Sustainability in Energy and Buildings: Research Advances ISSN 2054-3743
Vol. 10. Sustainability in Energy and Buildings (SEB-22) Short Papers pp.22-32 : seb22s-005

Critical issues of cooling BIPVT and its integration with low-temperature heating

George Aspetakis[1], Qian Wang[1,2]

[1] Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Teknikringen 78, Stockholm, Sweden
[2] Uponor AB, Hackstavägen 1, Västerås, 721 32, Sweden

The efficiency of photovoltaic (PV) modules is inversely correlated with their operating temperatures. Extensive research has shown that cooling PV systems to maintain a stable and low surface temperature enhances PV efficiency, power generation and prolongs the life span of the modules by limiting the degradation caused by thermal fatigue. The extracted heat can be potentially recovered by the rest part of building energy service systems. To implement this, Building Integrated PV-Thermal systems can be integrated with low temperature heating systems, such as existing heating and ventilation installations running on low-temperature level or integrated with heat pumps. BIPVT technology has however not disseminated successfully and this aspect is insufficiently investigated in current literature. The purpose of this study is to highlight vital performance and integration characteristics of BIPVT as well as roadblocks to their widespread adoption.

Nomenclature

BIPVT	Building Integrated Photovoltaic Thermal
COP	Coefficient of Performance
EPBT	Energy Payback Time
EU	European Union
GIS	Geographic Information System
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilation, and Air Conditioning
nZEB	nearly Zero Energy Building
PCM	Phase Change Materials
PVT	Photovoltaic Thermal
PV	Photovoltaic
RES	Renewable Energy Source

1. Introduction

Photovoltaic technology generates power from the full spectrum of the incident solar radiation. However only a part, up to 20%, is typically converted into electrical power. The rest is dissipated as thermal energy or transmitted back as radiation. Such heat in turn, not only have been conveniently treated as a waste heat source, but also inevitably increases the temperature of the PV module which causes a linear drop in efficiency of up to 0.5 %/°C [[1, 2, 3]. This is due to the electrical resistance losses of the cells [4], with such

Presented at KES-SEB-2022 14-16 September 2022

efficiency drops largely depending on the type and material utilized [4, 5]. Additionally, increased operating temperature of degrades the photovoltaic cells, which further leads to a diminished lifecycle [6]. Therefore, cooling PV panels is essential for achieving higher efficiency as well as maximizing the lifespan. Extensive research has carried out in the past decades to develop and test different cooling methods in this regard, such as [7, 8], and more specifically on Photovoltaic Thermal (PVT) as a combination [9, 10, 11, 12]. In a typical PVT system, both thermal and electrical energy is generated simultaneously. This is done by coupling PV panels with a heat extraction unit that utilizes the flow of a coolant fluid. Emphasis has been given particularly to the integration of such systems to buildings, given its nature of being generated and used onsite as a decentralized renewable. Building Integrated Photovoltaic Thermal (BIPVT) systems are not stand alone, or installed on/to the building envelope per se, such as roofs, but instead constitute or replace one or more of buildings actual elements. The BIPVT concept has been investigated extensively in recent years [13, 14, 15, 16, 17, 18]. However, a set of technical challenges exist, and have not led to its wide acceptance or commercialization. Most of the reported studies are limited to theoretical investigations on a case-to-case basis. Additionally, the available literatures have largely focused on the performance aspect, neglecting other traits that are also crucial for the adoptions of BIPVT technology. More specifically, attributes such as the practicality and heating system integration are insufficiently investigated. There is a lack of a thorough compilation listing critical issues and the next-step road map for system-wide solutions. Given the above motivation, the primary aim of this study is to outline the critical challenges faced by BIPVTs regarding performance and their integration with next generation heating systems of buildings, such as low temperature heating.

2. Key physical factors for enhanced performance

As mentioned, the bulk of BIPVT performance related research has been concentrated on the enhancement of heat transfer through various techniques. Such techniques involve addition of fins, thin sheets, porous media and Phase Change Materials (PCM) to the cooling duct or glazing above the modules. Asefi et al. [19] discussed various thermal management methods and selected a list of parameters that affect the performance of BIPV and BIPVT systems. A modified selection of these along with some additions are presented in Table 1, along with respective references. The need for the creation of control strategies under different conditions was highlighted.

Table 1: Modified list of BIPVT performance parameters, remarks and respective references.

