A novel design framework for solar thermal/electrical activation of building envelopes

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Abstract. Building integrated solar materials have a great potential for direct and indirect carbon emission reductions of the built environment. The main perceived barriers for wide-spread building integration of solar energy are economic feasibility, lack of available materials and lack of knowledge about the integration process. In the past, economical aspects and product diversity have been addressed by joint research and industry efforts, resulting in a growing number of products and decreasing costs. To further support knowledge transfer and foster the design with solar materials in the built environment, we present an early design stage framework for thermal and electrical activation of building envelopes with solar materials. The goal of the framework is to provide fast feedback of energy performance values and visualizations to study the interactions of building geometry, building systems and aesthetic design choices. Design choices include cover technologies with different colors, photovoltaic cell types and thermal absorber types as well as heating system choices. The calculations are based on physical and semi-empirical equations. Typical values have been implemented to make the framework accessible to non-experts. Results are compared with experimental data from literature and the impact of design choices is demonstrated by a case study where different combinations and different cover types were investigated.

1. Introduction
With recent regulatory frameworks promoting solar energy integration and decreasing prices of solar technologies, namely photovoltaics (PV), solar thermal and highly efficient aesthetic cover technologies, the installation of solar systems has rapidly grown [1]. While solar thermal systems were more popular than PV in the beginning of the century, solar electricity production is currently being installed at a much faster pace [1]. At the same time, hybrid photovoltaic thermal (PVT) systems have kept being a niche product despite their potential for achieving high thermal and electrical efficiencies. In particular, unglazed low-temperature PVT has been identified as a promising solution for building integration [2]. A wide range of building integrated photovoltaics (BIPV), solar thermal modules and PVT solutions are nowadays available [3, 4]. The most commonly used PV technologies are crystalline silicone solar cells and second generation thin-film solar cells that both offer various design opportunities [5]. Third generation solar cells so far only play a very limited role in BIPV technologies. Different solar thermal collector concepts at different temperature levels exist. Generally, it is agreed that the combination of PV and solar thermal collectors makes sense for low-temperature applications that do not compromise PV electricity production too much. Only a limited amount of commercial products...
are available despite efforts in research [6, 2]. Further, recent developments in cover technologies
like nanotechnology based spectrally selective glass coatings or digitally printed glass covers
that allow different colors, textures and reflective properties increase the design opportunities
for BIPV systems on the roof and at facades. The main perceived barriers among architects and
planners for integration of solar technologies in buildings are the missing economical benefits, the
lack of products and the lack of knowledge about the integration process [7]. Both, economical
benefits and range of products have been addressed in the past. It has been shown, that solar
systems are economical not only for PV or solar thermal but also for PVT systems [8]. While
we observe an overall increase in design flexibility of solar technologies, we also identify a lack
of making use of it. It is clear that if the integration of local solar energy production is not
well-considered in an early design stage, that no satisfying results will be produced. Also the
planning and designing with solar technologies, which wasn’t part of most architects training,
hinders the implementation [9]. Often, building performance simulation tools for engineers are
used for the early design stage. Most commercial solar design tools are made for solar experts
and are not directly integrated into CAD. There are only a small number of tools targeting
designers and architects [10]. For Rhino Grasshopper, several solar planning tools such as
Ladybug or Honeybee [11] exist focusing especially on BIPV. However, no integrated, flexible
tool that also considers appearance and systems could be found. We see the next step of solar
integration to be a free design space where solar materials can be freely combined by designers
to fit a building’s aesthetical requirements while also being well matched to the building energy
systems. In this paper we propose a shift from designing with solar modules towards designing
with solar materials and we present a framework for early design stage considerations.

2. Design Framework

To empower architects to design with solar materials in the early design stage, we want to
connect building system choices, solar material choices and solar potentials in an early design
stage framework. The framework is implemented in Rhino Grasshopper, a tool widely used by
architects and planners [12]. Existing components from the environmental plugin Ladybug [11]
are used and extended with customized python components. Basic geometric data of the building
envelope and a weather file from the building location are required as inputs. Solar material
and system choices are provided directly within the Grasshopper environment. In Figure 1 the
available design choices and their interdependencies with relevant measures, e.g. performance
and aesthetics, are shown.

