventilation and lighting. Vartiainen et al. (2000) reports on a study of the optimum division of window area and PV area. Considering the electric lighting requirement replaced by daylight through the window and the electricity produced by the PV section of the façade, the maximum electricity benefit for a south-facing façade is achieved by a window area of about 15% in Northern Europe. However, neither the heating or cooling energy requirements nor the visual effects were considered in this study.

4.8 BIPV and Heating, Cooling, and Ventilation Systems

The electrical conversion efficiency of a PV cell drops as the temperature of the cell increases (typically 0.4% per °C for crystalline silicon), so heat generation within a PV module has traditionally been viewed as a problem and efforts have been made to transfer the thermal energy to the surrounding air. However, if this heat can be harnessed, the overall efficiency of the system, a PV/thermal hybrid system, would be improved. This is of particular interest for building integrated systems where the heat can be utilised for space heating.

Some PV/thermal hybrid systems are already in existence and have been operating for several years on buildings, such as the Scheidegger Building, Switzerland and the Mataró Library, Spain. Other exist only as laboratory prototypes or are still at the conceptual stage, but the results of preliminary performance testing on these units indicates that PV/thermal hybrid concepts offer an important future energy source for buildings. Overall efficiencies (electrical and thermal combined) of over 70% are theoretically achievable, though in practical applications 30-40% is more realistic.

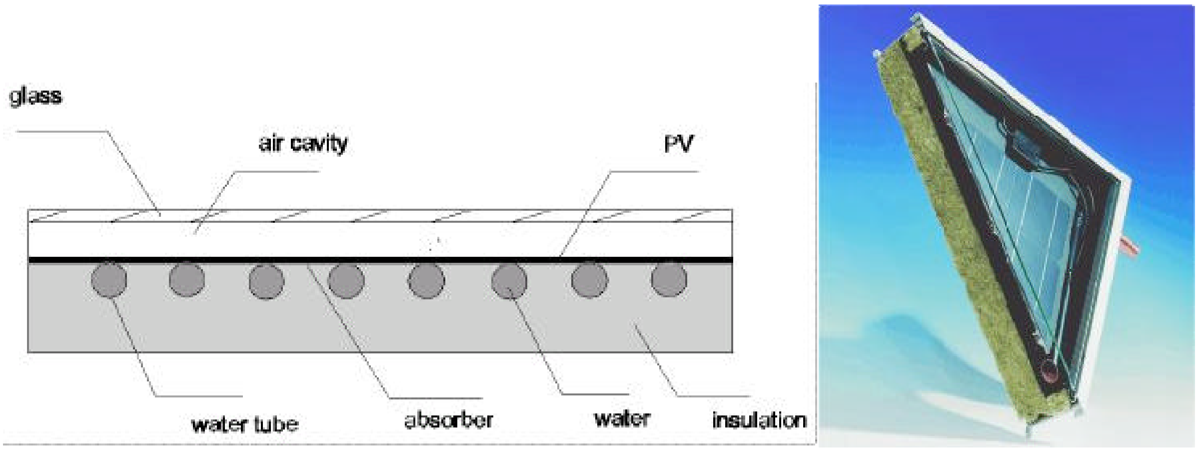

Figure 9. Example of a PV/Thermal water collector (Leenders et al. 2000) and the Spectrum PV water collector from SolarWerk (right).

PV is also used to run pumps in solar thermal collector systems. In this way, no electronic controllers or temperature sensors are required, since the pump will run automatically when there is sunshine striking the PV panel – which is ideal. There are several DC pumps on the market that are suitable for such applications. For single-family home solar water heaters, a 10-20 W PV module is usually adequate.

Figure 10. A solar water heater with a PV panel that powers the circulation pump.

Pedersen (2001) reports on an EU/Joule project (PV-VENT) that aimed at developing low-energy heat recovery DC ventilation systems supplied with electricity from PV. The fresh air for the ventilation systems is preheated behind the PV modules, thereby also cooling the PV modules and increasing their efficiency. The use of new energy saving DC fans makes it possible to use PV modules to cover part of the electricity demand directly. The electricity use for these ventilation systems was reduced to 25-50 W per dwelling, compared to 87 W per dwelling for a standard system. The project showed that with a PV-VENT system it is possible to have an electric to thermal performance ratio of 1:15 (electricity used in relation to the heat savings), a pay-back period of 7 years and a saving of primary energy per dwelling of about 4000 kWh per year. This is compared to a conventional heat recovery system with a ratio of 1.3, a payback time of 8 years, and annual savings about 2000 kWh.

