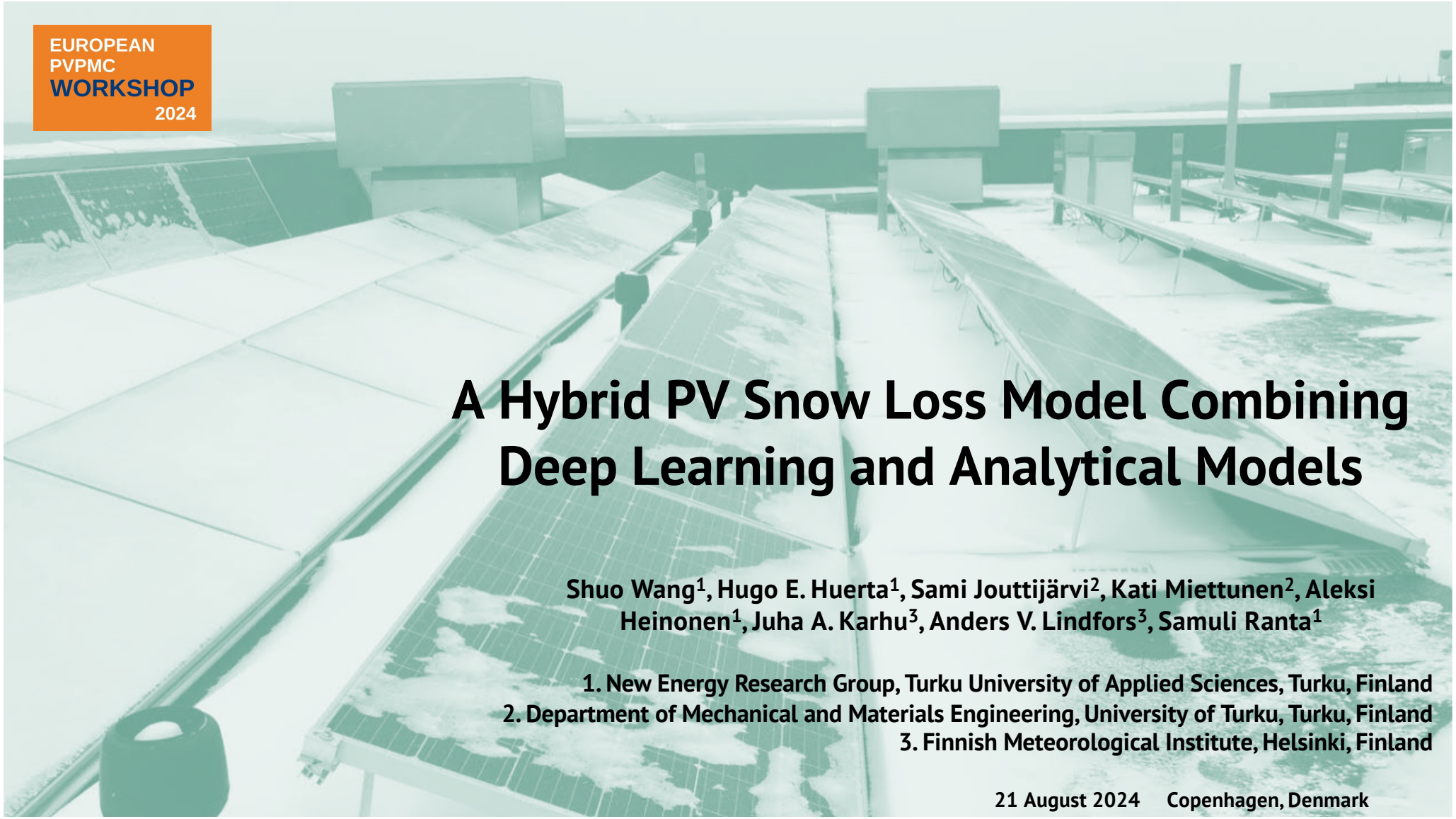
EUROPEAN PVPMC WORKSHOP 2024



A Hybrid PV Snow Loss Model Combining Deep Learning and Analytical Models

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21 August 2024 Copenhagen, Denmark

Motivation

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Snow Loss:

