# ABSTRACT

Li, Siwei. Ph.D., Purdue University, May 2014. Modeling of Photovoltaic Thermal Systems with Transpired Solar Collectors Integrated in Building Operation Simulation. Major Professor: Panagiota Karava.

Solar energy is so far the most promising and sustainable alternative energy source to fossil fuels. The new solar technology proposed in this research, building-integrated photovoltaic-thermal (BIPV/T) systems, can be attached to the façade or replace conventional cladding, enabling on-site generation of solar electricity and heat, which can fulfill a significant portion of the building energy requirements. The overall objective of this research is to develop (a) prototype BIPV/T systems coupled with open-loop corrugated Unglazed Transpired Solar Collectors (UTC); (b) new modeling representations for design, analysis, and control of BIPV/T integrated in the operation of building Heating, Ventilation and Air Conditioning (HVAC) systems; (c) an innovative energy management framework, over a future planning horizon, based on model-predictive control algorithms that can anticipate the variability of solar irradiance and building load, enabling the optimal operation of high performance buildings with distributed solar energy resources and active thermal energy storage.

To this end, high-resolution, three-dimensional Computational Fluid Dynamics (CFD) models are developed to investigate the complex airflow and heat transfer mechanisms in BIPV/T systems and provide a solid foundation that supports the formulation of thermal analysis models. The CFD models are validated using data from an experimental set-up in a state-of-the-art solar simulator facility, in terms of the cavity exit air temperature (the error less than 1°C), the stream-wise development of plate surface temperature (the error less than 1°C), and vertical profiles of stream-wise velocity (average error within 10 %) and turbulent kinetic energy (average error within 20 %).

Energy prediction models for both corrugated UTCs and UTCs integrated with BIPV/T systems are established to evaluate their performance (electrical and thermal energy output, outlet air temperature, etc.) for different weather (incident solar radiation and wind speed) and system design parameters (corrugation geometry, PV module coverage ratio, suction velocity, etc.). Comprehensive Nusselt number and effectiveness correlations, representing both the exterior and interior convective heat transfer processes in BIPV/T systems, are obtained from the CFD simulations and subsequently used in the energy models. Experimental data for prototype BIPV/T collectors installed at Purdue's Architectural Engineering Lab are used to validate the energy models. Comparison between the model predictions and the experimental data verifies the dynamic response of the collectors to weather and operating conditions, with the root mean square error within 1 °C in terms of cavity exit air temperature for the UTC configuration and within 2 °C (PV surface temperature) for the model of UTC with PV modules. The methodology for the analysis of the thermal boundary layer development and convective heat transfer process can be generalized to uniform approaching flow over corrugated plates with discrete suction, while the Nusselt number and effectiveness correlations and the physical modeling approach can be adopted to other BIPV/T systems.

Then the energy models are implemented in building simulation platforms to enable integration of BIPV/T with building HVAC systems (air handling unit and radiant floor heating) and active thermal storage systems. Finally, a deterministic model-predictive control algorithm is formulated for the integrated solar system. This includes building up a detailed dynamic system model in TRNSYS, presenting a system identification approach to obtain simplified gray and black-box models that capture the relevant system dynamics and are computationally efficient for implementation in real controllers, formulating the cost function and setting up the constraints and the optimization environment, and examining the potential impacts associated with the prediction accuracy of the solar irradiance, which is the most significant disturbance acting on the system. The energy saving potential of the integrated system and the predictive controller is investigated in comparison with baseline operation strategies used in commercial buildings, using the Hydronic Laboratory at Purdue's Living Laboratories as a simulation test-bed. The investigation shows that efficient integration concepts and optimal control strategies are necessary to predict and plan the energy cost for the integrated solar system, resulting in total energy savings for the integrated solar system that can be up to 45 %. The modeling representations and approaches developed in this study can be generalized and extended to other commercial buildings with different integrated solar systems, HVAC systems and energy storage.

In summary, the solar technology (prototype BIPV/T collectors), systems representation, validated models, and the numerical prototypes of predictive-control algorithms developed in this dissertation found to be an efficient approach for building-scale renewable energy generation and utilization in high performance commercial buildings. The research presented herein is a necessary precursor for future investigation and expansion of smart buildings or net-zero energy buildings and the adoption of innovative energy management concepts in engineering practice. With large-scale deployment, this could be an effective pathway to reduce greenhouse gas emissions and the need to build new fossil fuel power plants.