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Diffusion of solar energy use in the built environment supported by new design

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Abstract
Places of large potentials of sustainable energy production and places of energy consumption are often very different and separated by large distances across the globe. This paper first discusses potentials of solar technology in terms of global availability using PV technology and actual energy production. Solar energy is widely under-used and one way to reduce this is to improve production in low-energy places with high demand: large cities.
According to this option, about 40% of the electricity consumption in the built environment could be produced by solar PV systems. To reach this goal we need appropriate solar PV energy conversion devices and energy storage systems. This paper discusses conditions in the built environment and functional and design qualities enabling an increased diffusion of the technologies. In a comparative analysis of PV technologies, the criteria taken into account encompass efficiency of the type of solar cell and commercial availability. Special attention is paid to the design features of different PV systems, like flexibility, colour and transparency that might help in their utilization as integrated in building material and ornaments in modern architecture. The same procedure is followed for electricity storage devices. The preliminary conclusion is that at present the freedom of design is largest for a combination of crystalline silicon PV cells and Li-ion batteries.

Key words: solar PV energy systems, battery storage systems, design qualities for the built environment.

Introduction

There are many reasons for considering an increased use of renewable energy sources that can supplement or perhaps even replace part of the conventional fossil fuel-based energy production types that are most prevalent today. First is the future security of supply. It is not clear, how long we can be sure of deliveries of coal, oil, and natural gas at affordable prices. An undisrupted energy supply is needed for a growing population and economy, particularly as fossil fuels become more costly and harder to find/extract. Secondly, environmental considerations are a reason to choose alternative sources of energy. In general, the scientific community involved in investigating climate change, agrees that burning fossil fuels contributes to global warming that enhances melting of glaciers and rising of the sea levels. Global warming is also expected to increase severity of tropical storms, to shift the location of viable agriculture, to harm ecosystems and animal habitats, and to change the timing and magnitude of water supply. A third reason to focus on renewable energy technologies is the employment and export possibilities, which emerge in connection with research and development in the field.

To date a large part of the population in the world lives in cities and - if current trends continue - two-thirds of the world's population will be urbanized by 2050 (Badcock 2002). This means that cities will be the largest energy consumers and contributors to greenhouse gasses. Vogel mentions that currently 75% of energy is consumed by large cities. Cities are thus an important frame to connect solar PV technology with the built environment. In addition, there is growing consensus that distributed solar PV systems providing electricity at the point of use, will be the first to reach widespread commercialization. Chief among these distributed applications are systems for individual buildings (WBDG, 2012).

Solar PV systems produce energy without noise and emission, in a safe manner and only with small maintenance needs, and it seems likely that solar PV systems become integrated in buildings in roofs, facades, windows etc. and start even to perform as building material. Commercialization may be particularly enhanced based upon design qualities in the context of modern architecture, like flexibility to allow use in curved facades, being colored or allowing a change of color, and performance as a distributed system of clusters of PV cells as ornaments, also inhibiting certain aesthetical qualities. Indeed, the International Energy Agency Technological (IEA) Roadmap says: Solar Photovoltaic Energy presents the short-term, mid-term, and long-term R&D priorities for PV (IEA, 2012). Among these short- and mid-term R&D priorities are: design solar PV as a building material and architectural element that meets the technical, functional, and aesthetical requirements, along with cost targets. To reach such goals, we need appropriate solar PV energy conversion devices and also battery storage systems, the latter because of the variation in solar radiation and in energy consumption.

The question addressed in this paper is the optimal combination of solar PV systems and battery storage systems. The paper discusses important conditions in the built environment and various functional and design qualities that enable an increased application of the technologies. In an assessment, the same analysis is followed for PV technology and battery storage devices. The paper is structured as follows. First, solar PV technology is reviewed with regard to availability of the source, progress in research to combat disadvantages of the technology, and various economic characteristics (section 2). Next, attention moves to a comparative analysis of solar PV systems from the viewpoint of the built environment and architecture (section 3). This is followed by a similar type of analysis of storage systems using batteries (section 4). The last section concludes on the most promising systems.