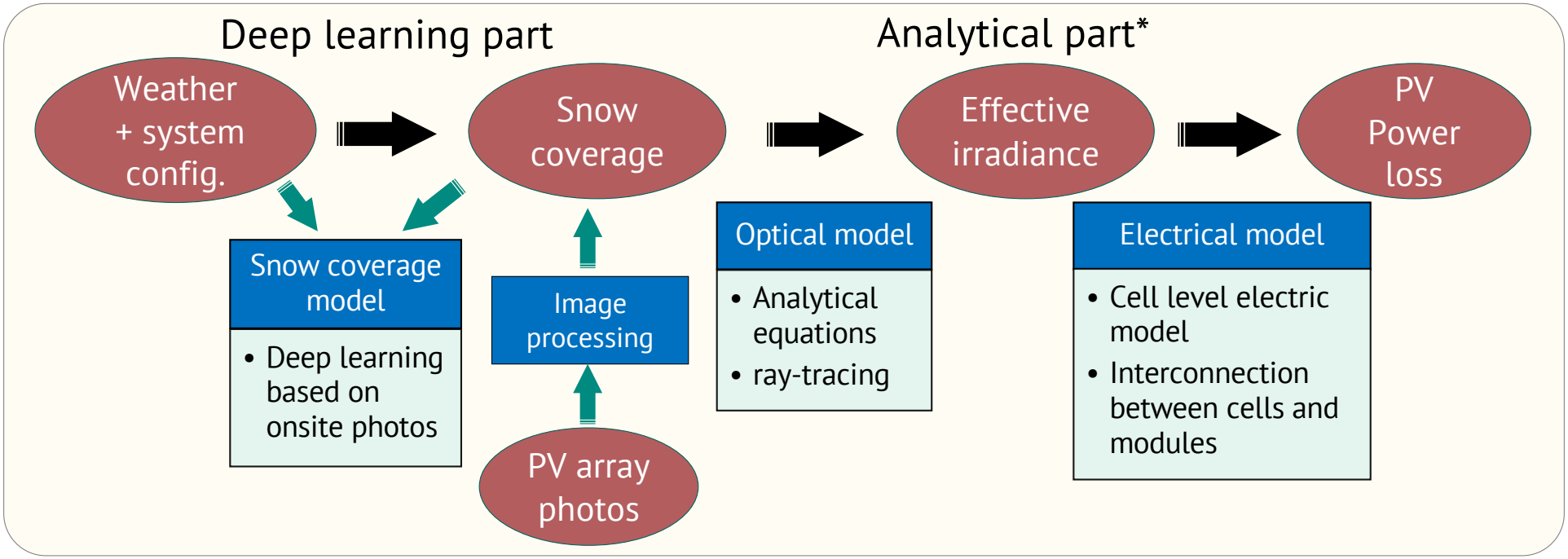
- Uncertainty in PV performance estimation in high latitude area
- The annual electricity generation loss caused by snow cover is typically within 10%, could be higher than 30%
- Several snow loss models have been proposed, e.g. Marion model*

Objective

Higher time resolution	Dealing with complexity of snow	Applicable for system configuration
• Sub-hour modeling • For performance monitoring and forecasting	• Easy implementation • Applicable for different snow processes, climates, and systems • No need of site-specific parameters	• Different orientation • portrait/landscape • Half-cut cell module • Bifacial module

