A Concise Overview on State-of-the-Art Solar Resourcing and Forecasting

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Jan Kleissl

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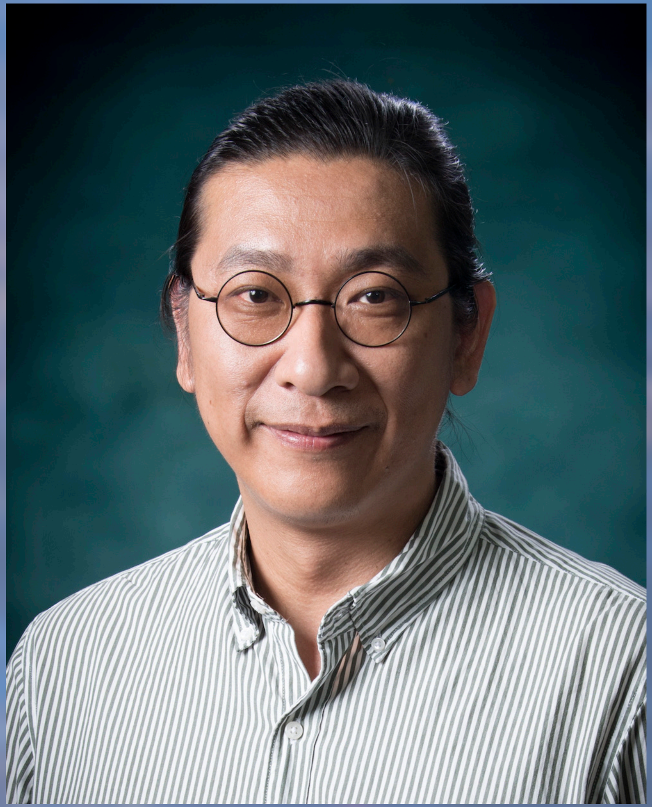
He received his B.Eng., M.Sc., and Ph.D. degrees from the National University of Singapore in 2009, 2012, and 2015, respectively. Currently, he is a Professor with the School of Electrical Engineering and Automation, **Harbin Institute of Technology**. He has a profound interest in solar resource assessment, forecasting, and grid integration. He has been the youngest associate editor of the **Solar Energy** journal, which has 65 years of history, and since 2019, he has been one of the four Subject Editors of that journal. In the past decade, he authored more than **100 journal papers**, with a total citation of 4400, and an H-index of 36. In 2020, he has been identified as one of the **world's top 2% scientists** by Stanford University.



Solar energy meteorology

Solar forecasting

Characteristics

- Reproducibility
- Operational
- Physics-based
- Ensemble
- Skill

Five aspects

- Forecasting method
- Post-processing
- Irradiance to power
- Verification
- Forecast to value

Solar resource assessment

Data

- Ground-based
- Satellite-derived
- NWP-generated

Models

- Solar constant
- Spectral irradiance
- Clear-sky
- Separation
- Transposition
- Angular distribution
- Site adaptation

DATA FOR FORECASTING

SOLAR RESOURCE ASSESSMENT – GROUND DATA

/ Data for solar resource assessment

Ground-based measurements:

- **Radiometers**

  Different pyranometers and pyrheliometers are subject to different measurement uncertainties and performance.

- **High cost of research-grade radiometers**

  Operations and maintenance cost.

