



COST Action TU1205 (BISTS)

Building Integration of Solar Thermal Systems

**OVERVIEW OF BISTS STATE OF THE ART, MODELS
AND APPLICATIONS**

© COST Office, 2015.

No permission to reproduce or utilise the contents of this book by any means is necessary, other than in the case of images, diagrams or other material from other copyright holders. In such cases, permission of the copyright holders is required. Neither the COST office nor any person acting on its behalf is responsible for the use which might be made of the information contained in this publication. The COST Office is not responsible for the external websites referred in this publication.

This book may be cited as:

COST Action TU1205 – Overview of BISTS state of the art, models and applications

ISBN: 978-9963-697-16-8

Publication date: March 2015

Cost Action TU1205 – Basic Info

Chair of the Action: Soteris Kalogirou, Cyprus

Vice-Chair of the Action: Mervyn Smyth, UK

Rapporteur: Luis Braganca, Portugal

Working Group 1 Leader: Werner Platzer, Germany

Working Group 1 Deputy Leader: Aleksandra Krstic-Furundzic, Serbia

Working Group 2 Leader: Daniel Chemisana, Spain

Working Group 2 Deputy Leader: Alberto Coronas, Spain

Working Group 3 Leader: Aggelos Zacharopoulos, UK

Working Group 3 Deputy Leader: Manolis Souliotis, Greece

Working Group 4 Leader: Brian Norton, Ireland

Working Group 4 Deputy Leader: David Kennedy, Ireland

Management Committee

Gerald Leindecker, Austria

Jan Belis, Belgium

Aleksandar Georgiev, Bulgaria

George Xydis, Denmark

Christian Christofari, France

Gilles Notton, France

Yiannis Tripanagnostopoulos, Greece

Guedi Capeluto, Israel

Galit Shiff, Israel

Adolfo Palombo, Italy

Roberto Fedrizzi, Italy

Rosita Norvaisiene, Lithuania

Simon Paul Borg, Malta

Vincent Buhagiar, Malta

René Wansdronk, Netherlands

Dorota Chwieduk, Poland

Mariusz Fitowski, Poland

Joao Ramos, Portugal

Manuela Almeida, Portugal

Milorad Bojic, Serbia

Muhsin Kilic, Turkey

Andy Ford, UK

Working Group Participants

Rumen Popov, Bulgaria

Rafaela Agathokleous, Cyprus

Constantinos Christofi, Cyprus

Georgios Florides, Cyprus

Charalambos Tsioutis, Cyprus

Andreas Savvides, Cyprus

Constantinos Vasiliades, Cyprus

Christoph Cappel, Germany

Christoph Maurer, Germany

Christophis Koroneos, Greece

Aritra Ghosh, Ireland

Donal Keys, Ireland

Tim Oleary, Ireland

Sarah McCormack, Ireland

Mick Mckeever, Ireland
 Lacour Ayompe, Ireland
 Carlos Ochoa, Israel
 Annamaria Buonomano, Italy
 Tamasauskas Rokas, Lithuania
 Artur Rusowicz, Poland
 Laura Aelenei, Portugal
 Ricardo Mateus, Portugal
 Sandra Montaro da Silva, Portugal
 Eliseu Ribeiro, Portugal
 Ivan Miletic, Serbia
 Danijela Nikolic, Serbia
 Jasna Radulovic, Serbia
 Blagojebic Mirko, Serbia
 Kosic Tatjana, Serbia
 Luisa F. Cabeza, Spain
 Iñigo Iparraguirre, Spain
 Chrysovalantou Lamnatou, Spain
 Stefan Remke, Spain
 Lopez Lorenzo Jose, Spain
 Jayanta Deb Mondol, UK
 Trevor Hyde, UK