*DOI: 10.1016/j.solener.2013.07.029

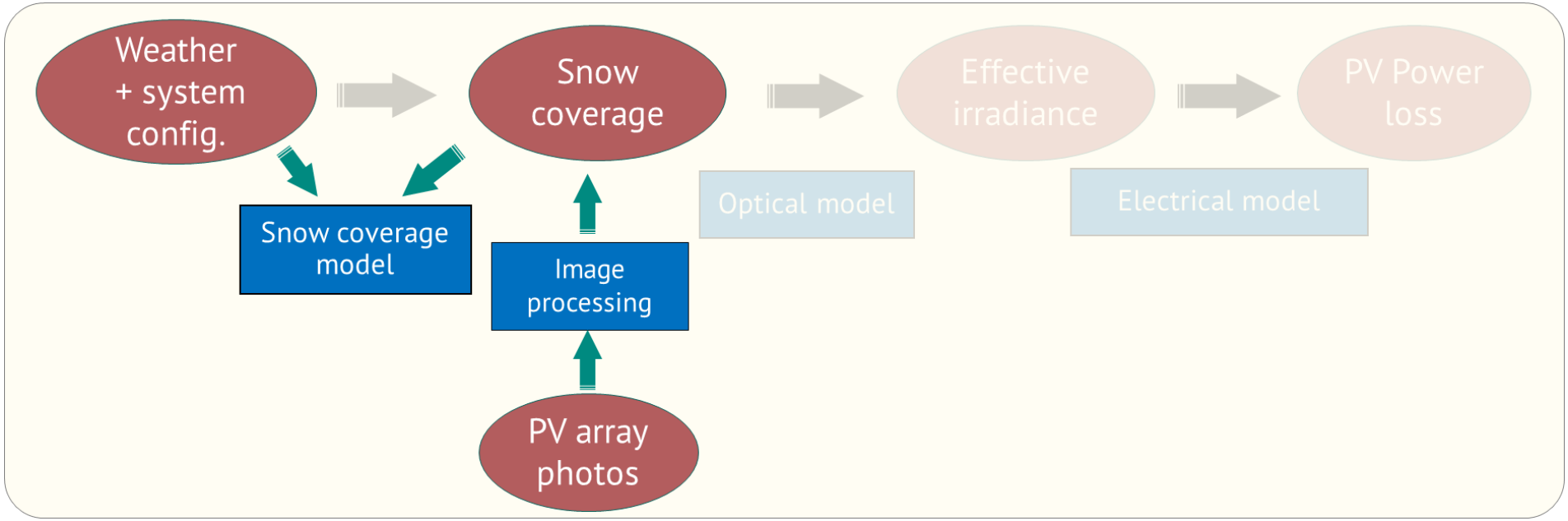
Model framework



*DOI: 10.4229/EUPVSEC2023/4BO.5.4

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Snow coverage model



1. Image processing algorithm

2. Train the deep learning model

Data sources

TUAS EDU campus roof test bench @Turku



Tilt: 45 degree
Resolution: 1min
Photo: from 11.2023

Ground system @Taivassalo

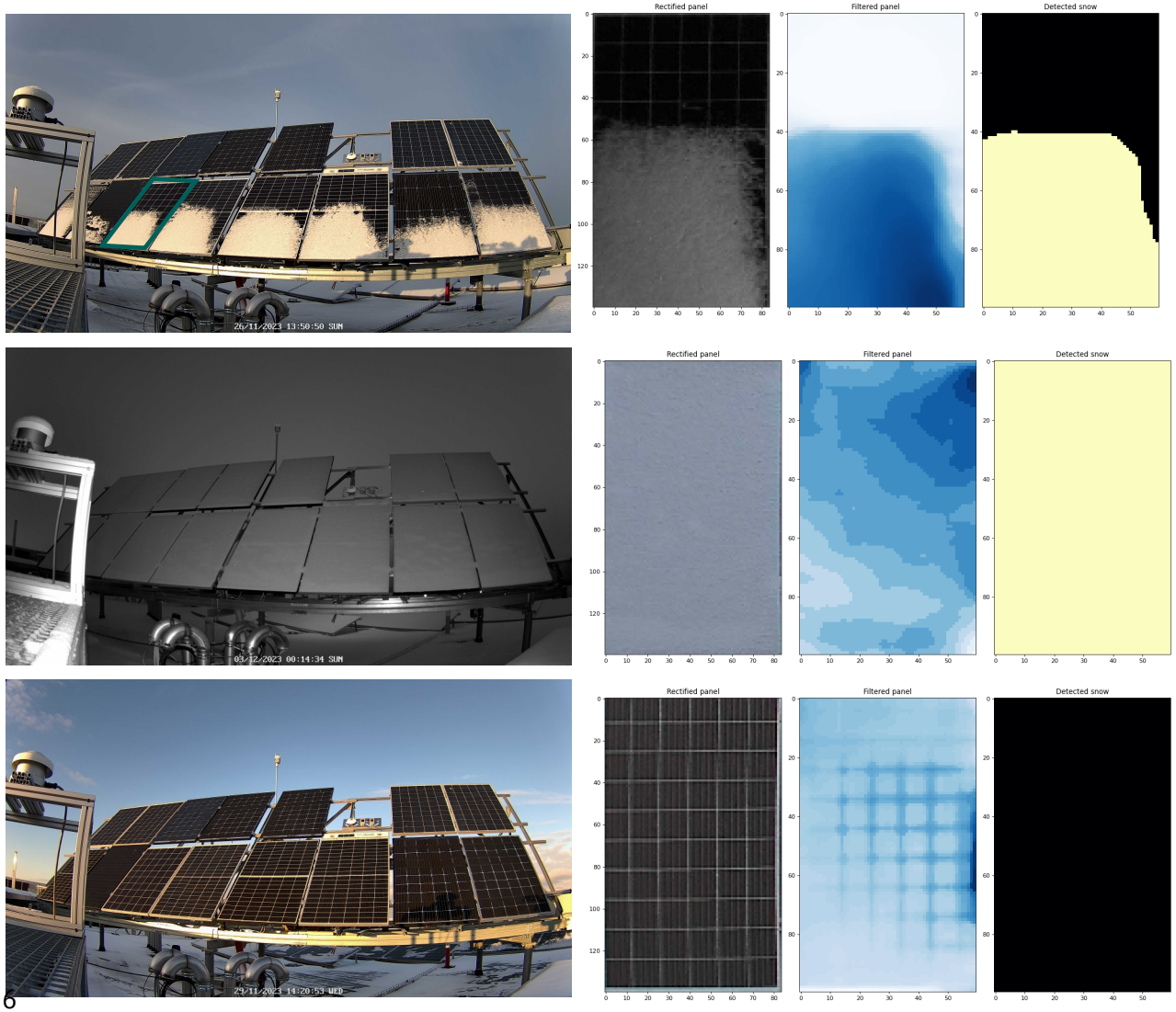


Tilt: 30 degree
Resolution: 5min
Photo: from 12.2023

FMI rooftop system @Helsinki



Tilt: 15 degree
Resolution: 1hour
Photo: from 12.2023



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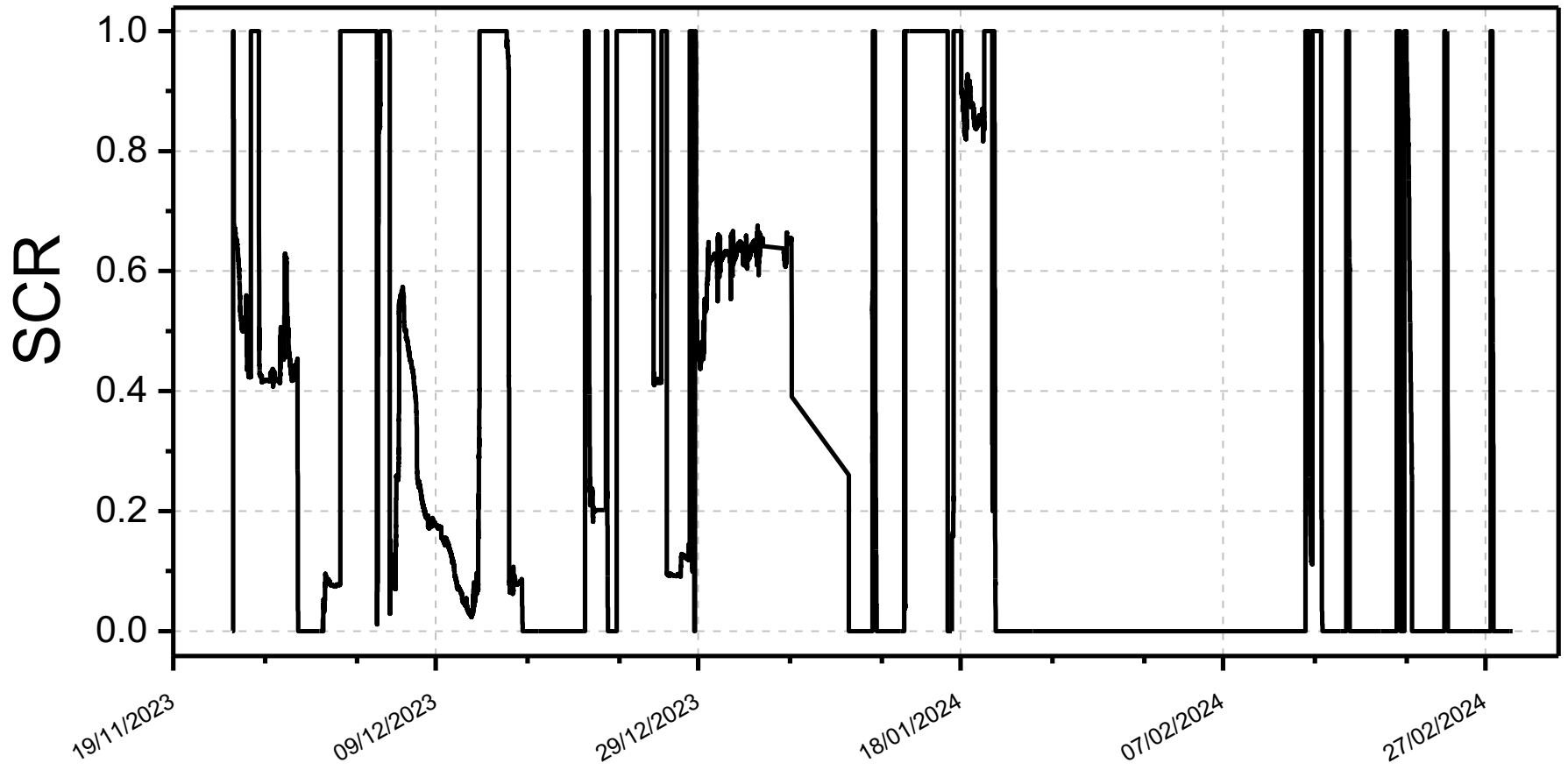
Image processing algorithm

