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Progress in building-integrated solar thermal systems

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ABSTRACT

Solar building envelopes are attracting increasing interest. Building-integrated solar thermal (BIST) systems are one of the subgroups of solar building envelopes. This paper summarizes the most important contributions of recent years and extends them. First, BIST elements are defined and available BIST elements are presented. Then, the general functions which BIST systems can provide are presented and the conflict between the constant U and g values of simple planning software and the variable g and U values of BIST elements is discussed. Measurements to characterize BIST elements are presented as well as a design parameter space in which the current BIST elements are located and which can be used when developing innovative new components. Methods to evaluate and compare BIST technologies are presented. The substantial cost savings which were achieved in three building projects between 2002 and 2009 are discussed. Roles within the building process are presented, as well as the general methods and challenges for economic BIST calculations and one economic calculation as an example. Based on existing building processes, a vision for future BIST building process integration is presented. Simple BIST models, which need no programming, are provided with easy-to-use equations. The challenges of standards and regulations are outlined and future research topics are presented. This paper summarizes important recent contributions to BIST research as a basis for future progress in building-integrated solar thermal systems. Instead of aiming to cover all recent BIST developments, the focus is on BIST research findings which are relevant for cost reduction of BIST components and therefore necessary for the economic success of BIST technology. These are discussed, together with proposals for future research.

1. Introduction

Many papers on building-integrated solar thermal (BIST) systems have been written in the last few decades. This paper aims to present the most important contributions to BIST research, with a special focus on results obtained in the 21st century. It aims to provide an overview of previous progress and the current state of BIST systems to document the starting point for future progress of the BIST approach.

First, building-integrated solar thermal (BIST) systems will be defined in order to clarify the terminology. Then the need for building-integrated solar systems to achieve a cost-effective transformation to a renewable energy system will be outlined. The state of the art will be discussed as well as current challenges and available components.

1.1. Definitions

Most solar thermal collectors on buildings have been installed until now with rear ventilation, which means that there was an air gap between the collector and the rest of the building envelope. This case is sketched in Fig. 1(a). This means that the solar thermal collector is surrounded, to a good approximation, by air of the ambient temperature. Therefore, the efficiency formula of (Cooper and Dunkle, 1980) uses only the ambient temperature and is widely used to calculate the solar thermal performance of such collector installations. When there is no rear ventilation, the case sketched in Fig. 1(b), then the collector performance is also influenced by the temperature of the building interior, which needs to be included in the formulas for accurate predictions. In the case of Fig. 1(b), the collector serves as insulation for the building envelope. Therefore, it can be called a "multifunctional building envelope component" with possible benefits from this synergy. However, many building envelopes serve more than one function. Another important difference between the cases of Fig. 1(a) and (b) is that the energy flux between the collector and the interior of the building should be considered in the case of Fig. 1(b), but can typically be neglected in the case of Fig. 1(a). Energy simulation models of non-ventilated solar thermal installations should thus include the temperature of the interior and the energy flux to the interior.

It would be possible to define "building-integrated" solar thermal as "non-ventilated" solar thermal. However, building

