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Energimyndighetens titel på projektet – engelska	
Innovative design of efficient cooling techniques for PV and cost-effective integrations with low-temperature heating	
Universitet/högskola/företag KTH	Avdelning/institution Byggvetenskap
Adress Teknikringen 78	
Namn på projektledare Qian Wang	
Namn på ev övriga projektdeltagare Giorgos Aspetakis, Youssef Elomari	
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Förord

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Innehållsförteckning

Sammanfattning

Att skala upp lösningar som är enkla att installera är lika viktiga för den breda användningen av PV-teknik med kyleffekter i byggnadsapplikationer. De kostnadseffektiva konfigurationerna utvecklas och analyseras genom att använda simuleringar, det vill säga Computational Fluid Dynamics och analytiska numeriska metoder, med experimentell testning för verkliga prestanda och valideringar. Nya luftkanalkonfigurationer och deras baffelmodifieringar utvecklades, testades och deras prestanda utvärderades. Speciellt har potentialen

Box 310 • 631 04 Eskilstuna
Telefon 016-544 20 00 • Telefax 016-544 20 99
registrator@energimyndigheten.se
www.energimyndigheten.se
Org.nr 202100-5000

för luftbaserad PVT-drift med termiska insatser, såsom V-bafflar och släta V-bafflar, utvärderats omfattande. Utvärderingsmått, särskilt för PVT-operationer, såsom Thermal Enhancement Factor, termisk effekt och yttemperatur, hotspots och fläkteffekt, bland annat, utvärderas också på djupet och kvantifieras, givet randvillkoren. För att ytterligare stärka replikerbarheten och skalbarheten genomfördes standardiserade testmetoder, det vill säga ISO 9806:2017 med riktlinjer genererade. Dessutom har genomförbarheten av olika integrationsstrategier med lågtemperaturuppvärmning kartlagts, med bedömning av deras potentialer under olika omständigheter och klimat, med hänsyn till LCC och LCA. Den sista delen av projektet fokuserade på att utvärdera systemkonfigurationer genom dynamiska simuleringar på systemnivå, huvudsakligen integrera PVT med lågexergisystem, såsom värmepumpar och lågtemperaturfjärrvärme.

Summary

The project developed cost-effective solutions for cooling PV panels and analyzing their performance through a combination of simulations, including Computational Fluid Dynamics (CFD) and analytical numerical methods, as well as experimental validation with real-world testing. Innovative air channel designs and their baffle modifications were created and tested, with their performance thoroughly evaluated. The project particularly emphasized the potential of air-based PVT systems, exploring the efficiency of thermal inserts such as V-Baffles and smooth V-Baffles. Key performance metrics, including Thermal Enhancement Factor, thermal power output, surface temperature, hotspot formation, and fan power consumption, were extensively analyzed and quantified under specific boundary conditions.

To ensure replicability and scalability, standardized testing methods, specifically ISO 9806:2017, were employed, and guidelines were developed based on these standards. Additionally, the project assessed the feasibility of integrating PVT systems with low-temperature heating solutions, mapping their potential across various conditions and climates, while considering Life Cycle Cost (LCC) and Life Cycle Assessment (LCA). The final phase of the project involved evaluating system configurations through dynamic simulations at the system level, focusing on the integration of PVT with low-exergy systems such as heat pumps and low-temperature district heating.

Inledning/Bakgrund

Efficient cooling of PV modules with low and stable nominal operating cell temperature (NOCT) are critical to the performance efficiencies, life-span and cost-effectiveness of any types of PV products. High ambient temperature and solar irradiance causes increased cell temperatures, and an increase in cell temperature would directly lead to efficiency degradation caused by the linear reduction in open circuit voltage [1-3]. This ultimately leads to consequences that the overall sustainability drops for PV products. Photovoltaic and Thermal (PVT) has emerged as a promising solution to cool the PV panels, and simultaneously produce waste heat that can be integrated with heat recovery systems. In addition, configuring the efficient transfer of waste heat from PV cells, by means of a coolant, allows for the synchronous generation of electrical and power in one system. Multiple types of PVT have being developed and researched internationally, as indicated in the critical reviews [4]. Significant focus has been given to water based systems so far, above all other forms, due to its thermodynamic properties, possibilities with seasonal storage and market availability [5-6]. It is however, the project's conviction that air based variants show other advantages for the application in buildings. For such PVT types, crucial factors are comprehensively studied in this project, which evaluate air based system and its integrations of recovering the waste heat for low temperature heating.