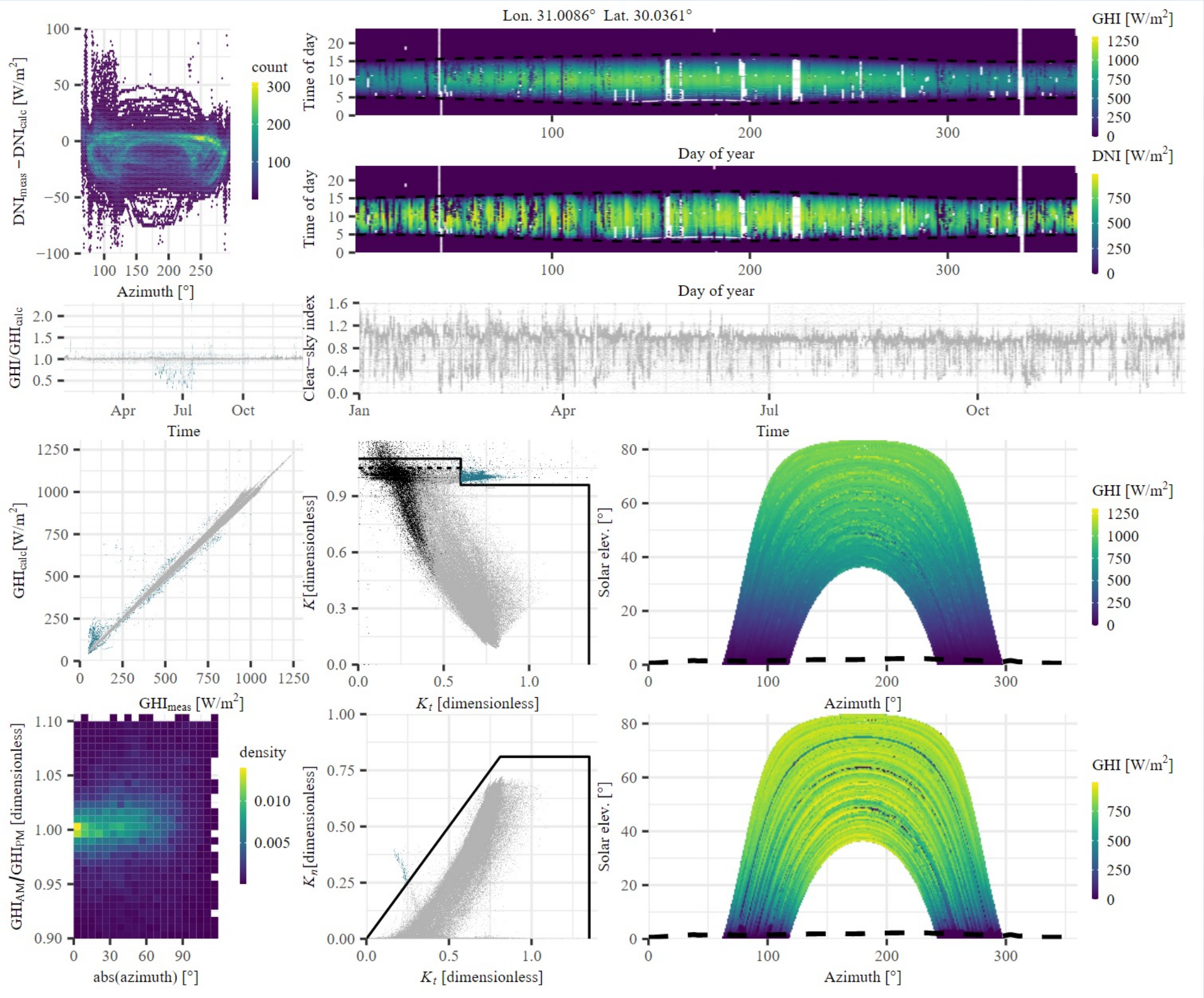
- **Quality control (QC)**

  Ensure that the baseline for any subsequent validation is legitimate.

Four types of radiometry measurements:

- Global horizontal irradiance (**GHI**)
- Beam normal irradiance (**BNI**)
- Diffuse horizontal irradiance (**DHI**)
- Global tilted irradiance (**GTI**)

FIG. VISUALIZATION TO FACILITATE QUALITY CONTROL OF IRRADIANCE

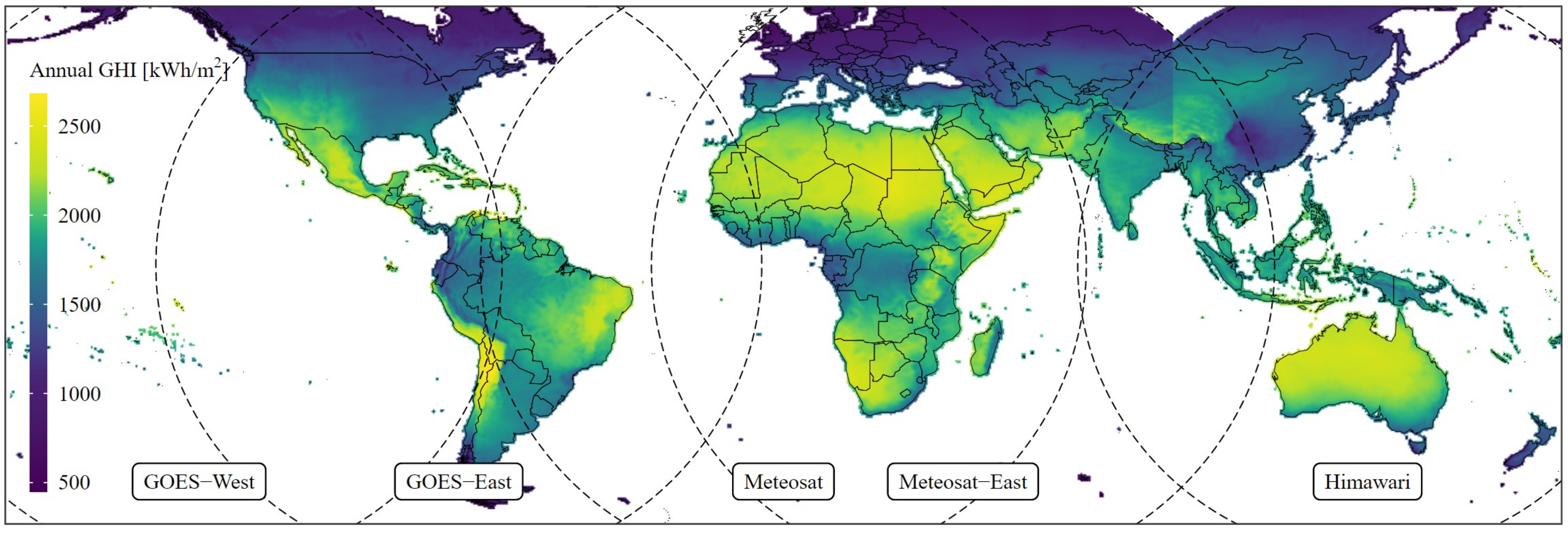


SOLAR RESOURCE ASSESSMENT – SATELLITE DATA

/ Data for solar resource assessment

Satellite-derived irradiance data:

FIG. FIVE GEOSTATIONARY WEATHER SATELLITES JOINTLY COVER ALL LOCATIONS ON EARTH BETWEEN +60° AND −60° LATITUDE.



SOLAR RESOURCE ASSESSMENT – WEATHER MODEL

/ Data for solar resource assessment

Output of NWP models:

Forecasts a few times a day, over forecast horizons of a few days, at a regional or global scale.