2.1. Physical Models

For the calculation of thermal and electrical energy yield, the simulation framework connects an
optical, an electrical and a thermal model as shown in Figure 2. The optical model accounts for
reflection losses by the cover and the PV cells as well as for the angle of incidence correction and
further transmission losses through the cover. The electrical model is based on the temperature-
dependent PV efficiency with the cell temperature calculated as a function of the temperature of
the thermal absorber, the thermal power and the conductive heat transfer through the lamination
or adhesion layer. The thermal model builds up on the ISO9806:2017 standard on solar thermal
collectors. It is based on semi-empirical equations requiring a set of module dependent factors.
Efficiency reductions depending on type and color of covers were collected from manufacturers
[13, 14]. Building energy demand calculations are based on Ladybug [11]. Further, to consider
electric requirements, auxiliary pumping power is estimated from the collector surface area [15].

The basic underlying principle for the yield calculation is shown in the following equations:

\[ E_{\text{electrical}} = I \cdot A \cdot \eta_{\text{optical}} \cdot \eta_{PV}(T) \cdot PR \]  
\[ E_{\text{thermal}} = I \cdot A \cdot \eta_{h}(T) \cdot PR \]
Figure 1. Designer’s choices in the early design stage. Exemplified with a semi-transparent cover of grey color, black multicrystalline silicon cells laminated on top of a microchannel thermal absorber in combination with a underfloor/heat pump system.

Where $I$ is the irradiation on the surface, $I^*$ the irradiation not reflected or absorbed by the cover and PV layer, $A$ the active area, $\eta_{\text{optical}}$ the optical efficiency of the cover, $\eta_{\text{PV}}(T)$ the temperature dependent PV efficiency, $\eta_{\text{thermal}}(T)$ the temperature dependent thermal efficiency and $PR$ the respective performance ratios. Heat pump systems are modeled with a COP according to the required temperature lift [16]. Tank storage with solar pre-warming is implemented in Ladybug according to the SAM Model [17]. Cold water temperatures are calculated by ladybug based on the weather data. In the case of ground heat regeneration it was assumed, that all the surplus energy can be absorbed in the borehole.

2.2. Simulation Implementation
As it is an early design stage framework, we implement typical values for the performance calculation. Typical efficiencies for solar cell technologies and ISO parameters for thermal absorbers were collected from literature [18]. Aesthetical properties such as colors and cover types are chosen by the user within the Grasshopper interface. This allows to visualize the examined building or building part simultaneously with the performance simulation as shown in
Figure 2. Energy conversion and losses from insolation to useful electrical and thermal energy.

Figure 3. All the calculations are carried out at an hourly time resolution. For each combination of solar materials an inlet and outlet temperature-dependent efficiency is calculated for the thermal and electrical yield. Based on the choice of building system, monthly and yearly net energy production is calculated. Simulation results with and without storage tanks for domestic hot water (DHW) were compared with PVT monitoring data from the Swiss Federal Office for Energy [18]. Even though several assumptions had to be made, good agreement was found for the cases with storage where deviation of simulated annual thermal yields from measured values was below 10%. Cases without storage showed less agreement where the annual thermal yield was generally overestimated by 30-40% as shown in Figure 4.

Figure 3. Visualization example of building with a selection of solar material choices.

Figure 4. Simulated and measured thermal and electrical yield. While DHW cases are modeled with storage, the ground regeneration cases are modeled without intermediate storage.
3. Case Study
In a single family home case study in eastern Switzerland we analyzed the use of PV cells and thermal absorbers on a pitched roof in combination with a heat pump system to cover space heat and domestic hot water demand. From a design point of view, the investigation of different cover technologies with different colors is interesting because it highly influences the aesthetics and electrical and thermal performance. While the difference between no cover and a semi-transparent cover is rather small, translucent, opaque covers have a large impact on the efficiency. The dependence of efficiency on the cover technology is shown in Figure 5.

