DESIGN, PRODUCTION AND MATERIALS OF PV POWERED CONSUMER PRODUCTS -
THE CASE OF MASS PRODUCTION

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ABSTRACT: Though many options exist, the application of integrated PV systems in mass produced consumer products is still unusual and rare [1]. Therefore, to date, design and manufacturing aspects of product-integrated PV systems have been explored only to a very limited extent. The requirements for the design of consumer products are evidently different from those for PV systems. Moreover, product designers and manufacturers are unaware of the use of PV cells in consumer products. Hence, the technical challenges of meeting space constraints and increasing performance [2] might be huge for PV system integration in consumer products, but the challenge of implementing PV cells in industrial design processes of mass manufacturing of consumer goods might be bigger. Therefore, we assess how industrial design methods, new materials and production processes can be applied in order to better integrate PV cells in consumer products. A number of possible methods and processes are presented and suggestions are given for further research and development.

Keywords: PV Systems, Design and Manufacturing, Product-integrated PV cells

1 INTRODUCTION

1.1 Why PV powered consumer products?

So far, the main focus of PV product development has been on flat solar modules. However, the growing need for autonomous electricity supply in consumer products can be a reason to partially shift this focus to product-integrated PV systems as an alternative for batteries. Namely, batteries continue to be a main source of power of not only products with audiovisual, communication and information functionality, but also of an increasing number of products that deliver mechanical work at their output. In general, costs and environmental issues are considered to be main reasons for reducing the use of batteries. In the specific case of consumer products batteries cause a lot of unwelcome user interventions [1] due to the recharging of batteries or due to required replacement if the batteries are flat. Product-integrated PV systems can cut down both the required capacity of batteries and the number of user interventions. Therefore, it will be useful to aim at integrating PV systems in consumer products in a easy-to-manufacture way.

1.2 The contents of this paper

In this paper we will assess how theories about industrial design methods, material selection in consumer products and production processes for mass-manufacturing can be applied in order to better integrate PV systems in consumer products. Section 2 will present several different approaches towards designing consumer products with integrated PV systems. Material selection and production processes will be discussed in Section 3 resp. 4. PV system sizing in consumer products will be presented in Section 5. Section 6 will merge the information provided in Section 2 to 5, by two case studies. The paper will be finished by conclusions and recommendations.

2 DESIGN METHODS

Design methods – the process of designing a product - have a large impact on the final product. Below, we will describe four different approaches towards designing products: prescriptive design, industrial product design, integrated product design and scenario-based design. We will assess how these approaches can be addressed for a successful integration of PV cells in products.

2.1 Prescriptive design

In prescriptive design, the designer interprets and translates a problem definition to a list of requirements and specifications. The application of a prescriptive design method results in a specific system. Such methods are often applied to technology-based products such as installations or when functionality is main focus - which is common to machine construction. The design of many PV systems, such as grid-connected PV systems and solar home systems, is the result of a prescriptive approach, as the main requirement is functional, namely optimal electricity production, see Figure 1. Often a PV system has been tailor-made for given local irradiation conditions and a specific load pattern. As such, the design is unique.

![Figure 1: PV system according to a prescriptive design.](image)

2.2 Industrial product design

Industrial design methods focus on the utility of consumer products. The field of industrial design is shown in Figure 2 and can be represented as a four-leaf clover of the following topics: technology, design & styling, ergonomics and marketing [3]. Technology refers to technologies and materials applied in a product and manufacturing processes. Design & styling refers to the appearance of products in relation to the wanted image. Ergonomics covers the user context of consumer products and the informational and physical ergonomics. To end with, marketing refers to costs, markets and sales.

Product designers perceive each of the four topics...
evenly decisive for the final success of a product. Hence, if these topics are required for a successful consumer product they should be applied to products with integrated PV cells as well. Developers of building integrated PV systems have partially included design & styling in the design process. However, industrial product design has not yet become common practice for PV systems. This might be due the fact that PV systems are based on technology. As such, integrated technology design could be useful for designing consumer products with PV systems.

