Building-integrated photovoltaic systems

Integrating photovoltaic systems into the built environment, connected to the electric grid, is being taken up as a rising solution, opening up new prospects, aside from the sole generation of electricity, for utilization of solar energy in developed countries.

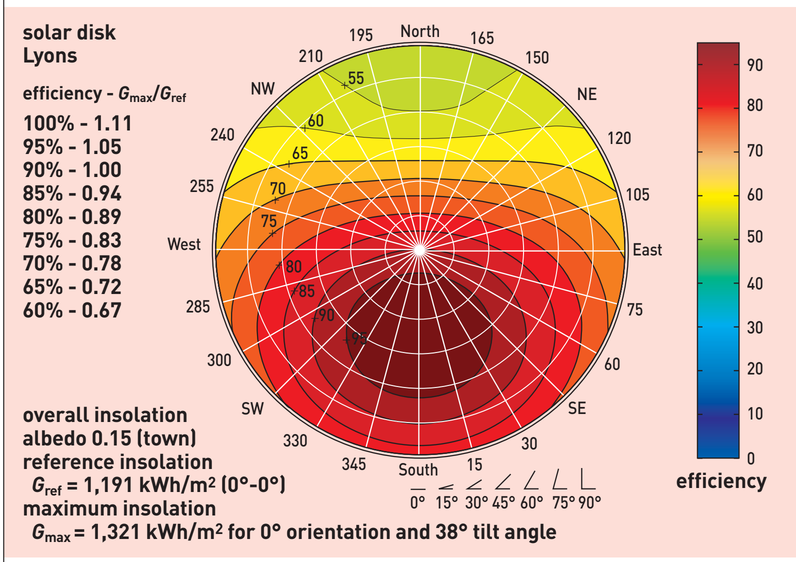
Patrick Wallet/Ademe 2003

Instance of architectural integration of photovoltaic generators, in the form of "sun-shield" panels at the CNRS Institute for Materials and Process Science and Engineering (IMP-CNRS: Institut de science et génie des matériaux et des procédés), in Perpignan, France. With a 15,000 kWh/year capacity, the installation is connected to the EDF grid.

The photovoltaic system stands as the interface between user and resource. It shapes the energy captured by **photovoltaic modules**, according to the type of application. In the case of systems integrated into buildings, aside from wiring modules together, an inverter allows conversion of direct current into alternating current, for use on the electric network. The user may then use the energy generated, with equal ease, either for specific applications, such as running an air-conditioning system, or to inject it into the electric grid, if, for instance, purchase terms offered by the grid operator are advantageous. As regards France, the order of 13 March 2003 sets the purchase price per photovoltaic **kilowatt-hour** at €0.1525 for mainland France, and €0.3050 in Corsica and overseas *départements* (administrative divisions).

Optimization of the performance/integration criterion

Underlying the seeming simplicity of such a setup, optimization of the performance/integration criterion is prioritized nowadays. This vouchsafes, with all due security, for both user and grid operator, a guaranteed annual solar electricity yield, and thus a guaranteed return on investment, while favoring integration solutions allowing substitution of photovoltaic panels for other building elements (tiles, parapets, ornamental facade elements…), thus bringing down overall cost for the installed system. Architectures and integration layouts preserving southward exposure of photovoltaic generators are thus to be favored (see Figure 1).



CEA

Figure 1.
Simplified diagram, showing the tradeoff between performance and integration, for a photovoltaic generator, as a function of tilt angle (concentric circles corresponding to 15° increments, from 0° to 90°) and orientation, for a given location, in this case Lyons, France. This highlights, compared to the theoretical maximum (due south orientation, 38° tilt), the fall-off in efficiency (color scale) linked to non-optimal orientation and tilt angle.

A soaring world market

The most developed countries, with respect to integration of photovoltaics into housing, are Japan (with an aggregate installed power of 638 **MW** by the end of 2002), Germany (aggregate installed power: 277 MW in 2002), followed by newly declared promoters of this form of value-added utilization of solar energy: the United States (212 MW), the Netherlands (26.5 MW), Spain, Switzerland… The world market for grid-connected systems overtook, in 2000, the market for stand-alone systems, and currently accounts for installed power of close to 1,800 MW (2003 estimate). Installed power in France, in 2002, stood at 17 MW (IEA-PVPS figures). The target set by the **European Commission** is to achieve 3 **GW** by 2010.

Research directions for cost reductions

Research and development directions, as regards building-integrated systems, are mainly concerned with bringing down production costs, and broadening the range of services provided. Such price reduction is obtained by working on both sides of the cost/performance ratio, for components making up the system, but equally on more overarching factors, concerning the architecture of these systems, energy-flow management, and integration processes.