![Figure 5. Influence of cover on performance. Temperature dependent efficiency curves for the case study with a laminated microchannel absorber, mono silicon PV configuration.](image)

The thermal absorbers not only reduce PV cell temperature but also preheat the heat pump inlet fluid and thus significantly reduce the electric energy required for the heat pump. In Figure 6, the monthly required electricity input is shown for the domestic hot water production. A pure heat pump system is compared to one, where low temperature PVT is used to preheat the water before the heat pump. Further, annual thermal and electrical yield of the building are shown for spectrally selective and digitally printed glass covers with different colors in Figure 7.

![Figure 6. Monthly required electricity input for DHW production once without a PVT system and once with a PVT system used for DHW preheating.](image)

4. Discussion & Outlook
An early design stage framework was developed that is able to combine aesthetic and building system performance considerations of building integrated solar materials. Thanks to the implementation of typical values, the influence of material choices can be assessed without detailed knowledge on solar technologies. We see this as a great opportunity for architects and designers new to the topic. Although, the framework was compared to measured data, it should
not be used for detailed building energy assessments. For more specific considerations in a later design stage, the implemented, typical values must be replaced with more accurate ones and demand calculations should be reconsidered. The presented framework was successfully applied in a case study. We showed that the use of low-temperature PVT can be beneficial for heat pump systems for the investigated building. Future additions to this framework could be early design stage life cycle assessment (LCA) and life cycle cost estimations leading to more comprehensive feedback on the design choices. We are further planning on integrating the developed framework into an educative building simulation tool currently under development. [19].

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References
[1] Kaufmann U 2018 Schweizerische Statistik der erneuerbaren Energien Tech. rep. Bundesamt für Energie
[2] Hischier I, Hofer J, Gunz L, Nordborg H and Schlüter A 2017 Energy Procedia 122 409–414 ISSN 18766102
[3] Zanetti I, Bonomo P, Frontini F, Saretta E, van den Donker M, Vossen F and Folkerts W 2017 Bipv status report 2017 Tech. rep. SUPSI
[4] Wu J, Zhang X, Shen J, Wu Y, Connelly K, Yang T, Tang L, Xiao M, Wei Y, Jiang K, Chen C, Xu P and Wang H 2017 Renewable and Sustainable Energy Reviews 75 839–854 ISSN 13640321
[5] Becker G, Haselhuhn R, Hemmerle C, Kämpfen B, Krippner R, Kuhn T, Maurer C, Reinberg G and Seltmann T 2017 Building-Integrated Solar Technology 1st ed (Munich) ISBN 978-3-95553-362-5
[6] Joshi S S and Dhole A S 2018 Renewable and Sustainable Energy Reviews 92 848–852 ISSN 13640321
[7] Prieto A, Knack U, Auer T and Klein T 2016 Journal of Facade Design and Engineering Vol 5 No 1 (2017): Special Issue PowerSkin–
[8] Brahim T and Jenni A 2017 Solar Energy 153 540–561 ISSN 0038092X
[9] Munari Probst C 2015 Tec21 24 25–26
[10] Shady A 2011 State of the Art of Existing Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools Tech. rep. Université catholique de Louvain Louvain, Belgium
[11] Roudsari M S, Pak M and Smith A 2013 13th International Conference of the IBPSA 3128–3135
[12] Grasshopper3d Grasshopper - Algorithmic Modeling for Rhino URL https://www.grasshopper3d.com/
[13] SWISSINSO 2018 Kromatix URL https://www.swissinso.com/technology/
[14] Solaxess 2018 White solar technology URL https://www.solaxess.ch/en/photovoltaic-panels-pv/technical-details/
[15] 2010 Planning and installing solar thermal systems (London: Earthscan) ISBN 978-1-84407-760-1
[16] Staffell I, Brett D, Brandon N and Hawkes A 2012 Energy & Environmental Science 5 9291–9306
[17] DiOrio N, Christensen C, Burch J and Dobos A 2014 Technical manual for the sam solar water heating model Tech. rep. NREL
[18] Zennhaeusern D, Bamberger E and Baggenstos A 2017 PVT Wrap-UP Tech. rep. Institut für Solartechnik SPF Bern
[19] Elesawy A, Caranovic S, Zarb J, Jayathissa P and Schlueter A 2018 36th eCAADe Conference 657–666