To tackle the challenges with research problems, the project is motivated by investigating how critical components, such as PV with enhanced cooling (thermal) channel and baffles, should be designed so the overall cooling techniques are cost-effective and easy-to-install. Further, there is still a big knowledge gap when it comes to integrating the waste heat from PV, and understand the feasibilities with low temperature heating as one integrated system. All these challenges lead to this project: new cooling techniques for PVT module design on component level, and optimal integration feasibilities of such air-based PVT systems with reduced costs in building installations.

In summary, the project aims at investigating the research hypothesis that the overall energy efficiency in terms of both electric and thermal of a PV panel could be enhanced by novel air baffles, and map the feasible system to recover the waste heat to contribute the overall building sustainability, with improved energy savings and reduced cost of PV in the future.

Genomförande

The project has implemented three main steps to carry out the planned research activities. Partners, such as, Bravida, Uponor, Lowte, Maston, Daikin, PEAB, Einar Mattsson, etc, have greatly provided feedbacks, knowledge, discussions, and heat transfer expertise to succeed the modeling and experimental work, as well as future research concepts, summarized in the below steps:

Step 1. Development of novel configurations and air baffles to cool the PV panels. In this step, extensive simulations and modeling were carried out. Computational Fluid Dynamics (CFD) tools, such as Ansys software and supercomputing resources were used in this step. In addition, heat transfer analytical model were also applied to analyze the simulation results.

Step 2. Experimental testing and validations; further modeling work and simulation with various configurations. Experimental studies were carried out. An experimental testing rig located in in central Sweden was built for measurements. On a fixed angle base, situated on ground level, a prototype PVT system was installed, consisting of PV panel, cooling channel underneath panel, air ducts, air fan unit and measurement instruments. ISO 9806:2017 (ISO 9806:2017 Solar energy — Solar thermal collectors — Test methods, 2017) was followed for testing the thermal performance of the PVT prototype. A subsection is addressed to co-generating collectors. The testing rig has been described in details and can be referred in published articles [7].

The testing results have been providing a basis for both validation of the CFD models, and further design of configuration variations. These provide the inputs for integration strategies with low-temperature heating systems for Step 3.

Step 3. The final step focuses on understanding the feasibilities to integrate such PVT module with other low-exergy systems, as well as the estimated sustainability contributions, i.e., cost-effectiveness and environmental performance, using lifecycle approach. In this step, first, thorough technical literature review has been carried out to understand the state-of-the-art in Air based PVT technology and its integration with building energy systems. Second, highlighted critical limitations from Step 1-2 and literature review have led to a feasibility analysis to technically map the integration strategies for both heating and cooling applications. Engineering limitations and strategies were analyzed. Finally, a complete study was carried out to analyze the holistic contributions of PVT technology integrations in a solar district, located in Spain. This study analyzed in depth not only the operational energy savings, but also LCC and LCA, when assuming PVT are adopted in such solar district, where heat pumps and district heating are both at present. TRNSYS combined with python programming language was applied, with extensive co-simulation models, such as, FMU, were developed to perform the control system optimization.

Resultat

The results of PV cooling configuration selections are based on the findings from extensive literature reviews in this field, heat transfer analysis and discussions with both academic and industry partners. The validations were carried out to prototype and collect monitoring data. Validation data is obtained from the above mentioned standardized testing approach of air-based channel PVT collector, side-by-side with a normal PV module, located in central Sweden. In the end, technical feasibilities of integrating such waste heat with low-temperature hating systems were mapped. And a use case (a selected solar district) was studied, combining PVT with heat pump and existing district heating network with data-driven control strategies (reinforcement learning). To summarize, the project has achieved the below key results, from both component development and system integration perspectives:

1). Component level and modeling techniques perspectives for air-baffle configuration to cool PV: Simulation of the operation of Air-Based PVT with baffles has been performed after experimental validation by testing a prototype. PVT performance with the addition of V-Baffle designs. CFD model was developed. The k-epsilon RNG turbulence model was found to have higher prediction accuracy with Normalized Root Mean Square Error (NMRSE) = 9.42% than that of k-omega SST with NMRSE = 18.2%, in Air-Based PVT applications.