In decreasing order of expenditure, as regards initial outlay costs for a photovoltaic system integrated into the built environment, in rooftop position, for instance, i.e. substituting for tiles, the photovoltaic generator, on average, accounts for 60%, the inverter for 10-15%, other electronic safety and monitoring components for 10%, with integration, on average, accounting for 20% of overall cost, this possibly reaching 50%, in the most difficult cases. Substituting roof tiles with photovoltaic modules enables a reduction in overall cost by 10-30%.

Research on phototovoltaic modules has direct trickle-down effects on the cost of grid-connected systems, be it in terms of improved performance and **cell conversion efficiency** (higher power output, at constant price), or of lower production costs, through work on fabrication processes (cheaper photovoltaic modules, for an equivalent power output: see *High-tech cells for cheaper modules*). A reasonable estimate, currently, is that there is margin for further gains available, allowing a 30% cost reduction for a complete system.

As regards the other components, the aim is to keep conversion losses to a minimum. So-called *solar* inverters exhibit much higher performance than standard inverters. They achieve efficiency of over 95%, for a self-consumption (1) of a few percent of nominal power, whereas inverters intended for uninterrupted power supplies achieve barely over 80% efficiency, with self-consumption higher by an order of magnitude. Prices vary accordingly.

Technical measures and responses

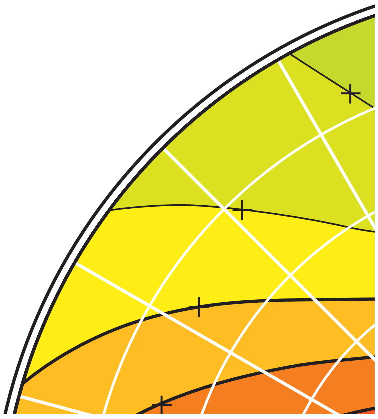
In the case of complete systems, the main technological levers, to which research efforts are directed, essentially relate to three sets of issues:


Olivier Sébart/Ademe 2000


Olivier Sébart/Ademe


IEA-pvps.org/Apex-BP Solar


STMicroelectronics


Solarte

Types of solar photovoltaic integration into buildings: rooftop (detached housing estate in the Netherlands, Niewland); terrace penthouse (4-kW grid-connected photovoltaic system in a villa, Reunion Island); facade (STMicroelectronics building, Grenoble, Isère *département*, France); roof-mounted, associated to sustainable materials, such as wood and glass (Energy House, Saint-Alban-Leysse, Savoie *département*, France); wall elements (210 photovoltaic modules, yielding 9,000 kWh/year, fitted to the new Tourism House, Alès, Gard *département*, France).

Integration of systems into the electric grid

The first technological lever concerns integration of systems into the electric grid. In the short and medium term, this is one of the most effective measures to undertake. Investigations are addressing development of electronic conversion devices ensuring faultless grid connection quality, by allowing automatic system disconnection in case of failure, to preclude the local grid branch to which it is connected being kept energized. Investigations further seek optimum utilization of energy flows in all components, by endeavoring to keep photovoltaic modules at output levels close to maximum power, and designing inverters exhibiting high efficiencies over wider insolation ranges.

From the grid operator's standpoint, widespread dissemination of this type of generator across the electric grid raises concerns with respect to grid quality management (load shedding, voltage, frequency). This is in no way specific to solar energy, however it does take on peculiar significance, with the rise of decentralized energy sources, of diverse character (wind power, hydropower, solar power, microturbines, electric generators…), and modest output (from a few kilowatts to several megawatts). European programs, aimed at development of new electricity distribution grid concepts, were initiated as early as 2000. Participants include CEA's Systems Integration Laboratory (CEA/LIS:

(1) Self-consumption: the energy used internally by the inverter when active (i.e. not on standby).

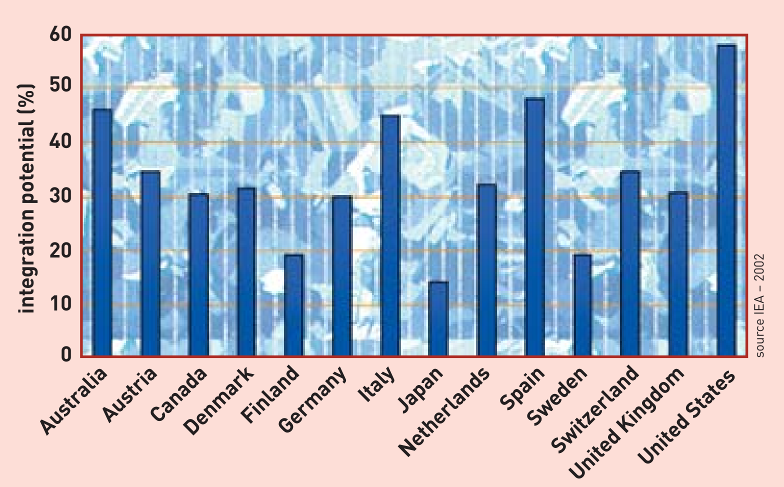
Photovoltaic solar roof tiles by Imerys-Toiture, designed for optimum integration into traditional roofing. They may be laid by regular tilers or roofers.