- **Forecast**

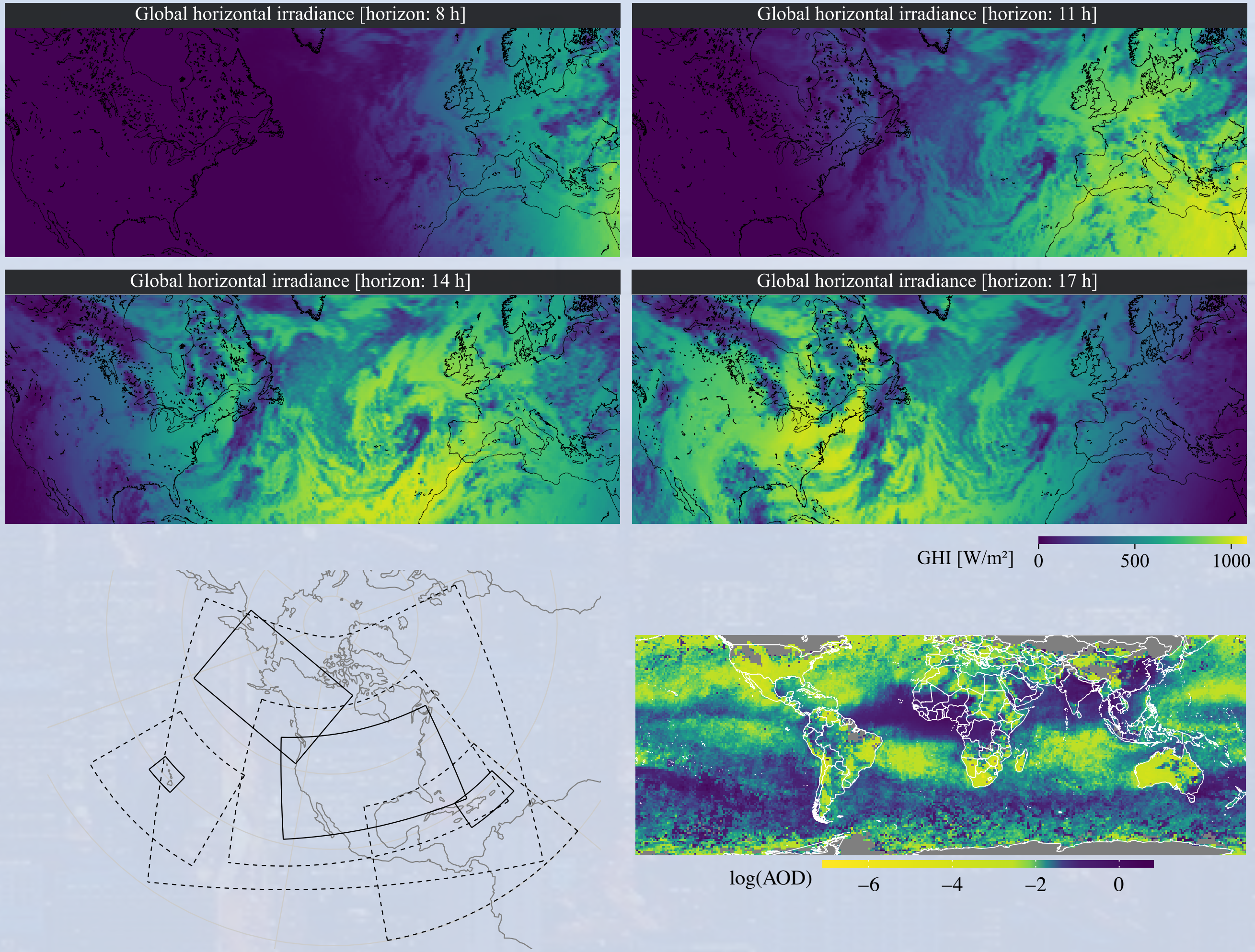
  Operational models constantly undergo development.

- **Reanalysis**

  In contrast, reanalyses use “frozen” models and produce estimates of weather variables over a period typically spanning a few decades. For example:

  - ECMWF Reanalysis, Version 5 (**ERA5**)
  - Modern-Era Retrospective Analysis for Research and Applications, Version 2 (**MERRA-2**)

FIG. VISUALIZATION OF ECMWF GHI FORECAST; NAM DOMAIN; MODIS AOD



SOLAR FORECASTING CHARACTERISTICS

SOLAR FORECASTING – CHARACTERISTICS

/ Salient characteristics of solar forecasting

The acronym of "ROPES":

Reproducibility

- Falsifiability is an essential feature of scientific progress.
- Reproduction solely based on textual description is cumbersome.
- Instant reproducibility through data and code as supplementary materials.

Operational

- Forecast submission guidelines.
- Time parameters: forecast lead time, forecast horizon, forecast resolution, forecast refresh rate.

Physics-based

- Camera, satellite and NWP to produce initial forecasts.
- Post-process physics-based forecasts with machine learning.