Parameter	Remarks	Impact	Reference
1. Cooling Channel Inlet Temperature	Lowest possible temperatures preferred	Low	[7][8][9][10][22][25][26][27] [28][30]
2. Packing Factor	Higher factor favored in unglazed systems	Medium	[7][9][10][20][21][22][23][28]
3. Cooling Channel Length	Affects thermal efficiency of PVT	High	[7][10][21][23][28]
4. Cooling Channel Depth	Minimal depth is favored	High	[7][8][9][22][28][34]
5. Thermal Resistance	Effect on temperature field	Low	[8][9][26][28][33]
6. Ambient Temperature	Decreases efficiency, not enough tests for high ambient temps.	High	[1][2][3][5][6][9][10][21][23] [25][26][27][28]
7. Mass Flow Rate of Cooling Medium	Requires continuous adjustment	High	[9][10][21][22][24][25][26][27] [28][30][33]
8. Wind Effect	Can potentially increase electrical performance due to convection	High	[1][5][6][9][10][20][22][23][24][28][29]
9. Tilt Angle	Vertical or horizontal in certain cases	Low	[1][8][10][26][28]
10. Air Gap Ventilation	Favorable for BIPV	Low	[9][15][23]
11. Fins/Baffles in cooling channel	Increase efficiency but also pressure drop	High	[8][9][10][22-26][28]
12. PV Transmissivity	High transmissivity preferred	Low	[2][3][21][28]
13. PV Layer Arrangement	Minimal thickness desired	Low	[2][3][5][10][23][24][27][28]
14. Materials	High conductivity favored	Low	[2][9][23][32]
15. Building Shading And Color of Modules	Affect performance yet wider application more significant	Medium	[2][6][9][35][40]
16. Friction Factor Of Channel	Increases pressure drop but thermal efficiency as well	Medium	[26]
17. Dust Deposit	Decreases efficiency, removal method must be considered	Medium	[10][23]
18. Irradiation	Increases total generation but decreases efficiency due to temperature rise	High	[10][24][25][27][29]

More specifically for BIPVT, Chow et al. [20] identified the main hindrance in evaluating BIPVT performance is the inability of correctly predicting its thermal behavior. Even when temperature and sun shading data are accessible, one has to take into consideration entrance effects, wind loads and the laminar or turbulent flow of the working fluid. Thus, the calculation of heat transfer coefficients becomes complicated. Moreover, for the transparent BIPVT system calculation, an additional heating mechanism is needed. Agrawal and Tiwari [21] examined the interconnectivity of BIPVT panels and the factors that influence that aspect. For systems connected in parallel, a constant mass flowrate is favored, whereas for systems connected in series, a constant velocity is preferred. For the cooling configuration design, a number of studies focused on the addition of fins and baffles. Such configurations have been mostly conducted through both active and passive design, mostly on air-cooled solutions, to increase heat transfer rate between backplate and cooling medium [22–25]. Shrivastava et al. [26] performed a numerical and experimental study of energy and exergy efficiency for different finned duct layouts. The findings indicated a substantial enhancement in exergy efficiency, from 20% to 28 %, as well as in thermal efficiency from 12 to 18 % of certain designs. In addition, the friction fraction profile was analyzed. No information was provided however regarding the pressure drop caused by elevated friction levels, which are detected in all proposed designs. It should be noted that measuring pressure drop and in extent the auxiliary energy usage, such as fans, is critical for the design of the efficient and economically viable BIPVT systems. A porous channel for PVT cooling was devised by Zhang et al. [27]for optimized flow of PVT [27]. A downwards directed flow was shown to provide a lower surface temperature than an upwards directed flow. The geometry of the cooling channel proved to be of significant importance. A dense arrangement of holes near the outlet and a downwards flow are optimal. The authors recommended further studies for the refinement of its parameters. Similarly, Riffat and Cuce [28] concluded that further research into the optimization of the cooling channel geometry of PVT is needed as well as the minimization of heat resistance between the absorber surface and the heating medium.