- Improvements made on the algorithm* to ensure the algorithm works well for photos taken at night
  - Use k-means clustering to replace static threshold
  - Use edge detection to differentiate between fully covered and clear cases.
- Snow coverage ratio (SCR) between 0 and 1

*DOI: 10.1109/JPHOTOV.2023.3264644

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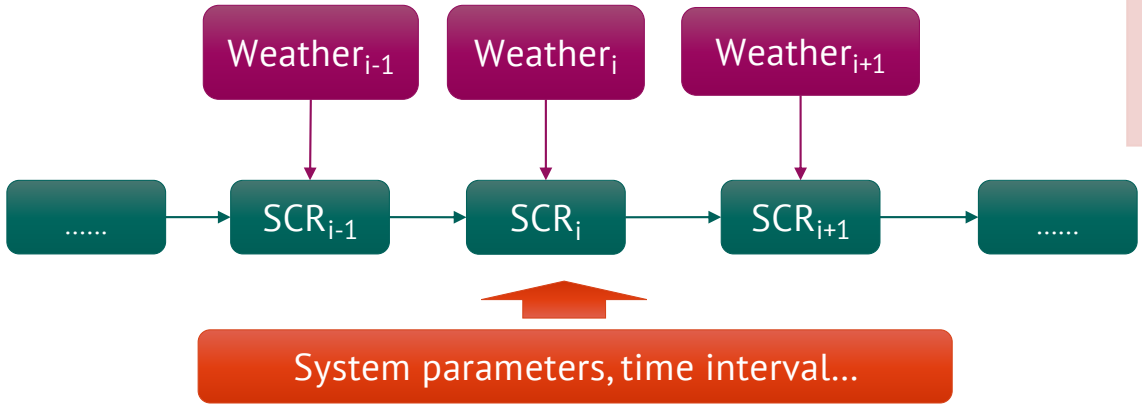
Snow coverage ratio evaluated from TUAS test bench



Snow coverage model with deep learning

Model structure

- Timeseries modeling
- The SCR_i is related to both $Weather_i$ and SCR_{i-1}
  - Long Short-Term Memory (LSTM) architecture is used
- Consider physical process of snow accumulation/removal
- To solve the problem of starting point
  - Multiple continuous inputs → one output



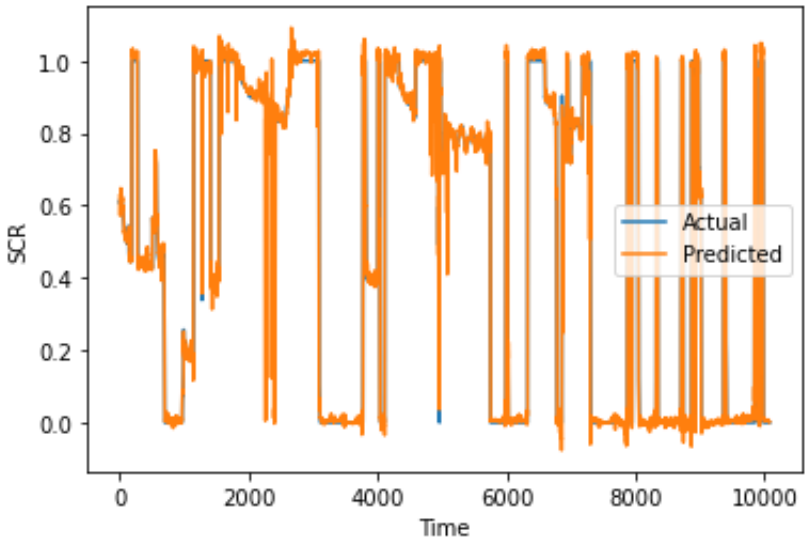
Variable candidates :

Weather	System	Other
• Irradiance • POA Irradiance • Air temperature • Snow depth • Wind speed • Pressure • Humidity • Precipitation • Snow fall •	• Tilt • Azimuth • Clearance height •	• Time resolution • If edge • If coating • .....