Ensemble

- Dynamical ensemble (meteorology)
- Combining forecasts (statistics)
- Ensemble learning (computer science)

Skill

- Benchmark against reference and "perfect" forecast:
  - $S = (A_f - A_r)/(A_p - A_r)$
- Predictability

SOLAR FORECASTING – SKILL

/ Five aspects of solar forecasting research

- **Skill**
  - $S = \dfrac{A_f - A_r}{A_p - A_r}$
    - A_r comes from CLIPER (optimal convex combination of climatology and persistence)
    - A_p comes from predictability error growth (the difference between a controlled run and a perturbed run)

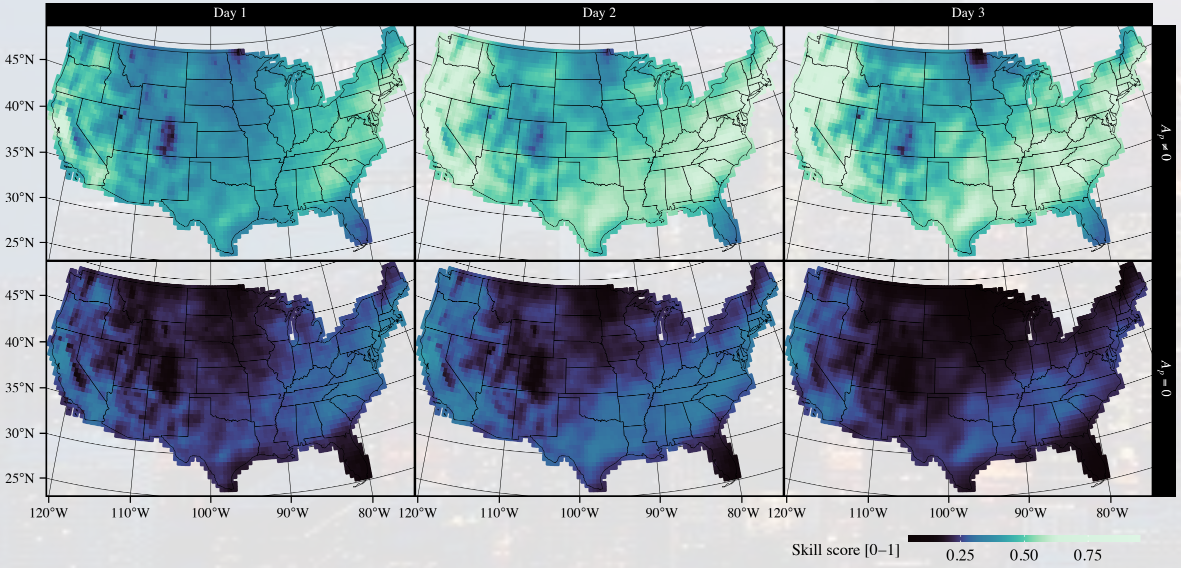
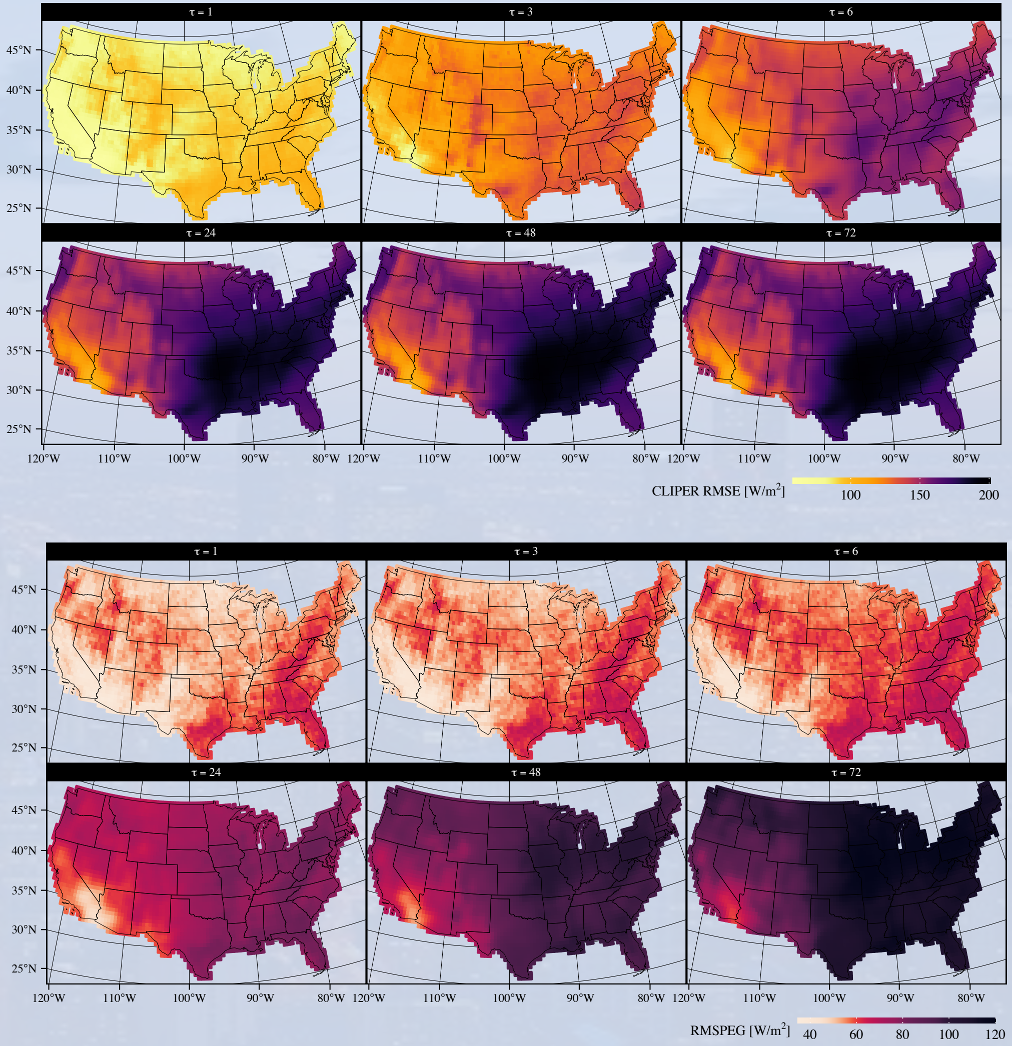