2.3 Integrated technology design

By integrated technology design both the product to be designed and the technology integrated in the product are considered as evenly important, see Figure 3. This approach may be necessary if a relatively new technology is implemented in existing processes of industrial product design. A very important aspect in product innovation is the integration of new solutions. In actual practice, ‘isolated’ solutions seldom appear fit for adaptation to, and integration in existing environments. For instance, PV cells applied in consumer products might require different technology than applied yet in large-sized grid-connected PV systems. Therefore, problem definitions always need to include integration aspects. As such, integrated technology design includes communications between designers, researchers, manufacturers and customers to define both product and technology requirements.

Possible results of integrated technology design could be PV cells which perform well under low irradiation conditions, or non-flat PV modules which can be shaped like a product surface and be easily implemented in manufacturing processes.

2.4 Scenario-based design

Finally, products are used by many different persons in different contexts, see Figure 4. If rather dynamic circumstances of use are expected, industrial product design could be extended by the scenario-based design approach [4]. In such an approach users define their situations of experience and related solutions, instead of the designer. This approach may result in functional products under many dynamic circumstances.

3 MATERIALS

3.1 Common materials in consumer products

Despite the ‘low cost’ perception of consumer products, the materials selected will be by no means ‘low performance’. Rather, the materials and production processes form a delicate balance with the design, appearance and costs involved. A typical geometry of consumer products has double curvature, for reasons of appearance, ergonomics or other functionality. Plastics are extensively used in this context for their design freedom, low density, robustness, and low costs for mass production methods.

Plastic materials can be subdivided into thermosets, thermoplastics and rubbers. Thermoplastics are often recognised as a typical material for consumer products. These materials can be heated, formed and cooled within minutes, enabling short production cycle times. Complex product geometries can be accomplished by injection moulding processes. Thermosets can be formed using similar processes, where the reactants have to form a polymer network which is no longer (de)formable afterwards. Often the cycle times will be longer than for their thermoplastic counterparts.

3.2 New substrate and encapsulation materials for PV cells

Combining PV cells with consumer products requires careful consideration of many aspects different from the conventional flat panels. The PV cells will be supported by the substrate. On one hand this will have to fit to the rest of the construction (which will distort under mechanical and thermal loads), but on the other hand it has to be compliant to rather fragile PV cells. A similar thermal expansion of the structure and the PV cells will be favourable to prevent premature failure due to thermal stresses. Where plastics have a relatively high coefficient of thermal expansion, fibre reinforced plastics (Figure 5)
more or less match the thermal expansion of silicon. A glass structure is not a very attractive encapsulation of the PV cells for consumer products: it is relatively heavy and brittle. A transparent plastic can resolve both shortcomings.

**Figure 5:** Various carbon fabric reinforcements

### 4 PRODUCTION PROCESSES

#### 4.1 Conventional processes

A wide variety of production processes is available for thermoplastics materials. Large series will however mostly be produced using sheet forming or injection moulding processes. Both methods involve relatively high process loads. Thermoset materials can also be processed using sheet forming processes and resin injection, but spraying can be an option as well. Usually the viscosities of thermoset materials are lower during the forming stage than for thermoplastics, which decreases the process loads.

Thermosets seem favourable for the substrate of the delicate PV cells from this perspective, whereas the encapsulation can be accomplished in various ways: e.g. by spraying, injection or using an adhesive film.

**Figure 6:** Resin transfer moulding

#### 4.2 New processes

Integration of the various components is preferred from the manufacturing point view. Resin transfer moulding (RTM) is a popular method to impregnate dry fibre reinforcement structures, see Figure 6. This process consists of filling a rigid and closed mould cavity by injecting a resin through one, or several, points, depending on the size of the component. Usually, polyesters, epoxy, phenolic & acrylic resins are used. RTM allows the moulding of components with complex shape and large surface area with a good surface finish on both sides. The process is suited for medium to large series production. When the PV cells are mounted on a structure before injection, they can be integrated in one step. A protective transparent resin film should be formed simultaneously, which of course puts further constraints on the material properties [5].

In addition, the non-flatness of the product causes an intrinsically non-uniform radiation on the cells. The standard connections of multiple cells (i.e. in series or in parallel) will lead to a very poor power generation. Therefore a novel connection method has to be developed. Of course, this novel connection method is useful only when it can be combined within the integral manufacturing process.