There are also a number of small PV-ventilators on the market. These are typically used in cottages or residential buildings for ventilation of sunspaces, attics, etc.

Figure 11. Attic vent fan that runs solely on sunlight. PV cells on top of fan provide power at the time it is most needed - when it is sunny! Generates 600 to 800 CFM. Price: $350 (Eco-Smart, Florida).

There are few reports on PV cooling systems. Michel (1999) reports on an EU/Joule project with the aim of developing low electricity cooling systems for dwellings and office buildings of 50 to 250 m² floor area in Mediterranean and developing countries. In this project, two systems have been developed, one using PV and evaporative air-cooling with rotary and vertical fixed pads, the other using PV and ground cooling through buried pipes. The systems developed in the project can provide cooling in small to medium sized buildings in warm, dry climates, reducing indoor temperatures by between 3K and 7K below the outdoor dry bulb temperature.

Used as a shading element, PV may contribute to passive cooling. There are several examples of PV shading elements.

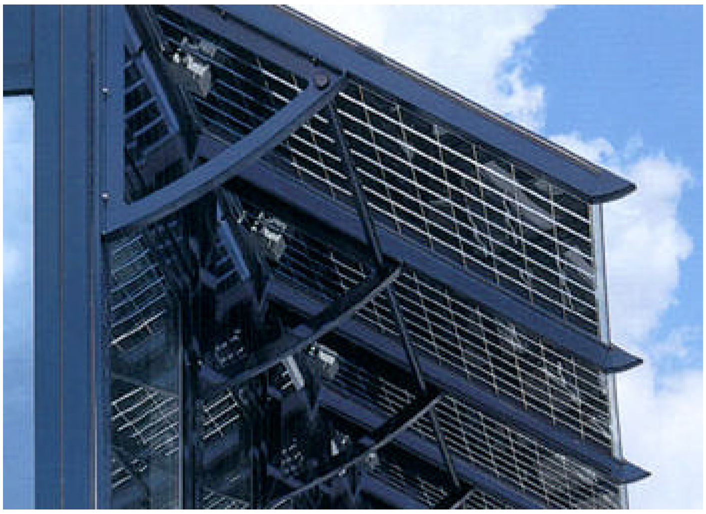

Figure 12. The TopSky semi-transparent PV overhang shading from Schüco.

4.9 BIPV and Heat Pumps

A literature survey conducted by Leenders et al. (2000) shows a few PV-Heat Pump systems under development. Wassenaar (1998) presents a system where an unglazed PV/Thermal collector supplies pre-heated air to a heat pump that supplies hot water and space heating (figure 13). Additionally, a heat recovery unit is installed to reduce the heat losses.

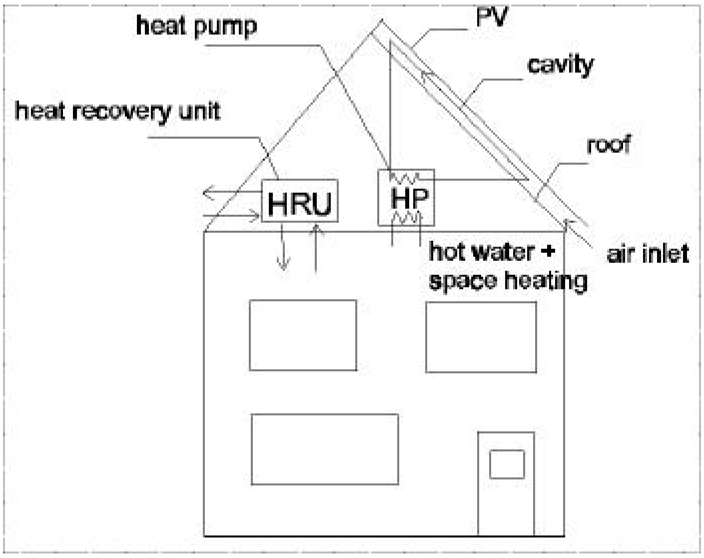

Figure 13. The unglazed PV/Thermal air collector with heat pump and heat recovery unit reported by Wassenaar (1998).