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Nomenclature

Acronym	Explanation
$a_{1,BIST}$	first-order collector efficiency coefficients in the BIST case, W/(m^2 K)
$a_2, a_{2,BAST}, a_{2,BIST}$	second-order collector efficiency coefficients in general, in the BAST case, in the BIST case, W/(m^2 K^2)
A_{BISTS}	BIST area on the building envelope, m^2
BAST	building-added solar thermal
BIPV	building-integrated photovoltaics
BIPVT	building-integrated photovoltaic-thermal
BISS	building-integrated solar systems
BIST	building-integrated solar thermal
c_a	annual costs per square metre of the BIST installation for operation and maintenance, the electricity of the pump and renting the space for the storage tank, €/m^2
c_{dBISTS}	investment cost for the solar thermal function of the building envelope including the necessary technical building plant, €/m^2
$c_{idBISTimage}$	added value of the building due to a better image per square metre, €/m^2
c_{idbs}	investment cost for the technical building plant including the solar thermal function per square metre of BIST area, €/m^2
c_{idsenv}	investment cost per square metre for the additional solar thermal function of the building envelope, €/m^2
c_{irbs}	investment cost for the technical building plant of the reference case per square metre, €/m^2
c_{irenv}	investment cost per square metre of a conventional part of the building envelope, €/m^2
c_{isbs}	investment cost for the technical building plant for the BISTS case per square metre, €/m^2
c_{isenv}	investment cost per square metre of a BISTS part of the building envelope, €/m^2
c_{isubs}	subsidies per square metre collector, €/m^2
c_{rec}	costs per square metre for recycling the BISTS, €/m^2
c_{sCO2}	cost of saved carbon dioxide emissions, €/kg
c_{snrpe}	cost of non-renewable primary energy saved by the BIST system, €/(kW h)
CEN	European Committee for Standardization
CO_2	carbon dioxide
$\Delta T_{stag,BAST}$	temperature difference between the absorber and the ambient air during stagnation in the BAST case, K
DIBt	German Institute for Construction Technology (Deutsches Institut für Bautechnik)
DLL	dynamic-link library
e	average carbon dioxide emission per kW h of non-renewable primary energy which the reference case uses instead of the BIST contributions, kg/(kW h)
$\eta, \eta_{BAST}, \eta_{BIST}$, $\eta_0, \eta_{0,BAST}, \eta_{0,BIST}$	Collector efficiency η = η0 – a1x – a2x2G in general, in the BAST case, in the BIST case, collector efficiency at x = 0, in the BAST case, in the BIST case,
EN	European standard
f_{bl}	fraction of back losses in the BAST case
F'_{BAST}	collector efficiency factor in the BAST case
FMI	functional mock-up interface
FMU	functional mock-up unit
G	solar irradiance, W/m^2
IEA	International Energy Agency
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
LCA	life-cycle analysis
LCC_{wLCOH}	life cycle cost including the levelized cost of heat, €
LCC_{woLCOH}	life cycle cost without income for the solar thermal heat, €
LCOH	levelized cost of heat, €
NPV_{wLCOH}	net present value including the levelized cost of heat, €
q_{dBISTS}	non-renewable primary energy saved by the BIST system in one year for this specific application and per square metre of BIST area, kW h/m^2
$q_{use}, q_{use,BAST}, q_{use,BIST}$	solar thermal collector gain in general, in the BAST case and in the BIST case, W/m^2
Q_{BISTS}	non-renewable primary energy demand in kW h per year for the BISTS case, kW h
Q_r	non-renewable primary energy demand in kW h per year for the reference case, kW h
Q_{sts}	heat which is supplied per year by the solar thermal system to the demand of the building, kW h
.so	shared object
r	discount rate
R_{fa}	thermal resistance between the absorber and the average fluid temperature, m^2 K/W
$R_i, R_{i,BAST}, R_{i,BIST}$	thermal resistance between the absorber and the temperature of the building interior in general, for the BAST case, for the BIST case, m^2 K/W
SHC	Solar Heating and Cooling Programme of the International Energy Agency
T	service life of the system in years
T_a, T_{int}, T_{fav}	Temperature of the ambient air, of the building interior, of the fluid (average), K
TCO_{wLCOH}	total cost of ownership including levelized cost of heat, €
TCO_{woLCOH}	total cost of ownership without income for the solar thermal heat, €

envelopes can offer a large variety of functions, which will be discussed in Section 2.1 in detail. Two examples can illustrate the challenge of finding appropriate definitions. Rear-ventilated collectors can be installed without having a significant effect on the building interior. However, in general, they could be installed to act as acoustic insulation, too. Are they then part of the building envelope and do they need to be included in the definition of building-integrated collectors? Second, if an entire roof or facade is constructed of solar thermal collectors, matching the design of the building, e.g. with its windows, if this is perceived as "the roof" or "the facade" by people looking at the building, but there is rear ventilation, can these collectors really be named "not building-integrated"? Because of the large number of functions of a building envelope, a sharp separation line between "building-integrated" and "not building-integrated" is arbitrary in general. For a detailed analysis of "how building-integrated" an installation is, all the functions need to evaluated and compared to a typical reference case, including aesthetics as a function of the building envelope. For this, the applicable functions would need to be collected, evaluated, e.g. by points between 0 and 10 and presented as a radar chart. As one example to illustrate this, Fig. 2 presents an installation of semi-transparent solar thermal facade collectors, which provide (at least) the functions of solar thermal performance, aesthetics and classic solar control requirements. Fig. 3 presents a radar chart for these functions. The evaluation of the classic solar control requirements was based on Kuhn (2017) and the evaluation of the aesthetics will be discussed together with Table 1 in Section 1.3.

Definitions already exist like the one for building-integrated photovoltaics (BIPV) from (EN 50583, 2016), which defines BIPV as PV modules which provide a function from the European Construction Product Regulation (European Parliament and European Council, 2011) for the function of the building. If a BIPV module is removed, it needs to be replaced by another building product.