Laboratoire intégration systèmes). These new concepts are somewhat akin to what the Internet represents, in the telecommunications sector: anybody and everybody having the ability to be connected, anywhere and anytime.

This entails not only improved knowledge as to system reliability, and the deployment of communications, monitoring and user-assistance devices, but equally a degree of component standardization, and increased prevalence of a quality-assurance and standardization approach. Part of the work carried out at LIS concerns drafting of international standards for photovoltaic systems testing.

Integration into the built environment

The second lever concerns integration into the built environment. In the medium term, this solution is seen as the most promising. This involves, for instance, shortening installation times, by enabling the construction industry to take up the photovoltaic generator as a fully-fledged building component, for dwellings, whether for new housing developments or for the purposes of renovation. An International Energy Agency (IEA) study shows that the potential for roof integration of photovoltaic systems (with all roof surfaces fitted with photovoltaic generators complying with performance/architectural suitability tradeoff) stands at some 30-40%, for the various European countries (see Figure 2), this giving a foretaste of what solar town planning and architecture might achieve, on the scale of a town, or an entire planning area.



source IEA – 2002

Figure 2.
Potential for solar roof integration in the more advanced countries, with respect to photovoltaics integration into the built environment. Percentage for France would stand at around 35%.

Overall architecture of systems integrated into an environment

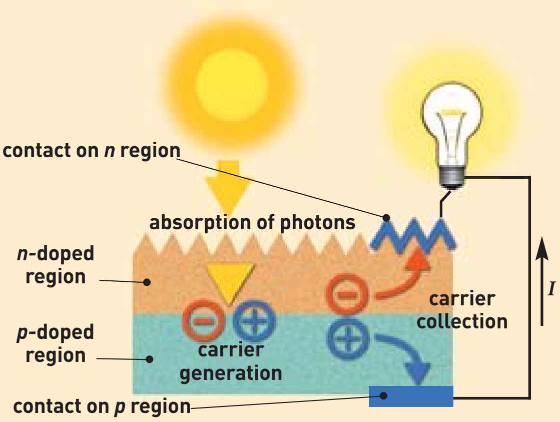
The third lever acts on the overall architecture of a system, integrated into its environment. This is undoubtedly the most innovative point, which should give rise to products featuring an architecture far removed from that of early systems. Investigations cover combinations of the various solutions afforded by photovoltaic systems (roofs, but equally sun shields, verandas, having an impact on heat comfort and lighting, for the building as a whole). Implementation of integral management methods for building construction, with regard to both outer fabric and interior comfort, as of "predictive" methods, i.e. methods seeking to predict future states for the resources, or the system, now represents a major direction for the work carried out at LIS.

Increasingly diversified products are being developed, to allow simpler, modular integration into buildings: "solar" roof tiles, slates or coverings, semitransparent roof or facade windows, and even multifunction components, carrying out, at one and the same time, one or more functions, such as building structural stiffness, insulation, solar shielding, air conditioning, communications, thermal energy collection, and photovoltaic electricity generation. Currently, the techno-economic optimum, for a combined thermal-photovoltaic system, i.e. a system having the capability to generate both heat and electricity, is arrived at through juxtaposition of a solar thermal array next to a photovoltaic array. Such a system thus takes up more space. LIS, in collaboration with CEA's Heat Exchanger Laboratory (LETh: Laboratoire échangeur thermique), is investigating hybrid solutions, combining both devices, affording the potential to result in high-performance, in technical terms, and economically profitable, all-solar **cogeneration**.

Such technical responses will allow end products to meet overall requirements better, or even new applications to be found. While improvements to complete systems are prevalently linked to the technological innovation process, the gains foreseen in the area of photovoltaic conversion concern upstream research.

> Pascal Boulanger
Technological Research Division
CEA Grenoble Center

D How does a photovoltaic solar cell work?