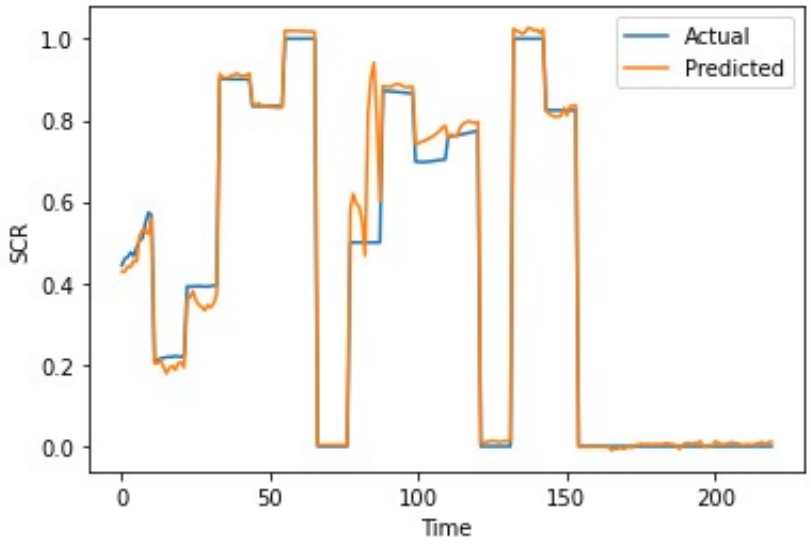
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Training for TUAS test bench

Training: 95% data



Testing: 5% data

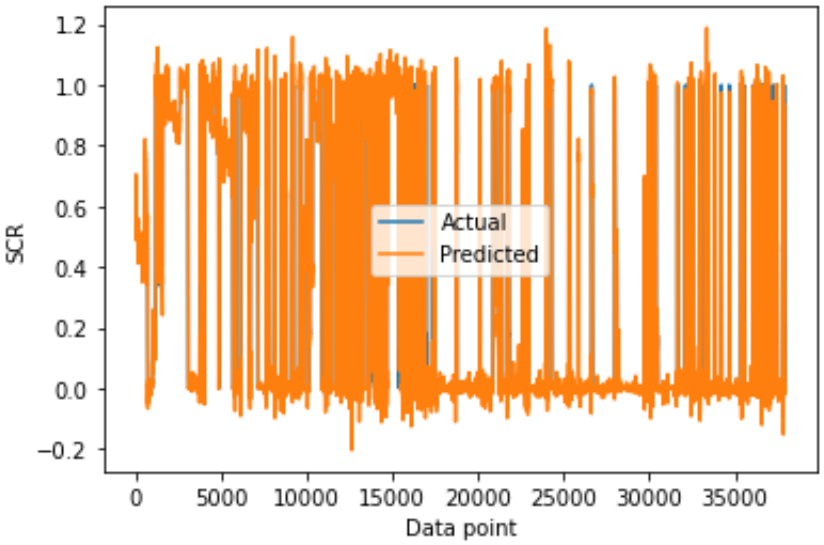


- 7 inputs: POA Irradiance, air temperature, snow depth, wind speed, pressure, humidity, precipitation
- Time interval: 10min
- RMSE of testing: 0.077

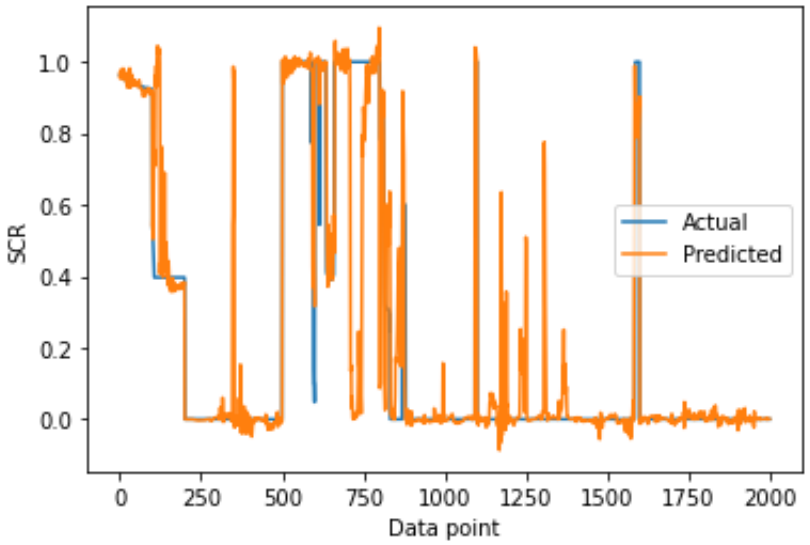
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Training for all the three systems & different time intervals