Solar photovoltaics (PVs)

Aside from solar radiation, a necessary resource is ground or buildings required for PV devices. What is unique for solar cell technology, as has recently become apparent, is that it can be used highly functional in solar farms but it can also support modern architecture of buildings.

Solar energy is widely available across the world and in much larger amounts than wind energy, the latter is used as a reference in our analysis. About 14,900 PWh yr^{-1} are theoretically available over land for PVs (Table 1) (Jacobson, 2009). The capture of even 1 percent of this power would supply more than the world's power needs. However, there are considerable differences in intensity of radiation (direct and diffuse light). Within Europe, for example, the difference in yearly average is a factor 1 to 2 from northern to southern Europe and, more importantly, the seasonal variation (summer-winter) in the north is 1 to 10 compared to 1 to 4 in the south (SEC, 2006). An estimation of solar PV power worldwide, assuming the use of 160 W solar panels, indicates overall higher scores compared to wind energy (6500 versus 1700 TW) (Jacobson and Delucchi, 2011) (Table 1). The same holds for power generated in high-energy locations (1300 versus 72-170 TW).

If we take into account current power delivered as electricity, however, the situation is reversed (0.0013 versus 0.02 TW), meaning that a large amount of solar energy is not used. On the availability side, this situation is related to variability in radiation and to availability of solar energy mainly in those places (high-energy locations) where there is virtually no local demand for electricity. Responses to this situation are twofold, that is 1) solar power could be produced in high-energy locations and then transferred to places of high demand, and 2) solar power could be profitably produced in low-energy locations with high demand, namely in cities in the built environment. This paper is concerned with the last, with special attention for solar PV devices as building material, including ones serving aesthetic goals.

Solar photovoltaics (PVs) are arrays of solar cells containing materials that convert solar radiation into direct-current (DC) electricity. Materials used today include various types of silicon, polymers, and new nano-structured materials. A silicon-based solar cell comprises a combination of a thin film of n-type silicon and a thin film of p-type silicon. In general, PV performance is limited when the cell temperature exceeds a threshold, but this varies with the material used. PVs can be mounted on roofs or combined into solar-PV farms. Such farms today may range from 10 to 60 MW and in the near future to 150 MW (Jacobson, 2009). Most capacity of PV modules is on rooftops, meaning that in historical cities PV modules may reduce aesthetic value of the buildings. However, solar cells are expected to be increasingly integrated in parts of buildings, like windows and walls, which can be applied in newly constructed buildings, but also in renovated buildings. The energy payback time for silicon-based solar cells is estimated to be relatively long, i.e., three to four years, depending on the type of silicon used (e.g. SEC, 2006).

Obstacles to adoption follow from a combined relatively low efficiency of silicon-based solar cells and relatively high price of silicon-based systems compared to alternative energy sources. Typical conversion efficiencies for silicon-based PV modules are in the range of 5 to 15 percent, depending on the type. Important improvements are expected among others based on a new production process of amorphous silicon thin-film solar cells on a flexible substrate deposited in a roll-to-roll process, causing a substantial decrease of use of silicon, and hence cheaper materials costs.

Table 1. Solar PV globally available energy, power in different locations and installed power (electricity) (wind energy as reference)

Technology	Available energy/PWh yr^{-1}	Power worldwide (TW)	Power in high-energy locations (TW)	Delivered as electricity (TW)
Solar PV	14 900	6 500 a)	1 300 c)	0.0013
Wind	630	1 700 b)	72-170	0.02

Source: adapted from Jacobson (2009) and Jacobson and Delucchi (2011).

a) Assuming the use of 160 W solar panels and areas over all latitudes, land and ocean.
b) Accounts for all wind speeds at 100 meter over land and ocean.
c) Same as a), but locations between latitudes 50S and 50N.