3. Key integration factors for overall system efficiency

Although the emphasis of BIPVT studies has been primarily given to the heat transfer aspect, a severe lack of investigations into its application or system wide solutions is detected. This ranges from limited instances exploring the integration of such systems into the building envelope, to the synergy with low temperature heating methods. Chen et al. [29] designed, modeled and monitored the performance of a BIPVT system application in a nearly Zero Energy Building (nZEB) in cold climatic conditions with thermal energy storage. The authors underlined the process of prefabrication, in contrast to on-site assembly. This process ensures air tightness, thermal insulation and proper pressure drop balancing of the overall heating configuration, through which uniform flow and heat collection can be obtained. Additionally, it provides the ability to perform the construction in winter, when on site work is not feasible. Kamel et al. [30] designed a full-scale heating system featuring BIPVT collectors combined with air source heat pump (HP) and thermal storage in cold climate. A decisive challenge was to optimally design the control system for the combined operation of the heat pump and thermal storage that should operate optimally in different weather conditions. The authors faced difficulty with the design of the ducts that connect the BIPVT with the HP. A louver box with dampers was suggested, to direct the air flow to different applications depending on the control strategy implemented. This however, requires the use of a custom HP design, thus limiting the scope of the study. Bambara [31] studied the performance of BIPVT utilizing Unglazed Transpired Collectors, in Montreal, Canada. The author noted that optimum orientation and close proximity to the HVAC system are essential for an effective design. Specifically, the length of ducting between the collectors and the mechanical room must be minimized in order to achieve a cost-effective system. In the study, preheated air was directly fed to the fresh air supply of the buildings ventilation configuration, covering up to 33% of the ventilation heat demand. Ma et al. [32] investigated three different BIPVT integration strategies utilizing numerical models. The options consisted of systems either providing heated air to the outdoor mixer intended for space heating by directly sending it to designated rooms, to the heat recovery ventilator (HRV) to preheat outdoor air or to an air-source HP. Direct space heating could not be achieved due to the low temperature levels of the introduced air flow. Frost turned out to be a major issue of the two latter scenarios, where a great amount of energy is required for defrosting, thereby severely limiting energy savings. On the other hand, distribution losses and disparities in local demand control of central systems exhibit severe impact on the efficiency of the overall buildings energy services. A decentralized approach was explored by Bigaila and Athienitis [33], where a BIPVT façade panel encapsulates an integrated micro HP and short term (approx.4–6h) PCM storage system. The results generated and the prefabricated materials approach utilized, led to reduced construction time, which indicates that such systems constitute an attractive solution for retrofitting older buildings. The authors noted that a great deal of detail in planning is necessary and feasibility is not guaranteed in all construction sites. Alternatively, the process described above can be inverted. In this case, the energy system of the building can be utilized to cool BIPV modules. A configuration was proposed by Salameh et al. [34] where exhaust air from the HVAC system is directed to BIPV panels instead of the other way around, reducing its operating temperature. This in turn improved their electrical generation. It was highlighted that minimal air duct height increased electrical efficiency. Supplementary suggestions were made, which included adding a second channel for removing dust accumulation on the frontal surface of the collector, and the addition of a vortex generator to induce turbulent flow. A summary of integration challenges and their corresponding low-temperature heating systems are presented in Table 2. On large scale, a holistic study investigated the application of façade mounted BIPVTs with Air source Heat Pumps for 5 different cities [35]. It was determined that in the conceptual design phase, several elements must be taken into consideration, including geographic location, local climatic conditions, fossil fuel profile of the district, building regulations, function and morphology of the site. Both electrical and thermal storage constitute a critical part of BIPVT systems due to the stochastic and intermittent nature of solar energy. Lamnatou et al. [36] compiled a review of the various storage methods combined with BIPVT. For storing electrical energy batteries are in widespread use and factors regarding battery lifespan, degradation, safety risks, capacity, recycling, toxicity and enviroeconomic elements were discussed. The incorporation of PCM for thermal storage is gaining traction steadily. The review presented various related issues including thermal performance, operation for long hot days, flammability, toxicity, corrosion and leakage. The elevated cost and difficulty in their disposal are highlighted. The simpler form of water storage tanks is analyzed from technical, socioeconomic and safety viewpoints as well as the environmental impact of its constituent components. It was indicated that water storage tanks exhibit small environmental footprint, more integration possibilities and an extended lifetime (up to 30 years).