FIG. CLIPER RMSE and predictability error growth



SOLAR FORECASTING RESEARCH THRUSTS

SOLAR FORECASTING – TYPES AND VERIFICATION

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Base methods

- Camera
- Satellite
- NWP

Post-processing

- Improve accuracy (D2D)
- Uncertainty quantification (D2P)
- Elicit forecast (P2D)
- Improve calibration (P2P)

Irradiance-to-power

- Direct (regression)
- Indirect (model chain)
- Hybrid (solar modeling up to effective irradiance + machine learning for the rest)

Verification

- Deterministic (Yang et al., 2020)
- Probabilistic (Lauret et al., 2019)

Materialization of value

- Grid-integration forecast penalty

SOLAR FORECASTING – COMBINATION OF METHODS

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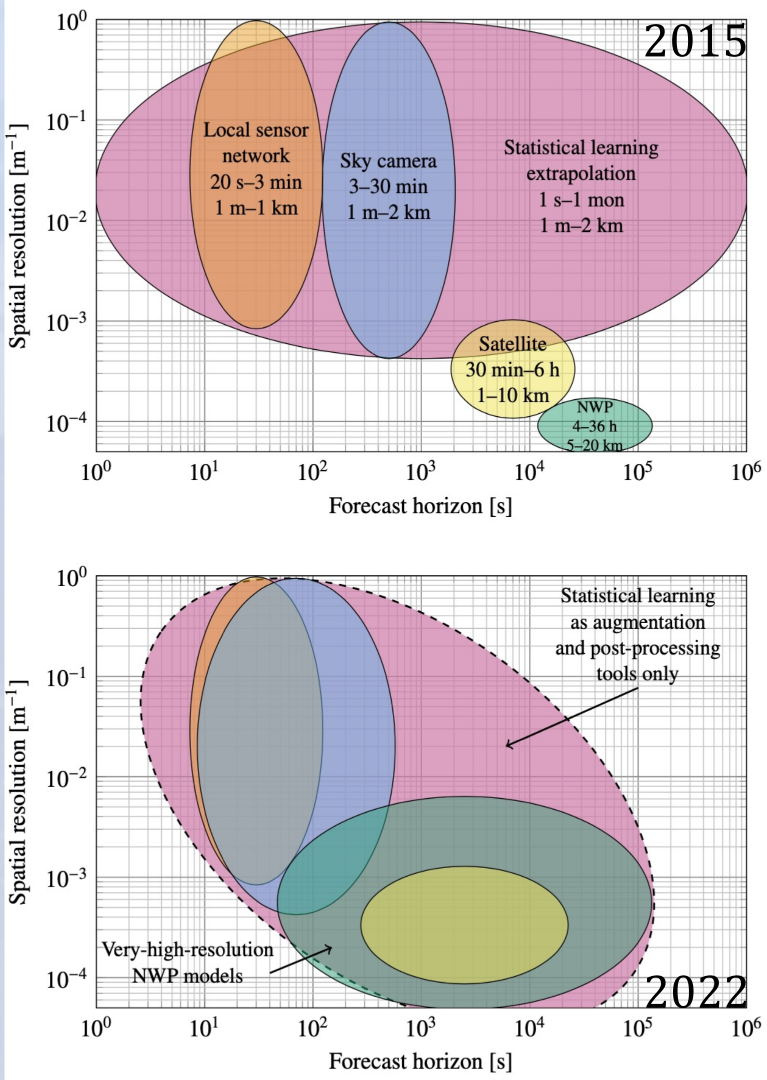
Forecast methods

- Association between data source and forecast horizon has weakened
- Most advanced methods use more than one data source
  - 15-min, 3-km NWP
  - 5-min, 2-km satellite

FIG. HISTORICAL AND CURRENT PERSPECTIVE ON CATEGORIZATION OF FORECASTING METHODS



SOLAR FORECASTING – POSTPROCESSING

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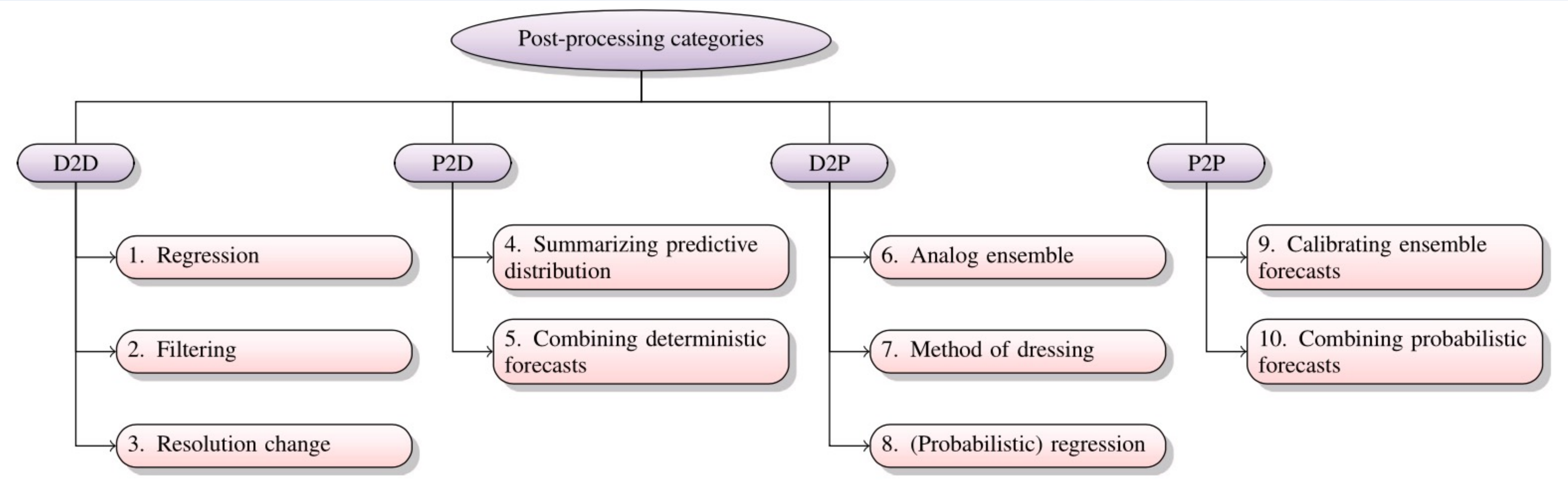
Post-processing