Other types of solar cells, which are substantially cheaper, include the Grätzel cell, which mimics the natural photosynthesis by using a dye-sensitized nanostructured semi-conductor based solar cell. The Grätzel cell comprises a thin film of n-type nano-porous anatase-structured titanium dioxide, TiO_2, covered with a monolayer of a ruthenium-based visible-light absorbing dye molecule. This photo-electrode is immersed in a liquid electrolyte, acetonitrile, containing an iodide/iodine redox couple and a counter electrode. The conversion efficiency of the commercial Grätzel cell is about 9 percent, but the use of a combination of two different visible-light absorbing dye molecules will increase the conversion efficiency substantially (by 25 percent).

Different from the above mentioned silicon-based solar cells, the energy payback time of the Grätzel cell is less than one year. Other major improvements on the cost-side are solar cells based on new nano-structured composite materials, e.g. titanium dioxide - copper indium disulfide and – copper indium gallium diselenide, which are cheap and face a relatively short energy payback time. However, these new types of cells do not exhibit an improved efficiency (around 7 percent). A next generation solar cell shall be based on the use of quantum dots and an estimated theoretical efficiency of about 82 percent, which means a substantial increase compared with current generations, but research has just taken off.

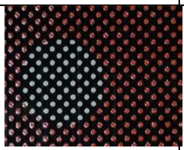
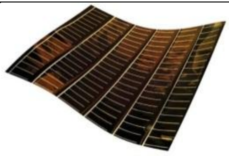
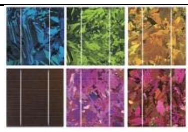
Of course, solar cells produce energy only during the day. In the case of solar panels on houses, this means that the system needs to be connected to the electricity grid. During night, electricity can be drawn from the grid, whereas in daytime a surplus of solar energy (compared to its use) can be delivered to the grid. At this point, agreements with electricity producers come in, particularly regarding the price of the solar energy delivered to the grid. Another solution would be to store surplus of solar energy in batteries. We will limit our self to this option.

Solar PV technology and design in the built environment

In this section, we focus on the following five PV technologies: single crystalline (sc-Si) and poly-crystalline solar cells (pc-Si); amorphous silicon-based solar cells (a-Si); dye-sensitized solar cells, i.e., the Grätzel Cell, abbreviated as DSSC; cadmium telluride, CdTe; and copper-indium-gallium-diselenide solar cells (CIGS). We investigate the opportunities to create different types of designs with these PV technologies, in particular with a focus on use of products in the built environment. Solar PV systems in this context are compared particularly on their potentials as an aesthetic building material and 'shaper' in modern architecture, or as ornaments. We explore these opportunities in three directions: (1) two-dimensional design, (2) three-dimensional design and (3) coloring and transparency (Table 2).

In our scope, two-dimensional design refers to (a) patterning and (b) shaping of edges, for instance for an ellipsoid PV roof. For three-dimensional design, we distinguish between (c) curvature of surfaces, like the PV elements of a so-called PV bubble module, and (d) spatially distributed structures like 500 butterfly-shaped silicon solar cells. We assume that the two visual features coloring and transparency speak for themselves.

Table 2. Design features of PV technologies

PV Tech	Typical size Substrate	Patterning	Shaping of edges	Bending and curvature	Color	Transparency
CdTe	Customizable from 10X10 to 1000X2000 Rigid and flexible	 Screen printing front glass	n.a.	 Flexible substrate	Cells are brownish or black. Color by colored front glass	Semi-transparency by wider space between cells Laser scribing
CIGS	Customizable from 10X10 to 1000X2000 Rigid and flexible	 Screen printing front glass	n.a.	 Flexible substrate	 Colored front glass	Semi-transparency by wider space between cells Laser scribing
a-Si	Customizable from 10X10 to 1000X2000 Rigid and flexible	Screen printing front glass	n.a.	 Flexible substrate	 Cells are usually brownish or black, other colors can be made	Semi-transparency by wider space between cells Laser scribing
sc-Si / pc-Si	156x156 (Cells) Rigid only due to the fragility of the cells	 Cells can be used as pixels	 Laser cutting	 Curvature by rigid carrier substrate	 Cells are usually blue, other colors can be made	 Semi-transparency by wider space between cells or Punching holes in cells
DSSC	Customizable from 10X10 to 1000X2000 Rigid and flexible	Cells can be used as pixels	Defined by cell geometry, i.e. shaping of cell	Flexible substrate	Orange, redish, purple, depending on the dye applied	Always transparent