Training: 95% data



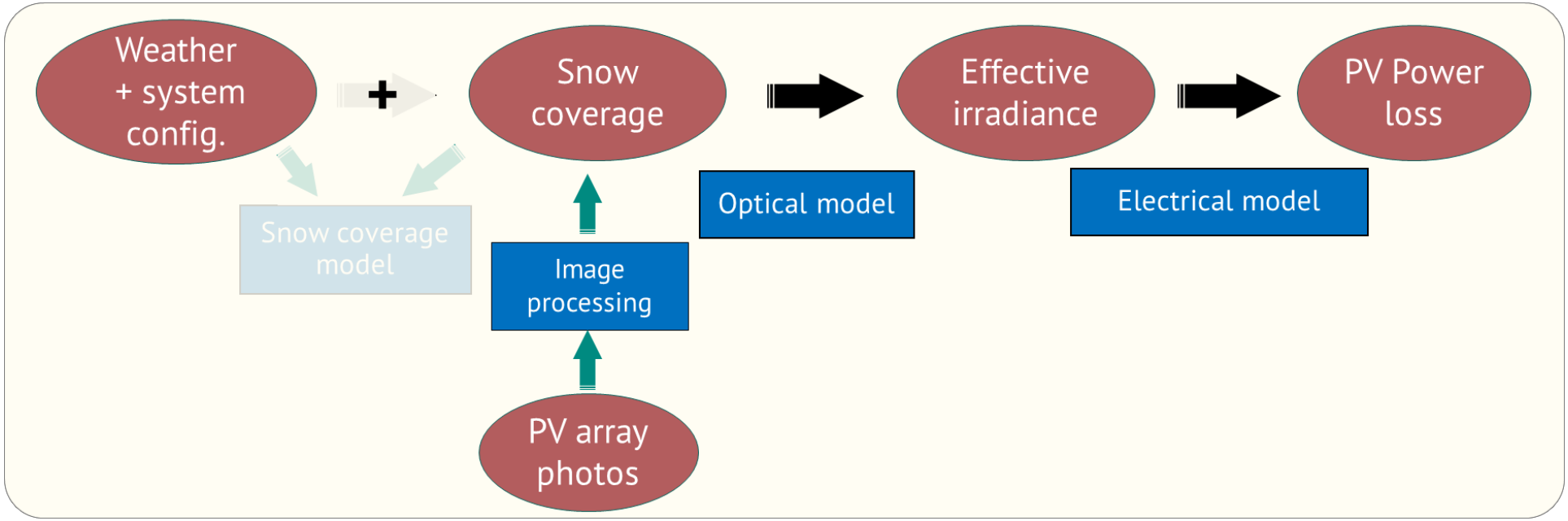
Testing: 5% data



- 8 inputs: POA Irradiance, air temperature, snow depth, wind speed, pressure, humidity, precipitation, tilt
- Time interval: 10min, 30min, 60min
- RMSE of testing: 0.158
- Less accurate: not enough values for tilts and time interval

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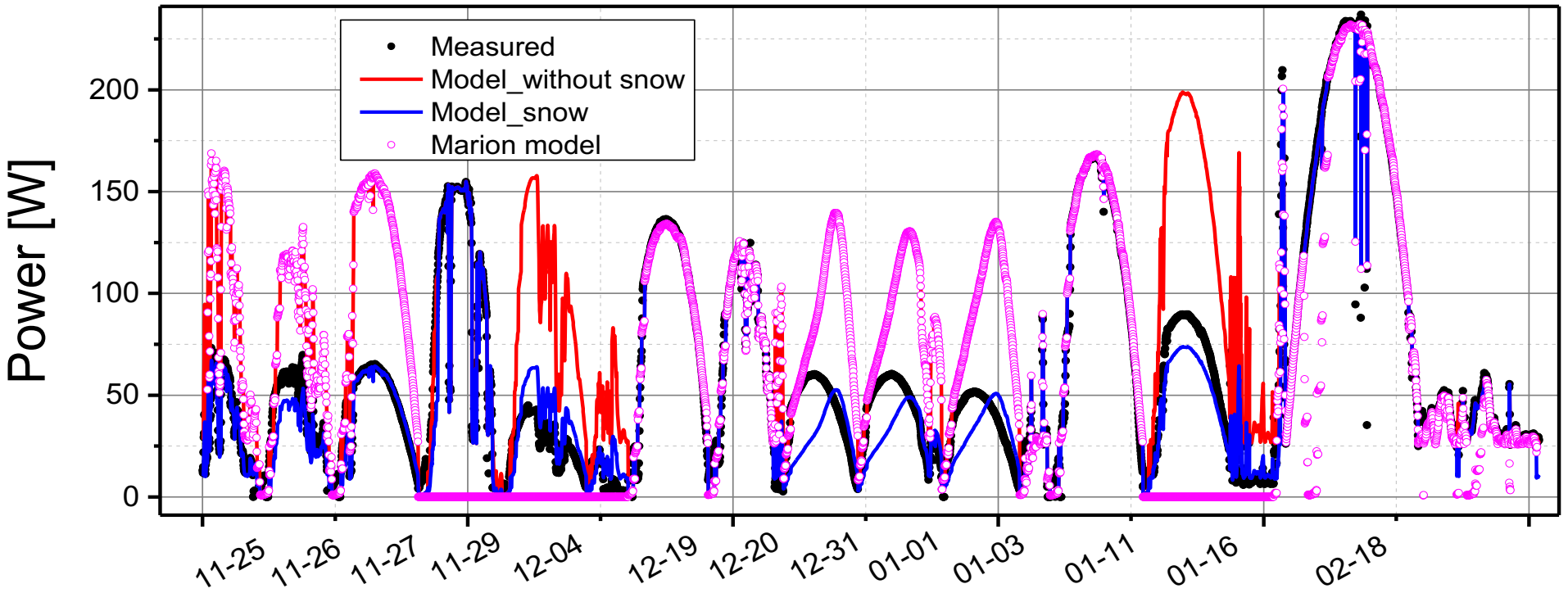
Snow loss evaluation with photos