Results of heat transfer show that the addition of baffles cools down the surface by around 8 K, compared to an unmodified channel. Hotspots may be formed in parallel supply setups but can be mitigated by use of baffles. This is crucial for the efficient, long-term operation of photovoltaic cells. Considering thermohydraulic, operational and manufacturing perspectives, and a new baffle design has been further proposed, that of "smooth V-baffles". The Thermal Enhancement Factor of the Smooth V-Baffle is in the range of 1.23-1.74, which is higher than the straight edge counterpart. This could be translated to an increase of 4% (in absolute term) for the PV efficiency, given the studied flow.

2). Experimental process and testing perspectives: methodology, guidelines for experiments and simulation were presented and verified by the investigations within the project. The paper describes the experimental testing of an Air-Based prototype, based on the procedure of the standard ISO 9806 for thermal collectors. The measured data was utilized for the validation of a CFD model, with which simulation of modified channels with baffles can be performed. The results indicated that the ISO 9806 thermal performance test can provide necessary inputs for the successful CFD simulation. Guidelines are summarized in possession of an ISO 9806 thermal performance report and the schematics of collectors to assist developing CFD models to reduce the efforts of performing repetitive measurements [7]. It was found that 30% increase of overall PVT efficiency can be achieved, given the selected boundary conditions.

3). PVT integrations with low temperature heating. A literature review was achieved, aiming to investigate why Air-Based PVT and BIPVT has not widely adopted yet. Causes include performance of PVT, insufficiently investigated applications and integrations of PVT as well as lack of standardized testing and development of PVT. Proposed measures for mitigation are a list of key physical factors for enhanced performance, a list of integration scenarios with the inherent challenges and recommendations regarding standardized procedures and significance of legislative action, respectively.

4). System level investigation on integration strategies and sustainability contributions. The feasibilities of 5 different major configurations for building applications were mapped, outlining strengths and deficiencies for each case. Findings highlight a significant lack of installations and demonstrations in real life, despite potential in, for example, exhaust air heat pump and low-temperature district heating (incl. pre-heating) integrations with additional thermal storage. Novel integrations should also be considered, e.g., solar cooling for dehumidification and latent heat management. The sustainability contributions are further studied in terms of peak power savings, LCC and LCA, on system levels, demonstrated by a selected solar district case. Simulations show that a reduction in net present cost of 14 % and environmental impacts by 11% are achieved, comparing to only PV, respectively. Comparative performance analysis also revealed the precision in temperature management under the reinforcement learning controller shows a higher efficiency and leads to substantial energy savings by minimizing unnecessary heating, than traditional on-off system control. This aspect could be an interesting research topic to further validate in real-life testbed before implementations.

Diskussion

Critical review on the state-of-the-art in air based PVT technology and its integration with low-exergy systems shows bright potentials and advantages in building applications. The installation and testing process carried out indicated that advantages, such as, avoid leakage, avoid freezing, minimized electrical hazard, less invasive installation as well as rather cheap to prototype the air baffles and channels can be achieved [6]. However, critical limitations exists, such as the relatively lower storage capacity than other coolant. This is particialriliy pronounced in a climate like Sweden, where seasonal disparities for heating and available solar largely mismatch. Therefore, ensuring a trade-off of increased efficiency improvements of the overall air-based PVT system with the cooling energy needed is critical.

In this instance, the investigators of this project propose the hypothesis that the utilization of techniques from Solar Air Heater technology is able to enhance performance, mainly through the addition of thermal inserts into the PVT cooling channel. To verify this, experimental testing was performed by means of an Air-Based PVT prototype, with the intent of validating a CFD model. With the validated CFD model, operation of PVT with baffles, a form of thermal insert, was explored. This project extensively investigated various designs focusing on V-baffle configurations with their modifications, which can assist industries to further prototype and exploit such or similar low-cost modifications.