All in all, we arrive at the conclusion that out of the five technologies the silicon-based PV cells and the dye-sensitized solar cells (DSSC) provide the best opportunities. At present, the life time of the DSSC, while commercially available, is not yet known and should be at least 20 years in order to compete with the silicon-based solar cells. Of these, the amorphous cells are preferred. The different colors of the sc-Si and pc-Si solar cells are due to differences in the layer thickness of the anti-reflection coating. In the usually blue-colored solar cells the thickness of the anti-reflection coating is most optimal.

Battery storage systems and design in the built environment

In this study, we will focus on storage using rechargeable batteries, their practical specifications and design potentials. To date, several rechargeable battery systems are available. They are based on the following electro-chemistries, i.e., Lead-acid (Pb-acid), Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), Lithium (Li) and Lithium-ion (Li^+), and the Zinc-air, or Lithium-air battery. The Ni-Cd battery is nowadays replaced by the Ni-MH battery, because cadmium is no longer accepted in the environment.

Batteries store chemical energy and convert it into electrical energy, e.g., Pb-acid batteries to start car engines. With slightly modified electrodes Pb-acid batteries are used for the decentralized storage of photovoltaic electrical energy. The nominal cell voltage, the specific energy, the energy density, the cycle life, and the efficiency of selected batteries are presented in Table 3.

Table 3. Practical specifications of selected battery types

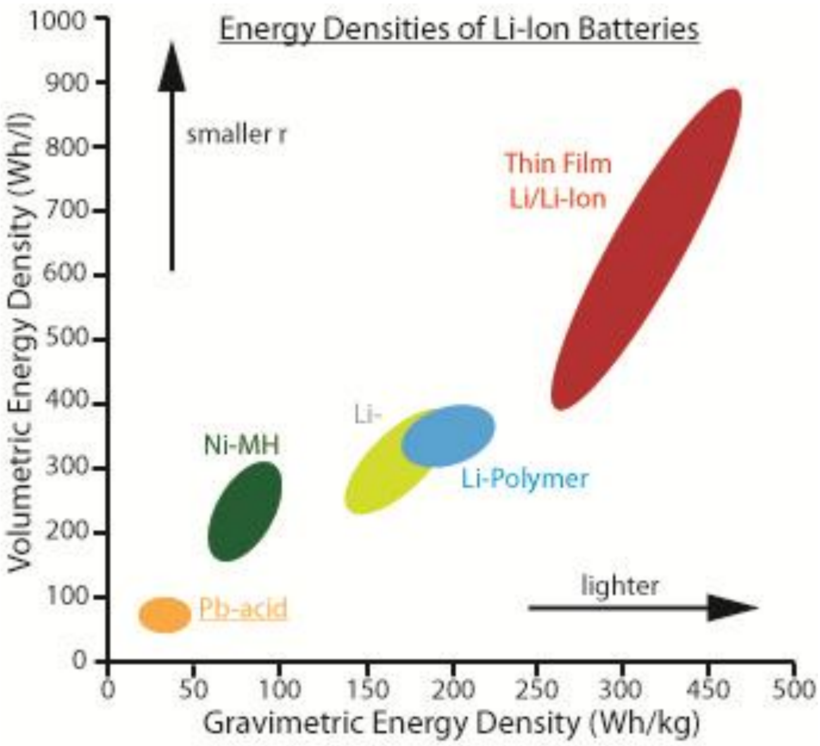
Battery type	Nominal cell voltage (V)	Specific energy (Wh/kg)	Energy density (Wh/L)	Cycle life, 20% fading (cycles)	Efficiency (%)
Sulphuric lead-acid	2.0	30 -50	80 – 90	200-500	85
Nickel Metal Hydride	1.2	75 – 120	240	300-500	
Lithium-ion	4.1	110 -160	400 – 500	500-1000	95-98
Lithium/Manganese dioxide	3.0	100 - 135	265 - 350	300-500 2000	

Source: Schoonman, 2012

The specific energy of the Pb-acid battery is small compared to the other battery types, because of its heavy weight. This would imply that for large-scale storage of photovoltaic electrical energy the required battery package would be very heavy.