- With snow coverage ratio from photos
- Applicable for systems with IP camera

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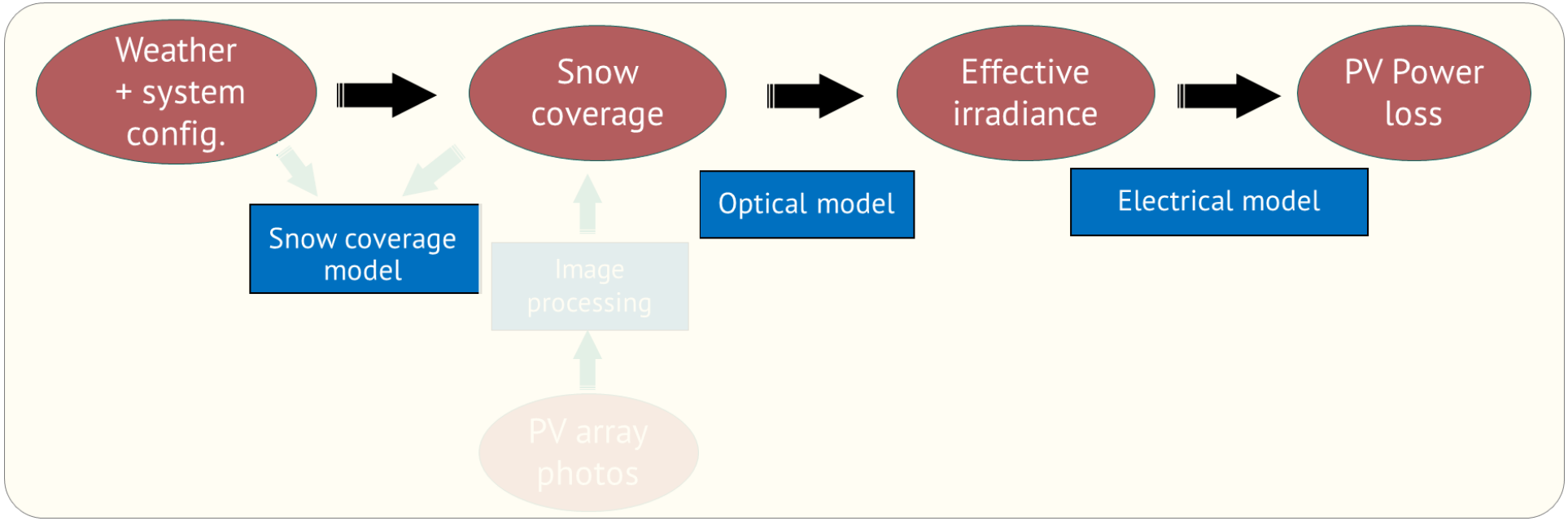
TUAS test bench, POA>100W/m^2, Contant Tsnow = 0.38, full cell module



Snow loss	Measured	Our model	Marion model
2023.11 to 2024.02 Energy loss	29.2%	32.5%	26.6%
2023.11 to 2024.02 RMSE		21.11	48.63
2023.06 to 2024.05 Energy loss	0.76%	0.85%	0.69%

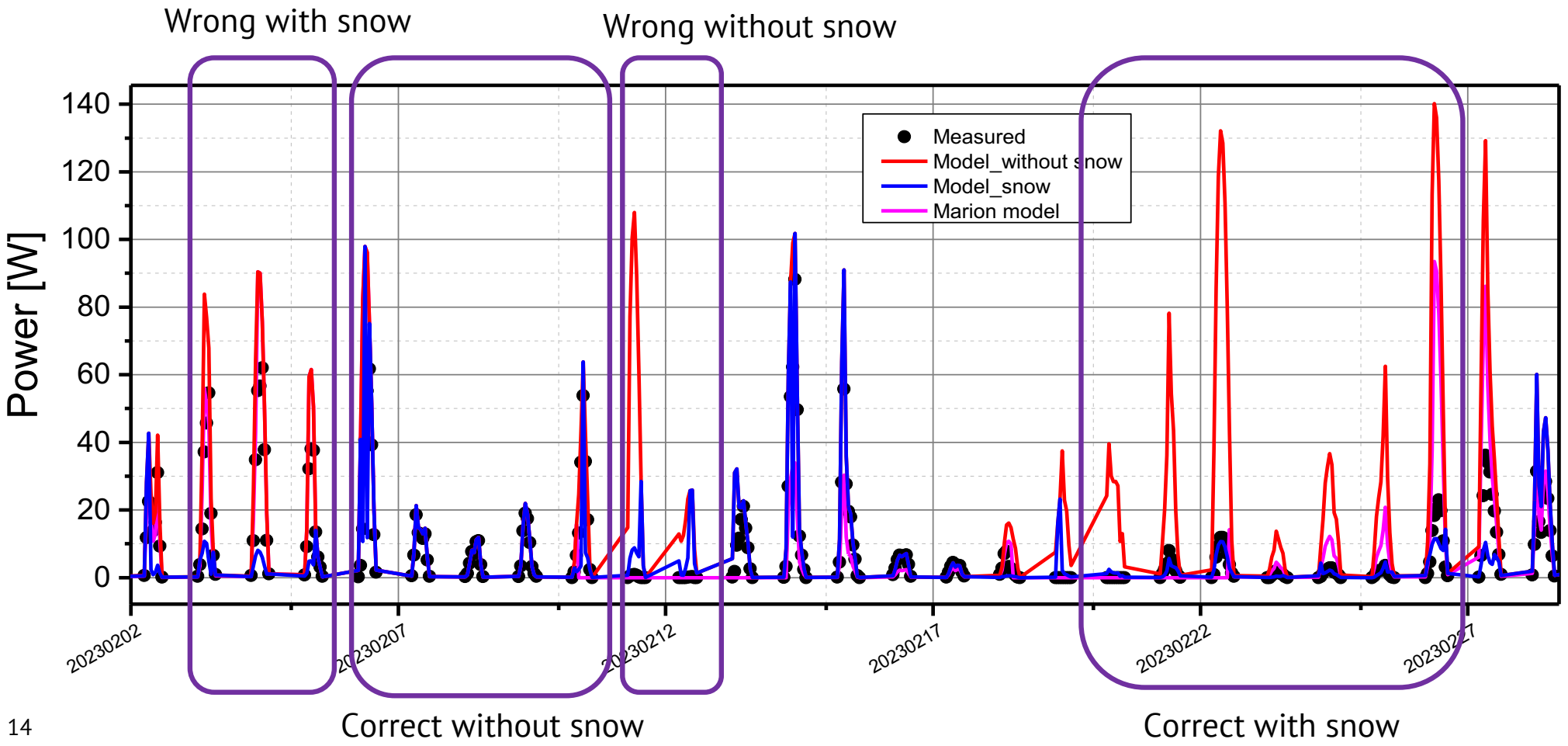
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Snow loss evaluation without photos