Non-COST countries participation

Andreas Athienitis, Canada
 James Russell, USA

General Table of Contents

PART I

1	Introduction	4
1.1	Abbreviations and Nomenclature:.....	5
2	BISTS Classification and Taxonomy	7
2.1	Classification	7
2.2	BISTS applications	8
2.2.1	Space heating	8
2.2.2	Air heating and ventilation.....	8
2.2.3	Water heating	8
2.2.4	Cooling and ventilation	8
2.3	Taxonomy.....	10
3	Solar thermal systems for building applications	12
3.1	Water heating	12
3.1.1	Fluid collectors	12
3.1.2	Storage	14
3.1.3	System types	14
3.2	Space Heating	16
3.2.1	Solar combi systems.....	17
3.2.2	Air collector systems	17
3.2.3	Solar heating with seasonal storage systems	17
3.2.4	Passive solar systems	17
3.3	Ventilation and cooling.....	19
3.4	Combined thermal-electricity generation - PVT	20
3.4.1	Integration element	21
3.4.2	Type.....	21
3.4.3	Application	22
3.4.4	Approach.....	22
3.5	Linked auxiliary systems.....	23
4	Architectural integration.....	27

4.1	Introduction	27
4.2	Architectural Integration of Solar Thermal Systems.....	27
4.2.1	Placement possibilities.....	29
4.2.2	Function possibilities.....	33
4.2.3	Aesthetical possibilities.....	34
4.2.4	Constructional mounting options	38
5	Building Physics	43
5.1	Weather Proofing.....	43
5.2	Thermal insulation	43
5.2.1	Mineral wool	44
5.2.2	Rigid polyurethane foam (PUR/PIR).....	44
5.2.3	Transparent/Translucent Insulation.....	44
5.2.4	Insulation Thickness	46
5.3	Vapour transport.....	46
5.4	Noise attenuation	47
5.5	Daylighting and solar protection.....	48
6	Environmental performance and sustainability	49
6.1	Environmental benefits of using BISTS	49
6.2	Environmental sustainability	49
6.2.1	Life-cycle inventory and life-cycle impact assessment	49
6.2.2	Critical issues related with the LCA of the solar thermal systems	50
6.3	Durability and payback period for BISTS.....	51
6.4	Health and fire safety issues	51
7	Standardisation, Testing and Performance Evaluation	52
8	Bibliography	53
 PART II		
1	Introduction	66
2	Studies of Energetic Simulation (emphasis: building).....	66
2.1	BI, Skin Façade	66
2.2	BI, Solar Chimney	68
2.3	BI, Solar Shades.....	69

2.4	BA, Solar Cooling/heating	69
2.5	General studies	70
3	Studies of Energetic Simulation (emphasis: system)	71
3.1	BI, Skin Façade	71
3.2	BI, Solar Chimney	72
3.3	BI, Trombe Wall.....	73
3.4	BI, PVT	73
3.5	BI, PV	76
3.6	BI, CPV.....	80
3.7	BA, Solar Cooling	81
3.8	General studies	82
4	Studies of Energetic Simulation (emphasis: building/system)	86
4.1	BI, Skin Façade	86
4.2	BI, Trombe Wall.....	87
4.3	BI, PVT	87
4.4	BI, PV	87
4.5	General Studies.....	89
5	Studies of Thermal Simulation (emphasis: building)	93
5.1	BI, Skin Façade	93
5.2	General studies	94
6	Studies of Thermal Simulation (emphasis: system)	95
6.1	BI, Solar Thermal Collectors.....	95
6.2	BI, Skin Façades.....	96
6.3	BI, Pipes.....	101
6.4	BI, Solar Chimney	103
6.5	BI, Trombe Wall.....	103
6.6	BI, PVT	105
6.7	BI, PV	108
6.8	BI, Several systems.....	111
6.9	BA, Several systems	113
6.10	General studies	115
7	Studies about Thermal Simulation (emphasis: building/system)	117