Since lithium is the lightest element on earth, lithium batteries have a very high specific capacity. Moreover, lithium has the lowest electrochemical potential, i.e., $E^o(Li^+/Li)$ = -0.3045 V/NHE (NHE-Normal Hydrogen Electrode as reference) and, therefore, the output potential is also high, as can be seen in Table 3. The great performances of Lithium-ion batteries are based on the use of lithium ions, Li^+, which are shuttled between the positive and the negative electrode through the electrolyte. At present, the lithium batteries attract widespread attention, because they almost fulfill the requirements for (hybrid) electrical vehicles, as the lithium battery technology is superior in terms of power and energy density, achieved by a combination of a large specific capacity, current, and a high output potential.

In addition, this is supported by a comparison of the gravimetric and volumetric energy densities of the various rechargeable battery systems is presented in Figure 2.



Source: Adapted from Simon (2007).

Figure 2. The gravimetric and volumetric energy densities of selected rechargeable battery systems.

The Pb-acid, the Ni-MH, the Lithium-ion (Li^+), and the lithium-manganese dioxide have different designs and the design aspects of these batteries are presented in Table 4.

Table 4. Design aspects of different battery technologies.

Battery type	Shape	Flexible	Safety / environmental	Operating temperature (°C)	Maintenance	Specific costs (Euro/Wh)
Sulphuric lead-acid	Cubic	Fluid	Hazard of shock Release of gas	-20 – 60	3 – 6 months	0.50
Nickel Metal Hydride	Cylindrical	No		-20 -60	60 – 90 days	3.80
Lithium-ion	Cylindrical and prismatic and pouch cells	Yes	Flammable	-20 - 45	not necessary	9.50
Lithium/Manganese dioxide	Cylindrical, prismatic and pouch cells	Yes		0 - 45	not necessary	19.00

Source: Schoonman (2012)

With regard to Lithium-ion rechargeable batteries, product opportunities by novel designs have recently attracted attention. The novel designs are especially related to material aspects and focus on the novel applications of nanostructured materials for transparent devices. However, transparent batteries, a key-component in fully integrated transparent devices, have not yet been reported. While transparent electrolytes are known, the Lithium-ion battery electrode materials are not transparent and have to be thick enough to store sufficient electrical energy, the traditional approach of using thin films for transparent devices is not suitable.

However, Yuan Yang et al. (2011) from Stanford University have reported very recently novel and unique grid-structured electrodes to solve this dilemma, which are fabricated by a micro-fluidics assisted method. The feature dimension in the electrodes is below the resolution of the human eye, and, therefore, the electrode appears transparent. Moreover, by aligning multiple electrodes together, the amount of stored energy increases readily without sacrificing the transparency. This results in a rechargeable battery with an energy density of 10Wh/l at a transparency of 60%. The device can also be manufactured on a flexible support, further broadening the potential applications. We may conclude that these features greatly improve applicability of these batteries connected with PV systems in integrated building materials.

Conclusion

Solar energy is widely under-used and one way to reduce this is to improve production in low-energy places with high demand: large cities. According to this option, larger amounts of electricity consumption in the built environment could be produced by solar PV devices. Accordingly, appropriate solar PV energy conversion devices and energy storage systems are needed. This paper discussed various functional and design qualities that enable an increased diffusion of solar PV and battery storage technology, particularly by using it as a building material with aesthetic qualities. In a comparative analysis of various PV technologies, the criteria taken into account encompassed efficiency of the type of solar cell (PV) and commercial availability. Special attention was paid to the design features of the different PV systems, like flexibility, colour and transparency that might help in utilization of these systems integrated in building material and ornaments in modern architecture. The same procedure was followed for electricity storage devices. The preliminary conclusion is that at present the freedom of design is largest for a combination of silicon-based PV cells and Li-ion batteries.

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