Results show that baffles achieve 10K lower PV surface temperatures than unmodified channels, as well as eliminating hotspots formations that are created from airflow dead zones. Thus, the nominal electrical efficiency is maintained, the thermal output is increased and degradation of photovoltaic cells is restricted. Moreover, a new baffle variation, featured as Smooth V-baffle configuration, was designed that reduced the airflow friction even further – this further impacts the cooling energy need. The experience gained from experimental testing can contribute to knowhow and technical issues of PVT for the installers and engineers who are interested in carrying out onsite installations [7]. CFD simulations and the detailed study of heat transfer proved beneficial when studying thermal energy systems and their sustainability contributions. The published modeling approach and applied turbulence model can provide insights and guidance for engineers and researchers to further develop air baffles with more variations based on their interests [8].

From a system level, improving the performance of Air-Based PVT collectors is of high value, yet system configurations have not been thoroughly established so far. The article, titled "Feasibility Analysis and Evaluation Framework of Integrating Novel PVT with Low-Exergy Systems" [9], carried out a feasibility analysis on this topic, by mapping out possible implementations. However, the actual contributions in real life environment of PVT systems has yet to be evaluated, both technically and economically.

To do this, simulations and field measurements of different integrated systems are under performing with PVT data from collected experimental studies and validated energy models of use case buildings and HVAC systems. Results can potentially indicate which integration configurations and operating scenario is suitable for different conditions, such as climates, existing HVAC systems and thermal load profiles [10].

As for the future research, investigation of PVT integration with established Swedish building energy systems in real-life conditions can be a starting point. In particular, there are already concepts discussed within the industry partners, such as connecting PVT output to the evaporator side of heat pumps advanced thermal storage systems, or different implementations of low temperature heating to preheat. Similar integrations with water-based PVT have proven advantages in reducing primary energy consumption. Therefore, the system specifics and potential contributions of using Air-Based in the same way need to be assessed.

Apart from that, relatively novel integration concepts have attracted our interest as well. Waste heat from Air-Based PVT can theoretically be utilized for desiccant dehumidification and cooling of conditioned spaces to prevent heat waves. The desiccant material removes moisture present in air but requires regeneration, i.e., to remove the water molecules that have been absorbed, before starting the process again, where the high-temperature cooling handles sensible heat only[11]. Hybrid high-temperature cooling techniques in building renovations can be further explored for low-exergy operation. Low grade waste heat from PVT could be used instead to regenerate the desiccant material [12]. This permits reduced storage capacities and higher self-consumption of solar energy. These aspects will be studied in depth in future steps to evaluate the sustainability contributions beyond heating solutions across seasons.

Future research looks bright, just like the sun!

Publikationslista

[Article 1]. Aspetakis, G., & Wang, Q. (2023). Critical review of Air-Based PVT technology and its integration to building energy systems. *Energy and Built Environment*.

<u>Summary</u>: *In this study, a critical review is conducted from both component design and system integrations for air-based PVT technology. The often overlooked air-based PVT technology is put on the spotlight and their suitability for integration with energy systems of buildings is assessed. The study is to highlight vital performance and integration roadblocks in PVT research and offer suggestions for overcoming them. The methodology of reviewed literature is examined in detail with the goal of contributing to a unified approach for more impactful research.*

[Article 2]. Aspetakis, G., Wang, C., & Wang, Q. Enhancing Air-Based PVT Performance: A Numerical and Experimental Assessment of V-Baffle Designs. *Manuscript*.

<u>Summary</u>: *In this study, the performance of an Air-Based PVT with developed baffles is evaluated. A prototype was experimentally tested to validate a Computational Fluid Dynamics model. To investigate the potential heat transfer enhancement, the performance with added V-Baffle designs was simulated. Based on the results of the analysis, a new baffle design was developed, that of smooth V-baffles. The new design exhibited a higher Thermal Enhancement Factor than that of the straight edge equivalents. Additionally, it was indicated that the use of baffles can be beneficial for PVT systems, by increasing heat transfer to the airflow with reduced friction penalty and by minimizing the formation of hot zones along the PV surface.*

[Article 3]. Elomari, Y., Aspetakis, G., & Wang, Q. A co-simulation framework for design and control optimization of PVT-integrated low temperature heating. *Manuscript*.