7.1	BI, Solar Thermal	117
7.2	BI, Trombe Wall.....	118
7.3	BI, PVT	118
7.4	BI, PV	119
7.5	BI, Several systems.....	119
7.6	BA, Space heating/water heating	120
7.7	General studies	121
8	Studies of Energetic/Thermal Simulation (emphasis: building)	122
9	Studies of Energetic/Thermal Simulation (emphasis: system)	122
9.1	BI, Solar Thermal	122
9.2	BI, Skin Façades.....	122
9.3	BI, PVT	123
9.4	BI, PV	127
9.5	BI, PCM for passive solar walls.....	128
9.6	BA, PVT.....	128
9.7	General studies	130
10	Studies of Energetic/Thermal Simulation (emphasis: building/system)	134
10.1	BI, Solar Collectors	134
10.2	BI, Skin Façade	134
10.3	BI, PVT	135
10.4	BI, PV	136
10.5	BA, Several systems	137
11	Studies of Optical Simulation (emphasis: building)	138
12	Studies of Optical Simulation (emphasis: system).....	138
12.1	BI, Several systems.....	138
12.2	BA, Low-concentration evacuated-tube solar collector	140
13	Studies of Optical/Thermal Simulation (emphasis: building/ system)	141
13.1	BI, Several systems.....	141
14	Studies about other types of simulation.....	143
14.1	Exergy analysis (emphasis: system)	143
14.2	Energetic/lighting simulation (emphasis: building/system)	143
14.3	Exergy analysis (emphasis: building/system)	143

14.4	Sunlight simulation (emphasis: system)	144
15	Conclusions	145

PART III

1	General Background	151
2	Water Heating BISTS.....	153
2.1	Introduction	153
2.2	Review of Water heating BISTS.....	153
2.2.1	Solar Thermal Façade by WAF.....	153
2.2.2	Flat plate collector by Energie Solaire.....	155
2.2.3	Soltech Sigma – Roof BISTS	157
2.2.4	Universität Stuttgart, IBK 2 – Façade system	158
2.2.5	Roof and facade BISTS – Citrin Solar	159
2.2.6	Residential Building – Belgrade.....	160
2.2.7	Residential Building – China	161
2.2.8	Residential Building – Holland.....	162
2.2.9	School building – New Haven, USA	162
2.2.10	Residential building – Florida, USA	163
2.2.11	Residential Building – Ireland.....	164
2.2.12	Office Building – Switzerland	165
2.2.13	Solar fence – JET Solar.....	165
2.2.14	Residential building – China	166
2.2.15	Solar Hybrid Shades in residential building – Hollywood, USA.....	167
2.2.16	Non-rectangular solar collectors for roof or wall integration.....	168
3	Air Heating BISTS.....	171
3.1	Introduction	171
3.2	SolarWall systems	171
3.3	The Kingspan Integrated Sol-Air Collector	172
3.4	Solar Cooling Systems	173
3.5	The SunMate™ Solar Air Heating Collector.....	174
3.6	Air BISTS projects	175
3.6.1	Commercial Building – Doncaster, UK.....	175

3.6.2	Residential Building – Japan	176
3.6.3	Industrial Building – Montreal, Canada	177
3.6.4	Research facilities – Colorado, USA	177
3.6.5	Avon Theatre – Ontario, Canada	178
3.6.6	Public School – Canada	179
3.6.7	Public Building – Erlangen, Germany	179
3.6.8	Industrial Building – Colorado, USA	180
3.6.9	Residential Building – Manitoba	181
3.6.10	Airport Building – Canada	182
3.6.11	Commercial Building – Leicestershire	183
3.6.12	Public Building – South Dakota, USA	183
3.6.13	Public Building – Minnesota, USA	184
3.6.14	Industrial Building – France	184
3.6.15	Commercial Building – Aurora, Colorado, USA	184
4	BISTS for Heating-Cooling-Shading (H-C-S)	188
4.1	Intro on BISTS for H-C-S	188
4.2	Review of H-C-S BISTS	188
5	PVT BISTS	199
5.1	Introduction on PVT BISTS	199
5.2	Review of PVT BISTS	200
5.2.1	Hybrid solar system integrated on roof	200
5.2.2	Building-integrated multifunctional PV/T solar window	202
5.2.3	Hybrid thermal insulating PV façade element	204
5.2.4	Office Building – Lisbon, Portugal	204
5.2.5	Institutional Building – Beijing, China	206
6	Combined BISTS for Heating Cooling and Shading	208
6.1	Review of Combined BISTS	208
6.1.1	Residential Building – Graz, Austria	208
6.1.2	Commercial Building – Lisbon, Portugal	209
6.1.3	Commercial Building – Satteins, Austria	209
6.1.4	Office Building – Ljubljana, Slovenia	210
6.1.5	Residential Building – Paris, France	211
6.1.6	Residential Building – Warsaw, Poland	212