FIG. A complete typology of solar forecast post-processing



SOLAR FORECASTING – IRRADIANCE TO POWER

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Irradiance-to-power conversion

Indirect approach considers explicitly the physics of different steps of the conversion, which include

- solar positioning
- separation and transposition modeling
- PV cell temperature modeling
- soiling, shading, mismatch
- degradation

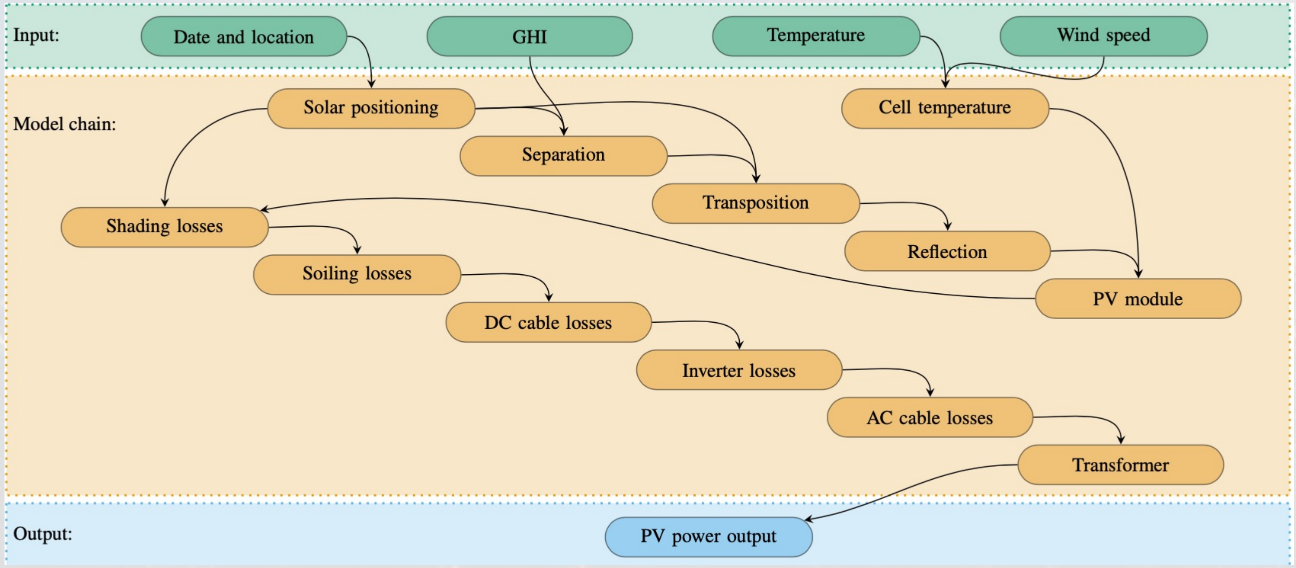
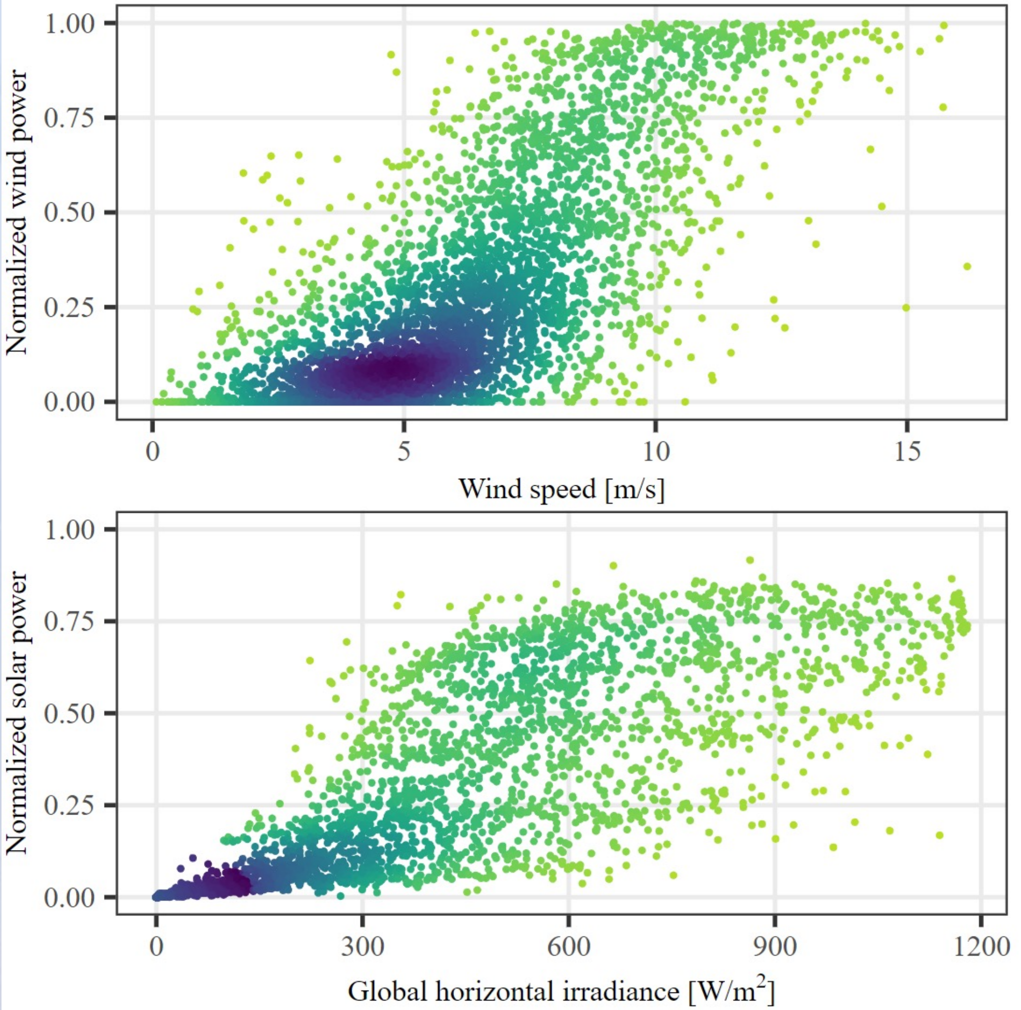