Schaap et al. (1999) reports an unglazed PV/Thermal collector system combined with a heat pump and aquifer. In summer, the PV/Thermal collector is cooled with 5-10°C from the aquifer. While cooling the PV/Thermal collector, the water is heated to about 20°C, and stored in the aquifer to be used as a heat source in winter. During winter operation, the heat pump upgrades the stored heat for low temperature space heating to about 40°C.

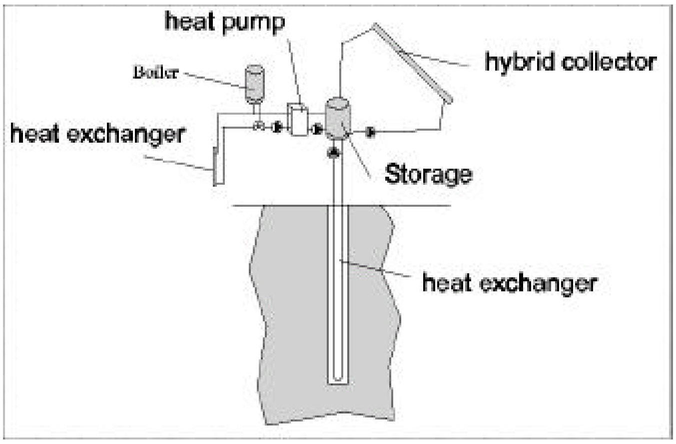

Figure 14. The PV/Thermal collector with heat pump and aquifer storage reported by Schaape et al. (1999).

From a technical point of view, PV/Thermal systems are especially suitable for low temperature applications like heat pump systems. For medium temperature applications, the thermal and electrical yield of the hybrid systems is lower than that of the two separate systems. This is due to the fact that the solar collector performs best by reaching high temperatures, while the PV panel reaches its' maximum yield at low temperatures.

4.10 BIPV and Operation and Automation

Wilk et al. (2001), lists a number of interesting options for integrating BIPV systems with building operation and automation systems:

- PV elements used as shading devices may be controlled by adjusting the tilt angle and orientation to optimise the shading effect, the lighting quality and the electrical output. This could be incorporated in the central control unit and information bus system.
- A central control unit could switch on special appliances like pumps or water heaters to optimise the in-house use of PV electricity during sunny periods. This would help the utility keep grid loads at lower levels.
- The inverter may become just another unit working together with all the electric equipment connected by a bus system. Figure 15 shows a PV system with inverter units integrated in a LonWorks bus network. Example of system data that can be displayed and communicated to the operator are current and voltage outputs from the PV array and the inverter, the PV yield, temperature and irradiance sensor data and various alarm signals in case of inverter failure or grid outage, etc.