Table 2: Remarks regarding the integration of BIPVT with energy systems

Integration methods	**Low temperature heating system**	**Key challenges**
BIPVT with heat pumps	Output of BIPVT is directly supplied to HPs or through a heat exchanger to increase the Coefficient of Performance	Difference of BIPVT output and required HP source input (evaporator)
BIPVT with HRV	Heat supply to the heat exchanger of the HRV for defrosting	Limited energy savings
BIPVT directly to HVAC	BIPVTs preheat fresh air intake or directly supply spaces with heated air or use the exhaust air for cooling modules	Distance between BIPVTs and mechanical room or space heating units.
BIPVT with Thermal Storage	BIPVTs charge sensible heat storage like Hot water tanks and/or latent storage like PCM	Thermal Performance, Leakage, Degradation

4. Lack of Standards, Testing and System wide practicalities

BIPVT designs should be compliant to industry standards, in order to gain wide access to the market. Architects and contractors need to be equipped with standard engineering guideline for the efficient introduction of such systems in their projects. Standard measurements and procedures need to be investigated, such as, health and safety, mounting fixture failure, noise, weather effects, cables and electrical wiring, waterproofing. Meeting such criteria plays a vital role for the penetration of the next generation of BIPVT to the market yet current literature does not address these implementations comprehensively. Rounis et al. [37] provided a review of air-based BIPVT systems. The study highlighted the significant variation in the testing procedure of performance studies and indicated the existence of research gaps regarding standardization and comparison of developed designs. A framework for standardized testing was presented with the intent of starting a discussion based on this concept. Brahim and Jemni [38] concluded that insufficient data concerning the performance, reliability and lifespan for system-wide applications. Field tests and long-term monitoring were suggested for the development of standardized solutions and the increase of public confidence. Al-Waeli et al. [39] predicted that PVT technology can readily be developed commercially given that an international standard is created, which would provide minimum requirements regarding the design, testing, monitoring and installation of such systems. This can lead to established manufacturing processes which in combination with public acceptance induced by awareness campaigns, should establish a stable demand in the market. Studies have focused on the design aspect as well. Kuhn et al. [40] specifically investigated the approach of either highlighting or camouflaging BIPV into the envelope and its surroundings through the application of diverse color schemes and patterns. Additionally, an analysis of the market and regulations was showcased. The authors determined that a growing amount of exemplary demonstration sites would increase awareness and contribute to installation know-how. European, Italian and Swiss frameworks regarding BIPV installation in protected areas were studied by Lucchi et al. [41] BIPV technology and generally Renewable Energy Source (RES) generation in the residential sector is regarded of outmost importance for achieving goals set by European directives for the two countries. Regulatory bodies have yet to fully consider implementing BIPV technology into their planning process due to its limited dissemination. It was suggested that by outlining guidelines for protected areas, quantifying the solar aptitude of investigated buildings and creating legislatively applicable criteria, widespread adoption in such areas could be attained. Figure 1 illustrates guidelines for the adoption of BIPVT technology.

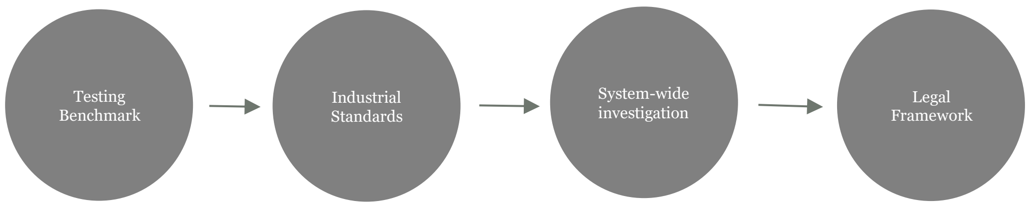

Figure 1: Milestones for BIPVT penetration.

5. Conclusion

A literature study was performed to showcase the factors hindering the commercialization and widespread implementation of BIPVT technologies. Researchers attested its potential through numerous investigations and denote the next steps towards its breakthrough into mainstream application. Multiple parameters affecting device performance have been discussed with the intent of improving efficiency. Practical issues such as the installation into the building envelope and the integration with the rest energy services are studied. The gap in standards development and absence of a unified approach in testing, measuring and reporting are emphasized. Overcoming such complications will lead to the wider application of BIPVT technology.

Acknowledgement
This work is financially supported by Swedish Energy Agency, with project No. 52488-1 and No. 51544-1. This work is also partly financed by EU H2020 programme under Grant Agreement No. 101036656. Special thanks to Mr.

Stefan Mastonstråle from Maston AB for providing valuable industry insights and user information.