### 5 PRODUCT-INTEGRATED PV SIZING

#### 5.1 Existing PV system sizing

A common approach towards PV system sizing is shown by Figure 1. Sizing of PV systems is generally based on the optimization of electricity production [6]. On the basis of climatologically expected solar irradiation conditions, fixed installation parameters such as the tilt angle of a PV array, inverter size or battery capacity can be optimized by computational software. Also, expected electricity production can be determined on the basis of installation parameters.

#### 5.2 Dynamic sizing of product-integrated PV systems

If a PV system is integrated within a product it will be used in dynamic situations, see Figure 4. Irradiation available to solar cells will be determined by the behaviour of the user of a product and the geometry of a product. The load pattern will be determined by the user as well. In order to realize a robust PV system, i.e. a system that can deal with many circumstances, the common approach towards sizing of stationary PV systems (5.1) will not be sufficient and a new approach needs to be developed.

Hence, the following topics need to be addressed:

- Movements of a product and resulting non-uniform irradiation due to the geometry of the product and due to shading by surrounding objects
- Various light sources, i.e. outdoor and indoor light sources.
- Various PV cell connections
- Different load patterns due to different users.
- Integrated electronics
- Consumer batteries

Moreover, a product with an integrated PV system has to be designed as a whole. Therefore it would be useful to integrate the sizing of PV systems with existing software for product design, such as visualization tools, and tools for structural analysis.

### 6 CASE STUDIES

The information provided in Section 2 to 5 will be discussed in the following two case studies; the design of a solar racing car and the design of a PV powered recumbent bike.
6.1 Solar car design

The Solar Team of the University Twente has designed a solar racing car for the World Solar Challenge 2005 in Australia [7]. The solar car which is a customized design (see Figure 7) has an improved aerodynamic design, new tires and in-house designed special strategic software. At this moment the students are working on the construction and assembly of the car. During a wind tunnel test the aerodynamic performance was measured. The PV system of about 2 kWp on the top of the car has been designed using simulation software and will be installed in the forthcoming period. Special attention will be paid to the integration of PV solar cells in the upper surface of the car.

![Figure 7: Solar racing car](image)

The solar car is a custom-made design. Prescriptive design has been applied for the autonomous PV system which provides full power supply. Main technical requirement is travelling as fast as possible on a fixed trajectory of 3000 km in the sunny climate of Australia. Design & styling is according to - aerodynamic - form follows function. Main ergonomic requirement is safety in traffic.

6.2 PV powered recumbent bike design

In the master course Design, Production and Materials at the faculty of Engineering Technology of University of Twente attention was paid to integration of PV solar cells in recumbent bikes, see Figure 8.

![Figure 8: Recumbent bike](image)

Recumbent bikes are consumer products. The design is based on an integrated technology approach. The PV system of about 150 Wp provides additional power for driving and for lighting by night. The technical requirement is performance anywhere in Europe under dynamic irradiation conditions such as cloudy weather or shading through trees. Considering this aspect scenario based design could be applied. Moreover the product should be easy to manufacture. RTM with integrated PV cells could be an option for the manufacturing process. Design & styling should be attractive to the consumer who is sporty, aged 25-45 and focused on health and environment. Ergonomics require simplicity of use, storage and cleaning. Also safety in traffic is an ergonomic issue. Consumers will use the recumbent bicycle for medium to long distances (10-40 km) instead of a car. Therefore, its retail price (hence, production costs) must fit to the competitive alternative and consumer's budget.

7 CONCLUSIONS AND RECOMMENDATIONS

The case study clearly illustrates the shortcomings of the current prescriptive design methods and manufacturing processes when PV systems are applied outside the conventional domain of flat solar modules. Future mass market applications are only feasible when:

- design methods will shift focus from prescriptive design to industrial product design using integrated technology design eventually added by scenario-based design,
- product design tools are integrated with PV system sizing tools, including batteries,
- integrated electronic systems are developed which allow for a significantly improved power generation in a dynamic context, compared with the current fixed connection systems for planar PV systems, and
- integrated manufacturing processes are properly developed.

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9 REFERENCES