6.1.7	Residential Building – Ajaccio, France	214
6.1.8	Asphalt solar collector incorporating carbon nano-tubes for combine HW and space heating	216
7	BISTS linked to other systems	218
7.1	Introduction on BISTS linked to other systems	218
7.2	Review of BISTS linked to other systems	218
7.2.1	BISTS with heat pumps	218
7.2.2	BISTS with Thermally Activated Chillers (TAC)	221
7.2.3	Other linked BISTS case studies	223
8	Thermal Energy Storage (TES) for BISTS	228
8.1	Introduction	228
8.1.1	Passive systems – Solar Wall	229
8.1.2	Active systems	233
8.1.3	External solar façade	235
8.1.4	Water tanks	236
8.1.5	Examples of single dwelling Seasonal TES (STES)	237

Wall, M.; Munari Probst, M. C.; Roecker, Ch.; Dubois, M.-C.; Horvat, M.; Jørgensen, O. B.; Kappel, K. (2012): Achieving Solar Energy in Architecture-IEA SHC Task 41. In *Energy Procedia* 30, pp. 1250–1260. DOI: 10.1016/j.egypro.2012.11.138.

Yang, H. X.; Marshall, R. H.; Brinkworth, B. J. (1996): Validated simulation for thermal regulation of photovoltaic structures. In IEEE Electron Devices Society (Ed.): Proceedings of IEEE 25th Photovoltaic Specialists Conference: Institute of Electrical & Electronics Engineers (IEEE).

Zakaria, M. A.; Hawlader, M.N.A. (2013): A review on solar assisted heat pump systems in Singapore. In *Renewable and Sustainable Energy Reviews* 26 286–293.

PART II:

Review on modelling and simulation of building-integrated solar thermal systems

Contributors:

Chr. Lamnatou, Spain

J. Mondol, UK

A. Ghosh,

D. Nikolic, Serbia

M. Bojic, Serbia

S. Kalogirou, Cyprus

D. Chemisana, Spain

Contents:

1 Introduction	66
2 Studies of Energetic Simulation (emphasis: building)	66
2.1 BI, Skin Façade	66
2.2 BI, Solar Chimney	68
2.3 BI, Solar Shades	69
2.4 BA, Solar Cooling/heating	69
2.5 General studies	70
3 Studies of Energetic Simulation (emphasis: system)	71
3.1 BI, Skin Façade	71
3.2 BI, Solar Chimney	72
3.3 BI, Trombe Wall	73
3.4 BI, PVT	73
3.5 BI, PV	76
3.6 BI, CPV	80
3.7 BA, Solar Cooling	81
3.8 General studies	82
4 Studies of Energetic Simulation (emphasis: building/system)	86
4.1 BI, Skin Façade	86
4.2 BI, Trombe Wall	87
4.3 BI, PVT	87
4.4 BI, PV	87
4.5 General Studies	89
5 Studies of Thermal Simulation (emphasis: building)	93
5.1 BI, Skin Façade	93
5.2 General studies	94
6 Studies of Thermal Simulation (emphasis: system)	95
6.1 BI, Solar Thermal Collectors	95
6.2 BI, Skin Façades	96
6.3 BI, Pipes	101
6.4 BI, Solar Chimney	103
6.5 BI, Trombe Wall	103
6.6 BI, PVT	105