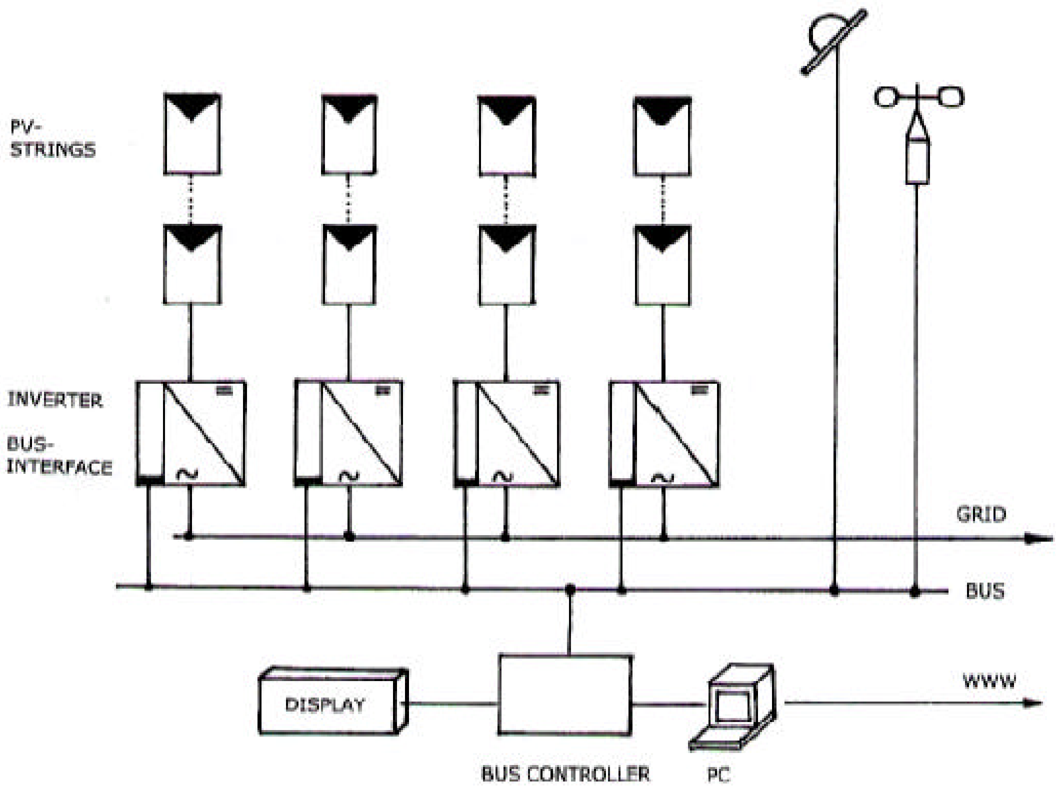

Figure 15. A PV system with inverter units integrated in a LonWorks bus network (Wilk et al. 2001).

- Advanced displays may be installed that assist the house owner/operator in getting full on-line information about the flow of energy and the status of all units. It may also improve the energy awareness of the residents of PV houses. Figure 16 shows an energy management tool for PV systems.

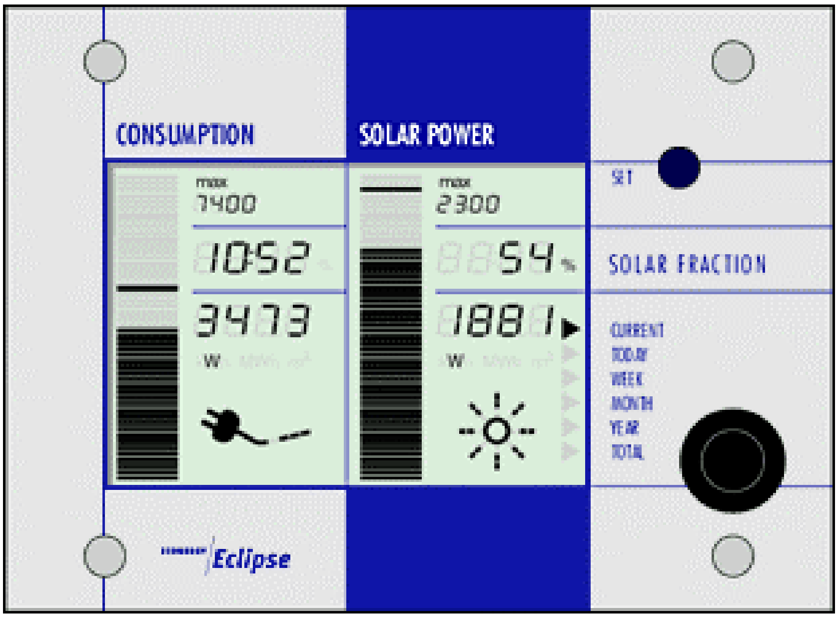

Figure 16. The Eclipse PV energy management system by Ecofys NL. It displays instantaneous figures (in Watt) and cumulative figures (in kWh) for electricity production and energy consumption. By a one-button operation, the user may switch between daily, weekly, monthly or yearly figures. The Eclipse also shows the Solar Fraction, i.e. the electricity production from the PV installation as a percentage of the electricity consumption.

- Uninterruptible power supplies (UPS) are devices that to protect electronic equipment like computers and phone systems against problems stemming from a temporary failure in the power supply. Standard UPS systems consist of a rectifier, a battery, and an inverter. By providing a constant source of electricity, the UPS prevent damage or data loss that can occur with the unexpected shutdown of computers, phone systems, and other sensitive equipment. UPS systems work by detecting decreases in the amount of electricity coming from the utility and boosting power to maintain a constant flow of electricity to connected equipment. This power boost is provided either by a transformer that enhances a weak electrical flow or from an internal battery that substitutes for the normal power source in the event of failure. Most UPS units also contain surge protectors, which help prevent equipment damage whenever there are power surges (sudden increases in the flow of voltage). In modern office buildings, central UPS systems with a battery bank are very common.

  A photovoltaic system may be used to charge the battery in an UPS-system. The advantage of this is that some electricity form the grid is replaced by PV energy at sunny periods, thus during periods of longer power outage, operation of the whole system may be possible at a reduced emergency power level. Depending on the weather conditions and the corresponding UPS load, the PV system can extend the time of autonomy by several hours. Figure 17 shows a standard UPS system supported by PV.