6. References

1. Kaldellis, J.K. Kapsali, M. Kavadias, K.A. Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. Renewable Energy. Vol 66, pp. 612–624 (2014)
2. Park, K.E. Kang, G.H. Kim, H.I. Yu, G.J. Kim, J.T. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy. Vol 35, pp. 2681–2687 (2010)
3. Skoplaki, E. Palyvos, J.A. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy. Vol 83, pp. 614–624 (2009)
4. Lorenzo, E. Araujo, G. Cuevas, A. Egido, M. Minano, J. Zilles, R. Solar Electricity: Engineering of Photovoltaic Systems. pp. 316 (1994)
5. Elibol, E. Özmen, Ö.T. Tutkun, N. Köysal, O. Outdoor performance analysis of different PV panel types. Renewable and Sustainable Energy Reviews. Vol 67, pp. 651–661 (2017)
6. Dwivedi, P. Sudhakar, K. Soni, A. Solomin, E. Kirpichnikova, I. Advanced cooling techniques of P.V. modules: A state of art. Case Studies in Thermal Engineering. Vol 21, (2020)
7. Siecker, J. Kusakana, K. Numbi, B.P. A review of solar photovoltaic systems cooling technologies. Renewable and Sustainable Energy Reviews. Vol 79, pp. 192–203 (2017)
8. Maleki, A. Haghighi, A. el Haj Assad, M. Mahariq, I. Alhuyi Nazari, M. A review on the approaches employed for cooling PV cells., (2020)
9. Chandrasekar, M. Senthilkumar, T. Five decades of evolution of solar photovoltaic thermal technology – A critical insight on review articles. Journal of Cleaner Production. Vol 322, pp. 128997 (2021)
10. Sultan, S.M. Ervina Efzan, M.N. Review on recent Photovoltaic/Thermal (PV/T) technology advances and applications. Solar Energy. Vol 173, pp. 939–954 (2018)
11. Diwania, S. Agrawal, S. Siddiqui, A.S. Singh, S. Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement. International Journal of Energy and Environmental Engineering. Vol 11, pp. 33–54 (2020)
12. Tripanagnostopoulos, Y. Huang, G. Wang, K. Markides, C.N. Photovoltaic/Thermal Solar Collectors. Reference Module in Earth Systems and Environmental Sciences. (2021)
13. Yang, T. Athienitis, A.K. A review of research and developments of building-integrated photovoltaic/thermal systems. Renewable and Sustainable Energy Reviews. Vol 66, pp. 886–912 (2016)
14. Yu, G. Yang, H. Yan, Z. Kyeredey Ansah, M. A review of designs and performance of façade-based building integrated photovoltaic-thermal systems. Applied Thermal Engineering. Vol 182, (2021)

15. Riaz, A. Liang, R. Zhou, C. Zhang, J. A review on the application of photovoltaic thermal systems for building façades., (2020)
16. Pugsley, A. Zacharopoulos, A. Deb Mondol, J. Smyth, M. BIPV/T facades – A new opportunity for integrated collector-storage solar water heaters? Part 1: State-of-the-art, theory and potential. Solar Energy. Vol 207, pp. 317–335 (2020)
17. Maghrabie, H.M. Elsaid, K. Sayed, E.T. Abdelkareem, M.A. Wilberforce, T. Olabi, A.G. Building-integrated photovoltaic/thermal (BIPVT) systems: Applications and challenges. Sustainable Energy Technologies and Assessments. Vol 45, pp. 101151 (2021)
18. Sailor, D. Anand, J. King, R. Photovoltaics in the built environment: A critical review. Energy and Buildings. Vol. 253, pp. 111479 (2021)
19. Asefi, G. Habibollahzade, A. Ma, T. Houshfar, E. Wang, R. Thermal management of building-integrated photovoltaic/thermal systems: A comprehensive review. Solar Energy. Vol 216, pp. 188–210 (2021)
20. Chow, T.T. Tiwari, G.N. Menezo, C. Hybrid solar: A review on photovoltaic and thermal power integration. International Journal of Photoenergy. Vol 2012, (2012)
21. Agrawal, B. Tiwari, G.N. Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions. Applied Energy. Vol 87, pp. 417–426 (2010)
22. Kumar, R. Rosen, M.A. Performance evaluation of a double pass PV/T solar air heater with and without fins. Applied Thermal Engineering. Vol 31, pp. 1402–1410 (2011)
23. Hussain, F. Othman, M.Y.H. Sopian, K. Yatim, B. Ruslan, H. Othman, H. Design development and performance evaluation of photovoltaic/thermal (PV/T) air base solar collector. Renewable and Sustainable Energy Reviews. Vol 25, pp. 431–441 (2013)
24. Vittorini, D. Cipollone, R. Fin-cooled photovoltaic module modeling – Performances mapping and electric efficiency assessment under real operating conditions. Energy. Vol 167, pp. 159–167 (2019)
25. Mojumder, J.C. Chong, W.T. Ong, H.C. Leong, K.Y. Abdullah-Al-Mamoon. An experimental investigation on performance analysis of air type photovoltaic thermal collector system integrated with cooling fins design. Energy and Buildings. Vol 130, pp. 272–285 (2016)
26. Shrivastava, A. Prakash Arul Jose, J. Dilip Borole, Y. Saravanakumar, R. Sharifpur, M. Harasi, H. Abdul Razak, R.K. Afzal, A. A study on the effects of forced air-cooling enhancements on a 150 W solar photovoltaic thermal collector for green cities. Sustainable Energy Technologies and Assessments. Vol 49, pp. 101782 (2022)
27. Zhang, Y. Shen, C. Zhang, C. Pu, J. Yang, Q. Sun, C. A novel porous channel to optimize the cooling performance of PV modules. Energy and Built Environment. Vol 3, pp. 210–225 (2022)
28. Riffat, S.B. Cuce, E. A review on hybrid photovoltaic/thermal collectors and systems. International Journal of Low-Carbon Technologies. Vol 6, pp. 212–241 (2011)
29. Chen, Y. Athienitis, A.K. Galal, K. Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated

concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept. Solar Energy. Vol 84, pp. 1892–1907 (2010)

30. Kamel, R. Ekrami, N. Dash, P. Fung, A. Hailu, G. BIPV/T+ASHP: Technologies for NZEBs. Energy Procedia. Vol 78, pp. 424–429 (2015)
31. Bambara, J. Experimental Study of a Faade-integrated Photovoltaic/thermal System with Unglazed Transpired Collector., https://spectrum.library.concordia.ca/id/eprint/974610/, (2012)
32. Ma, L. Ge, H. Wang, L. Wang, L. Optimization of passive solar design and integration of building integrated photovoltaic/thermal (BIPV/T) system in northern housing. Building Simulation. Vol 14, pp. 1467–1486 (2021)
33. Bigaila, E. Athienitis, A.K. Modeling and simulation of a photovoltaic/thermal air collector assisting a façade integrated small scale heat pump with radiant PCM panel. Energy and Buildings. Vol 149, pp. 298–309 (2017)
34. Salameh, W. Castelain, C. Faraj, J. Murr, R. el Hage, H. Khaled, M. Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis. Case Studies in Thermal Engineering. Vol 25, pp. 100940 (2021)
35. Hasan, J. Fung, A.S. Horvat, M. A comparative evaluation on the case for the implementation of building integrated photovoltaic/thermal (BIPV/T) air based systems on a typical mid-rise commercial building in Canadian cities. Journal of Building Engineering. Vol 44, pp. 103325 (2021)
36. Lamnatou, C. Notton, G. Chemisana, D. Cristofari, C. Storage systems for building-integrated photovoltaic (BIPV) and building-integrated photovoltaic/thermal (BIPVT) installations: Environmental profile and other aspects. Science of The Total Environment. Vol 699, pp. 134269 (2020)
37. Rounis, E.D. Athienitis, A. Stathopoulos, T. Review of air-based PV/T and BIPV/T systems - Performance and modelling. Renewable Energy. Vol 163, pp. 1729–1753 (2021)
38. Brahim, T. Jemni, A. Economical assessment and applications of photovoltaic/thermal hybrid solar technology: A review. Solar Energy. Vol 153, pp. 540–561 (2017)
39. Al-Waeli, A.H.A. Kazem, H.A. Chaichan, M.T. Sopian, K. Photovoltaic/thermal (PV/T) systems: Principles, design, and applications. Photovoltaic/Thermal (PV/T) Systems: Principles, Design, and Applications. pp. 1–282 (2019)
40. Kuhn, T.E. Erban, C. Heinrich, M. Eisenlohr, J. Ensslen, F. Neuhaus, D.H. Review of technological design options for building integrated photovoltaics. Energy and Buildings. Vol 231, pp. 110381 (2021)
41. Lucchi, E. Dall'Orto, I. Peluchetti, A. Toledo, L. Pelle, M. Polo López, C. Guazzi, G. Photovoltaic technologies in historic buildings and protected areas: Comprehensive legislative framework in Italy and Switzerland. Energy Policy. Vol 161, pp. 112772 (2022)

42. Saretta, E. Caputo, P. Frontini, F. A review study about energy renovation of building facades with BIPV in urban environment. Sustainable Cities and Society. Vol 44, pp. 343–355 (2019)