6.7 BI, PV	108
6.8 BI, Several systems	111
6.9 BA, Several systems	113
6.10 General studies	115
7 Studies about Thermal Simulation (emphasis: building/system)	117
7.1 BI, Solar Thermal	117
7.2 BI, Trombe Wall	118
7.3 BI, PVT	118
7.4 BI, PV	119
7.5 BI, Several systems	119
7.6 BA, Space heating/water heating	120
7.7 General studies	121
8 Studies of Energetic/Thermal Simulation (emphasis: building)	122
9 Studies of Energetic/Thermal Simulation (emphasis: system)	122
9.1 BI, Solar Thermal	122
9.2 BI, Skin Façades	122
9.3 BI, PVT	123
9.4 BI, PV	127
9.5 BI, PCM for passive solar walls	128
9.6 BA, PVT	128
9.7 General studies	130
10 Studies of Energetic/Thermal Simulation (emphasis: building/system)	134
10.1 BI, Solar Collectors	134
10.2 BI, Skin Façade	134
10.3 BI, PVT	135
10.4 BI, PV	136
10.5 BA, Several systems	137
11 Studies of Optical Simulation (emphasis: building)	138
12 Studies of Optical Simulation (emphasis: system)	138
12.1 BI, Several systems	138
12.2 BA, Low-concentration evacuated-tube solar collector	140
13 Studies of Optical/Thermal Simulation (emphasis: building/ system)	141
13.1 BI, Several systems	141

14 Studies about other types of simulation.....	143
14.1 Exergy analysis (emphasis: system)	143
14.2 Energetic/lighting simulation (emphasis: building/system)	143
14.3 Exergy analysis (emphasis: building/system)	143
14.4 Sunlight simulation (emphasis: system)	144
15 Conclusions	145

Abstract

In the present study, a literature review focusing on Building-Integrated (BI) solar systems is conducted. The review refers to systems which produce thermal, electrical or both thermal/electrical energy. Emphasis is given on the BI solar thermal systems while the solar electrical and solar thermal/electrical systems are also included in order to have a more complete picture of the current literature. The results of the review show that in the literature the greatest part of the models are thermal and/or energetic simulations of BI Photovoltaic-Thermal (PVT) (or BI PV) and skin façades. Thus, there is a need for thermal and/or energetic modelling works about BI solar thermal systems, especially for models which give emphasis to the building (since the greatest part of the investigations give emphasis to the system itself). On the other hand, the optical-models are very few and certainly, more optical-modelling studies are needed since they could provide useful information for the behaviour of the BI solar thermal systems from the optical point of view.

1 Introduction

The building sector is an energy-demand sector and the use of renewable energy technologies could provide considerable benefits. Among renewable energy systems, solar energy technologies are promising especially for countries with high solar radiation. In the frame of this concept, several solar systems have been already tested and applied in buildings. Nevertheless, there is a potential for further development and this could be achieved by adopting solar systems which are integrated into the building envelope. This specific type of systems in the literature is known as Building Integrated (BI) solar systems. BI configurations are a new tendency in the building sector and they provide several advantages given the fact that they replace a part of the building (façade, roof, etc.). Among the BI systems, solar thermal are a recent development; thereby, there is a potential for further development and this could be achieved by investigating this type of installations e.g. by means of modelling.

The present work provides an overview in terms of modelling works about BI solar thermal systems. References from the literature about BI solar thermal configurations along with other systems (which produce electrical and thermal or only electrical energy) are cited, separated into groups, based on the type of the model (thermal, energetic simulation, etc.) and based on the specific characteristics of each system (skin façade, solar thermal collector, Photovoltaic-Thermal (PVT), etc.). In this way, a complete picture of the studies available in literature is provided while the gaps in literature are identified. It should be noted that few works about systems which are Building-Added (BA) (and not real BI) are also cited for certain cases when the system/or the model is of great interest. Moreover, in some categories, some general studies (e.g. about modelling of building components) are also cited.

In the literature there are no review works about the modelling studies in the field of BI solar thermal systems and thus, the present work is an innovative study. The results of the present investigation reveal which types of models/systems are available in the current literature and which types need further development. In this way, the present work provides useful information for example for academic/research purposes while models/systems which would be interesting for future investigation are also proposed.

2 Studies of Energetic Simulation (emphasis: building)

2.1 BI, Skin Façade

1. Ciampi M., Leccese F. and Tuoni G., Ventilated facades energy performance in summer cooling of buildings, 2003: Solar Energy 75(6), 491–502.

<http://dx.doi.org/10.1016/j.solener.2003.09.010>

Contexts	Outcomes
An analytical, simple method for design applications → evaluation of electrical energy savings in buildings	In all cases, the energy saving increases as the air duct width increases, The positioning of the insulating