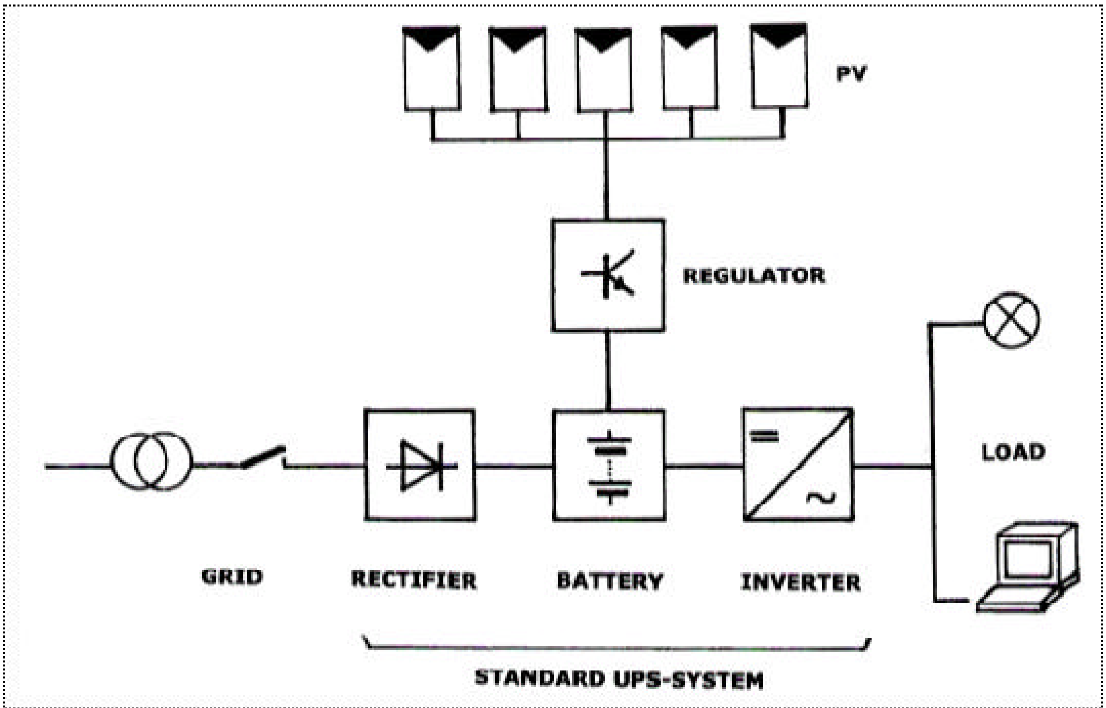

Figure 17. Standard UPS-system supported by PV (Wilk et al. 2001).

4.11 BIPV and Storage

In grid-connected applications, the utility grid is used as a "storage" in that PV electricity is sold to the utility during periods of surplus, and grid electricity is bought from the utility during periods of deficit. The IEA PVPS Task 5 project concluded that the existing utility networks could handle large amounts of PV without significant problems (PV Power Issue 16, June 2002).

However, if connection to the utility line is not feasible, a stand-alone storage system is necessary. The most common storage device for PV systems is deep discharge lead-acid batteries. Nickel-cadmium batteries are also suitable and have the advantage that they cannot be overcharged or discharged, but are considerably more expensive. The drawbacks to batteries are that they decrease the efficiency of the PV system, because only about 80% of the energy chandelled into them can be reclaimed. They also add to the expense of the overall system and must be replaced every five to ten years. They take up considerable floor space, pose some safety concerns, and require periodic maintenance.

Therefore, research is being conducted on new types of storage for PV systems, including gas and hydrogen storage with fuel cells, redox-flow systems, and supercapacitors. None of these systems are commercially available. There are a few examples of PV/hydrogen systems used in experimental buildings (e.g. the Self-sufficient Solar House in Freiburg, Germany).

In a PV/hydrogen system, electricity from photovoltaic panels is used to run an electrolyser, a device which splits water (H_20) into its elemental parts, hydrogen (H_2) and oxygen (O_2). The oxygen is released into the air and the hydrogen is pumped into storage tanks. At night or in bad weather when solar energy is not available, the hydrogen is recombined with oxygen from the air in a fuel cell, which directly converts the chemical energy in hydrogen into electricity. The only by-product of this process is pure water. Bolton (1996) reports that such a plant has achieved an overall efficiency of 6% for PV H_2 generation from water.