The photovoltaic effect used in solar cells allows direct conversion of light energy from the Sun's rays into electricity, by way of the generation, and transport inside a semiconductor material, of positive and negative electric charges, through the action of light. This material features two regions, one exhibiting an excess of electrons, the other an electron deficit, respectively referred to as *n-type doped*, and *p-type doped*. When the former is brought into contact with the latter, excess electrons from the *n* material diffuse into the *p* material. The initially *n*-doped region becomes positively charged, and the initially *p*-doped region negatively charged. An electric field is thus set up between them, tending to force electrons back into the *n* region, and holes back into the *p* region. A junction (so-called *p-n* junction) has been set up. By placing metallic contacts on the *n* and *p* regions, a diode is obtained. When the junction is illuminated, photons having an energy equal to, or higher than, the width of the forbidden band, or band gap, yield their energy to the atoms, each photon causing an electron to move from the valence band to the conduction band, leaving behind it in turn a hole, also able to move around the material, thus giving rise to an electron-hole pair. Should a load be positioned at the cell's terminals, electrons from the *n* region will migrate back to the holes in the *p* region, by way of the outside connection, giving rise to a potential difference: an electric current passes (see Figure).

The effect thus involves, basically, the material's semiconducting properties, and its doping, to improve conductivity. Silicon, now used in most cells, was selected for the presence of four valence electrons in its outermost shell (column IV of the Mendeleyev periodic table). In solid silicon, each atom - termed a tetravalent atom - is bound to four neighbors, and all electrons in the outermost shell participate in the bonds. Should a silicon atom be substituted for by an atom from column V (a phosphorus atom, for instance), one of its five valence electrons is not involved in the bonds; as a result of thermal agitation, it soon moves to the conduction band, thus becoming free to move through the crystal, leaving behind it an immobile hole, bound to the doping atom. There is electron conduction, and the semiconductor is designated as an *n-type doped semiconductor*. If, on the other hand, a silicon atom is substituted for by an atom from column III (boron, for instance), carrying three valence electrons, one electron is missing, if all bonds are to be maintained, and an electron may quickly move in to fill this gap, taking up the vacant orbital, as a result of thermal agitation. A hole thus arises in the valence band, contributing to conduction, and the semiconductor is said to be a *p-type doped semiconductor*. Atoms of elements such as boron or phosphorus are thus doping agents in silicon. Photovoltaic cells are assembled into modules.

Note: In *Organic photovoltaic cells: towards an all-polymer path...*, you will find the operating principle of organic photovoltaic cells (Box, p. 122).

Operating principle of an organic photovoltaic cell

Following absorption of photons by the polymer, bound electron-hole pairs (excitons) are generated, subsequently undergoing dissociation. Owing to inherent limitations in organic materials (exciton lifetime, low charge mobility), only a small fraction of photon-generated electron-hole pairs effectively contribute to the photocurrent. One of the main ideas is to achieve volume distribution of the photogeneration sites, to enhance exciton dissociation. This approach is based on increasing junction surface area, through deployment of an interpenetrating network of the donor-acceptor (D-A) type, effecting transport of holes (P^+) to the anode (indium-tin oxide [ITO]), and of electrons (e^-) to the metallic cathode (made e.g. of aluminum [Al]). While quantum separation efficiency, for photoinduced charges in systems associating a semiconducting polymer (of PPV or polythiophene type) with a fullerene derivative (PCBM), is thus close to unity, the challenge now is to restrict recombination and trapping processes limiting charge transport and collection at the electrodes, to improve overall device efficiency, this currently still being low (less than 5%). The rise of the pathway is also heavily dependent on mastery and understanding of cell aging mechanisms, but equally on mastery of thin-film technologies, to achieve protection of the device against atmospheric oxygen and water vapor.

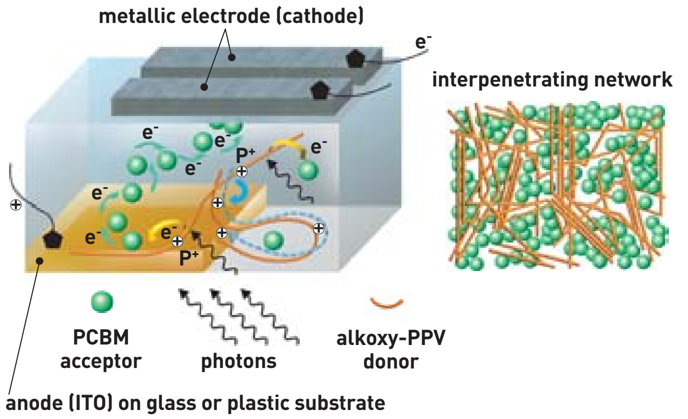


Figure from a presentation by S. Sariciftci (www.lios.at)

The blue dotted line shows the trajectory of holes inside the material.