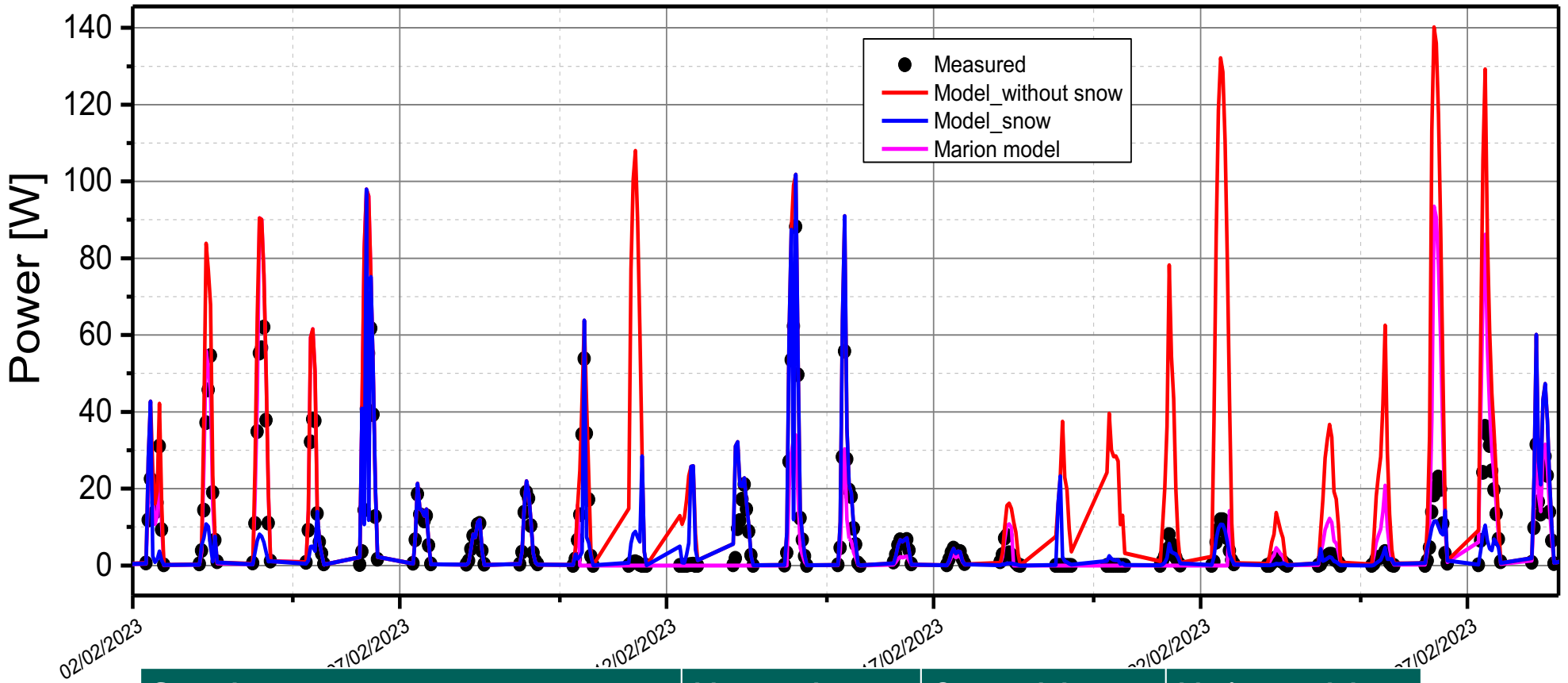


- With snow coverage ratio from trained model
- Applicable for any systems

FMI roof-top system, POA>1W/m^2, Contant Tsnow = 0.25, full cell module



FMI roof-top system, POA>1W/m^2, Contant Tsnow = 0.25, full cell module



Snow loss	Measured	Our model	Marion model
2023.01 to 2023.03 Energy loss	58%	45.3%	56.1%
2023.01 to 2023.03 RMSE		15	15.65

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Conclusion

- A new snow loss model is developed:
  - Decouple the challenges in snow loss modeling into two distinct physical processes, addressing them separately with deep learning and analytical methods, respectively
    - High time resolution up to minute
    - Capable of handling snow-related complexities: adaptable to various climates, systems, and snow conditions.
    - Aware of different system configurations: portrait/landscape, half-cell module, bifacial module
- The model shows promising results and great potential for time-dependent snow loss prediction, as well as other snow-related issues.
- More updates in 4BV.3 EU PVSEC, 24.09.2024

Challenges:

- Snow coverage model is not perfect so far: data from more systems & longer time periods are needed



Acknowledgement
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