Figure 18 shows an example of a photovoltaic hydrogen system used on a house. In addition to heat from the fuel cell and from a catalytic burner, the system includes a solar thermal collector for space and water heating.

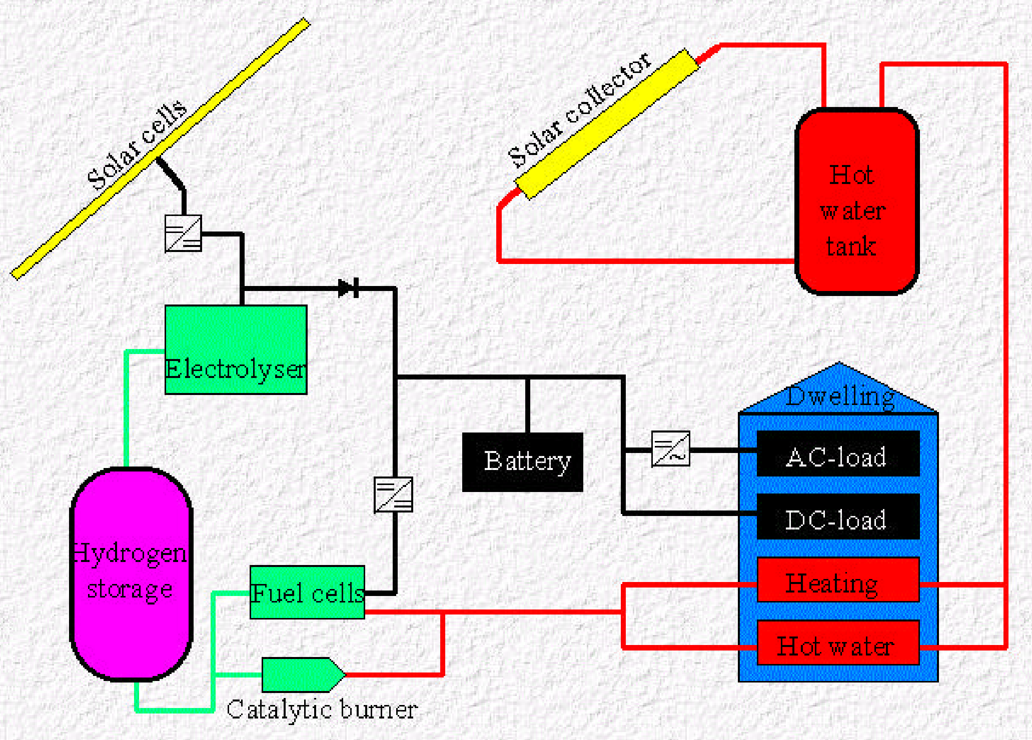

Figure 18. Example of a PV/hydrogen system used in a house (SEL, Wisconsin).

5 BIPV and SmartBuild

Future buildings will need very little thermal energy, because of well-insulating envelopes, high-performance windows, and energy-efficient ventilation. However, they will still need electricity for lights and appliances. PV is the renewable energy technology available today that is most likely to cover this need on-site. This is because it has the lowest environmental impact, and may be aesthetically integrated into the building.

If BIPV is going to fulfil this vision, further research and development is needed in several areas. Within the SmartBuild Project, two areas of work seems to be of particular interest:

- Development and optimisation BIPV elements that perform several functions, i.e. daylighting, shading, heating, cooling, and ventilation for different types of buildings and users. The multifunctional PV elements must be part of an “environmental low-energy package” that may be sold to different types of clients.
- Integration of the BIPV elements with the building management and information system.

Both of these areas require the co-operation between architects, building engineers, HVAC engineers, electrical engineers, and sociologists.

6 Literature and central R&D institutions and Industry

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6.2 Central R&D institutions

National Renewable Energy Laboratory (NREL), Golden, Colorado.
Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.
Ecofys, Utrecht, NL
ECN, NL

6.3 Industry

Renewable Energy Corporation (REC), Høvik.
BP Solar, UK / BP Norge
SCHÜCO Norge, Oslo.
Hydro Building Systems – Wicona, Ulm, Germany.
Flabeg, Hamburg, Germany.
Colt International, UK.
Esbensen Consulting Engineers, Denmark.
CENERGIA, Denmark.
Abbate & Viggevano Architects, Rome, Italy
GASA Architects, Norway.