<u>Summary</u>: *This study investigates the design and control optimization of solar district heating systems (SDHS) – integrating PVT with storage, district heating and heat pump solutions. The study developed a novel co-simulation framework that integrates TRNSYS and Python, applied to a medium-sized residential community in Falset, Tarragona, Spain. Through the developed control optimization (including energy, LCC and LCA), optimal design configuration are achieved with a reduction in net present cost by 14.71% and environmental impacts by 11.09%, respectively. Comparative performance analysis revealed that the Deep Reinforcement Learning controller maintained tighter control over temperature settings, with deviations as minimal as -0.48 K for domestic hot water (DHW) and -0.51 K for space heating, significantly surpassing the Rule-Based Controller which showed larger deviations (-2.06 K for DHW and 3.51 K for SH). The LCC analysis further supports DRL's economic viability, showing annual savings in operations and maintenance costs of approximately €0.08 million and a 4.28% reduction in economic net present cost.*

[Article 4]. Aspetakis, G., & Wang, Q. (2022). Critical issues and novel concepts of cooling BIPVT and its integration with low temperature heating. *Presented at 8th World Conference on Photovoltaic Energy Conversion, 26-30, September, Milan, Italy*.

<u>Summary</u>: *In this study, key challenges related to cooling PV are outlined and crucial parameters for thermal management concepts are presented. Practical aspects of the design and integration processes are explored as well, alongside the cost-effectiveness, sustainability and aesthetics of said systems. 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. In view of these characteristics, new BIPVT cooling concepts are proposed along with methods for simulating their thermal behavior utilizing numerical solutions, i.e., computational fluid dynamics (CFD).*

[Article 5]. Aspetakis, G., & Wang, Q. (2022). Critical issues of cooling BIPVT and its integration with low-temperature heating. *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.*

Summary: *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.*

[Article 6]. Aspetakis, G., & Wang, Q. (2023). Numerical study of novel air-based PVT designs validated using standardized testing approach. *ISES Solar World Congress, 30 Oct - 04 Nov 2023, New Delhi, India.*

Summary: *The study focuses on the simulation of a novel Air-Based Photovoltaic Thermal (PVT) prototype, experimentally investigated according to ISO 9806, specifically for collectors generating thermal and electrical energy. Experimental studies are carried out to validate a benchmark Computational Fluid Dynamics (CFD) simulation model in a previous study. The results indicate the optimal design selections for next-step experimental prototypes. The secondary objective is to assess the feasibilities of the PVT prototype for operational characteristics at different climate conditions. Insights are provided regarding the reliability, workflow and overall methodology of validating CFD models by testing through an international standardized process. Outlines for system-level modelling are presented as well.*

[Article 7]. Elomari, Y., Aspetakis, G., & Wang, Q. (2023). Feasibility Analysis and evaluation framework of integrating novel PVT with low-exergy systems. *ASHRAE International Building Decarbonization Conference, April 17-19, Madrid, Spain.*

Summary: *This study analyzes and maps various integration strategies for air-PVT with low-exergy systems, by examining their feasibilities critically. This study primarily focuses on five integration strategies that built upon commonly used existing building installations in Scandinavian climate, Moreover, the study explores other potential operations with, e.g., medium to long-term thermal storage applications by considering borehole heat exchangers, latent heat storage from both stand-alone tanks and building envelopes.*

[Article 8]. Aspetakis, G., Elomari, Y., & Wang, Q. (2025). Air-Based PVT integrated low-temperature heating systems: analysis and optimization of configurations. *To be Presented in Decarbonizaed, Healthy and Energy Conscious Buildings in Future Climates, June 4-6, Milan, Italy.*

Summary: *The main focus of this study is the multifaceted exploration of Air-based PVT to building energy system integration configurations. Based on simulation models validated with long term testing data of prototyped PVT* *collector, an analysis of integrated systems is performed. Configurations include combined exhaust air heat pump systems and an examination into storage capabilities. Potential interactions with 4th generation of district heating solutions in buildings are also covered. Optimization of sizing and control is implemented utilizing machine learning algorithms (ML) with the aim of enhancing flexibility in a system containing heat and electricity flows, heat pumps and storage.*

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[9]. Elomari, Y., Aspetakis, G., & Wang, Q. (2023). Feasibility Analysis and evaluation framework of integrating novel PVT with low-exergy systems. *ASHRAE International Building Decarbonization Conference, April 17-19, Madrid, Spain.*

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