FIG. A TYPICAL WIND/SOLAR POWER CURVE



SOLAR FORECASTING – SEPARATION MODEL

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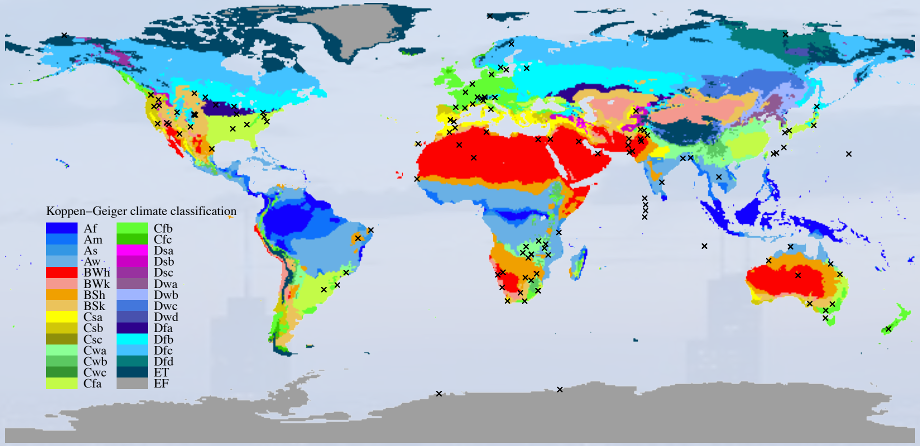
- Irradiance-to-power conversion

Separation model:

- Yang 4
  - Yang, D. (2022). Estimating 1-min beam and diffuse irradiance from the global irradiance: A review and an extensive worldwide comparison of latest separation models at 126 stations. Renewable and Sustainable Energy Reviews, 159, 112195.

FIG. Worldwide validation of separation models

(a) Location of 126 test stations



(b) Linear ranking for model performance

Model	Site 1	2	3	···	126	Mean rank
Engerer2	4	1	6	···	6	4.32
Engerer4	7	6	7	···	8	6.68
Starke1	3	5	2	···	3	3.00
Starke2	5	8	3	···	2	5.04
Starke3	2	4	4	···	1	3.01
Abreu	8	7	8	···	7	7.87
Paulescu	6	2	5	···	5	4.67
Every1	10	9	9	···	9	9.10
Every2	9	10	10	···	10	8.84
Yang4	1	3	1	···	4	2.47

SOLAR FORECASTING – TRANSPOSITION MODEL

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- **Irradiance-to-power conversion**

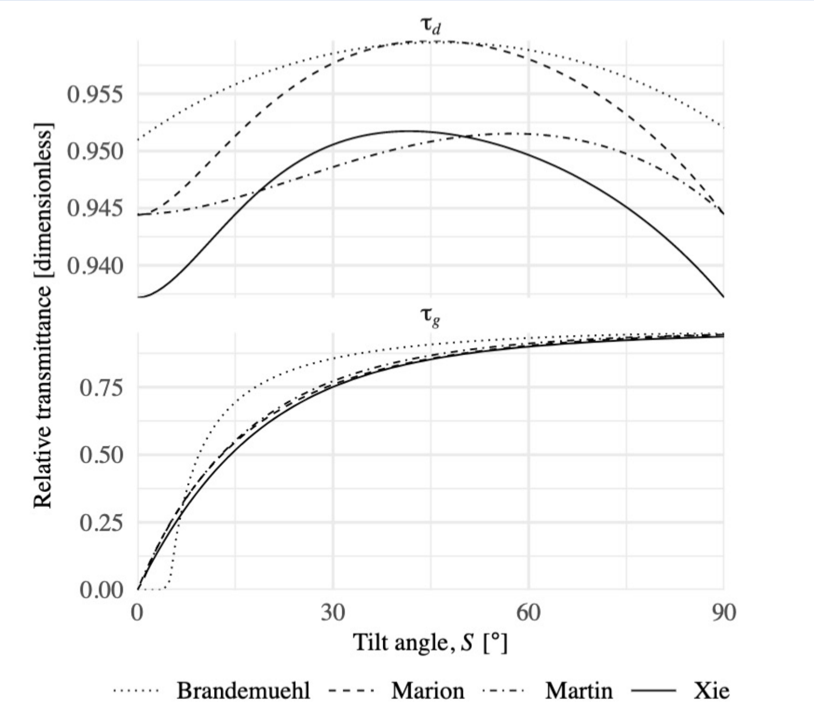
Transposition model:

- Perez model

Angle-of-incidence (AOI) models:

- Brandemuehl & Beckman 1980 (empirical)
- Martin & Ruiz 2001 (empirical)
- Marion 2017 (physical, numeric integration)
- Xie et al. 2022 (physical, analytic solution)

FIG. Latest advance in angle-of-incidence modeling



- AOI modifier for beam component (τ_b) has always been known: Snell's law and Fresnel equation.
- AOI modifier for diffuse and ground-reflected components (τ_d and τ_g) have no analytic form
- Xie et al. derived an analytical form based on the Fresnel equation.

SOLAR FORECASTING – DC MODELS

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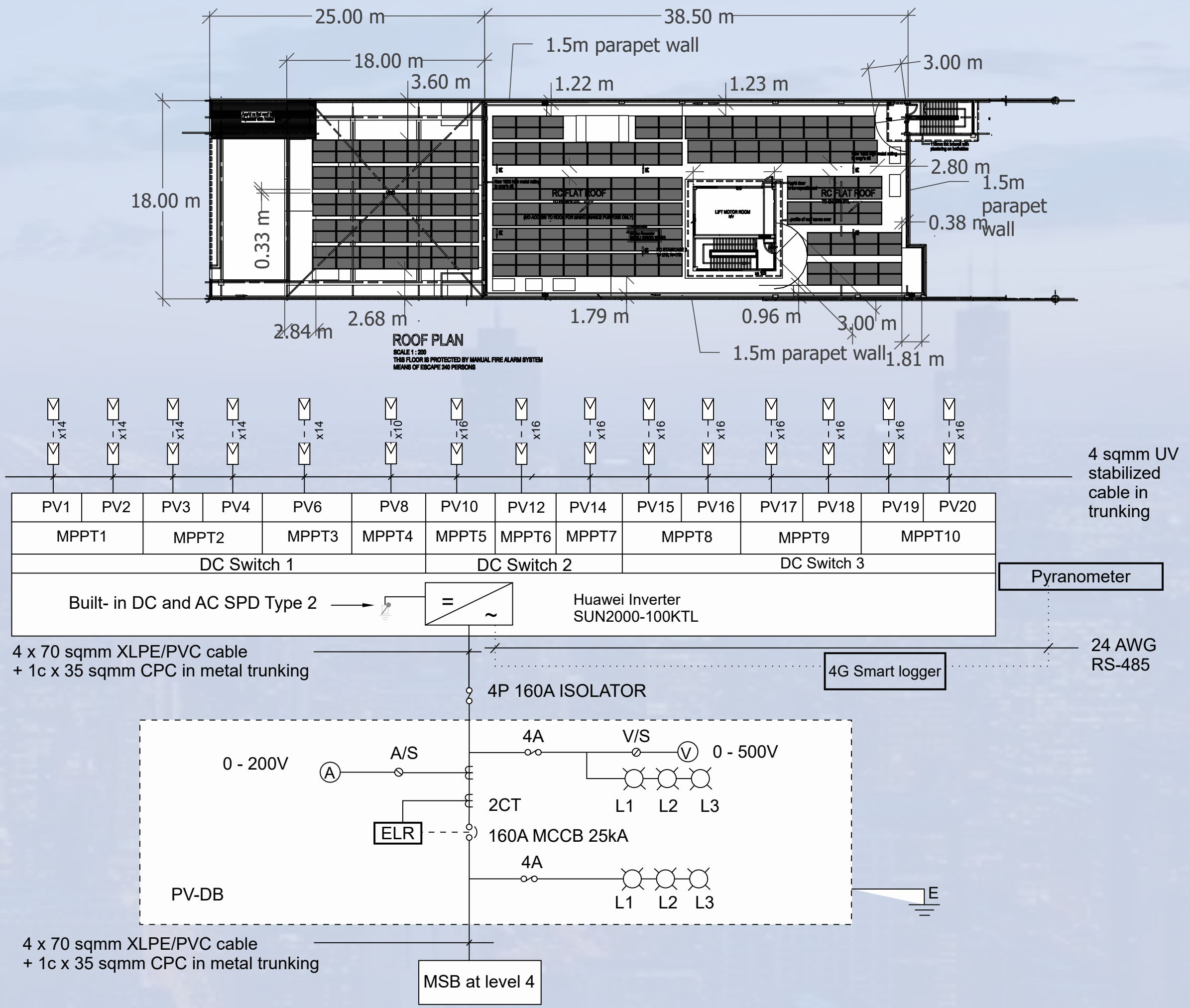
- Irradiance-to-power conversion

DC models:

- Surrogate versus detailed modeling
- How often do we have system design information?
- What is the difference between one-diode model and the PVWatts model

$$P_{\mathrm{dc}} = P_{\mathrm{dc,mpp,ref}} \frac{G_c'}{1000\ \mathrm{W/m^2}} \left[1 + \gamma \left(T_{\mathrm{cell}} - 25^{\circ}\mathrm{C}\right)\right]$$

FIG. The design of an actual roof-top PV system with DC capacity of 103 kWp



SOLAR FORECASTING – VERIFICATION AND VALUE

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Forecast verification

Consistency, **quality**, and **value**

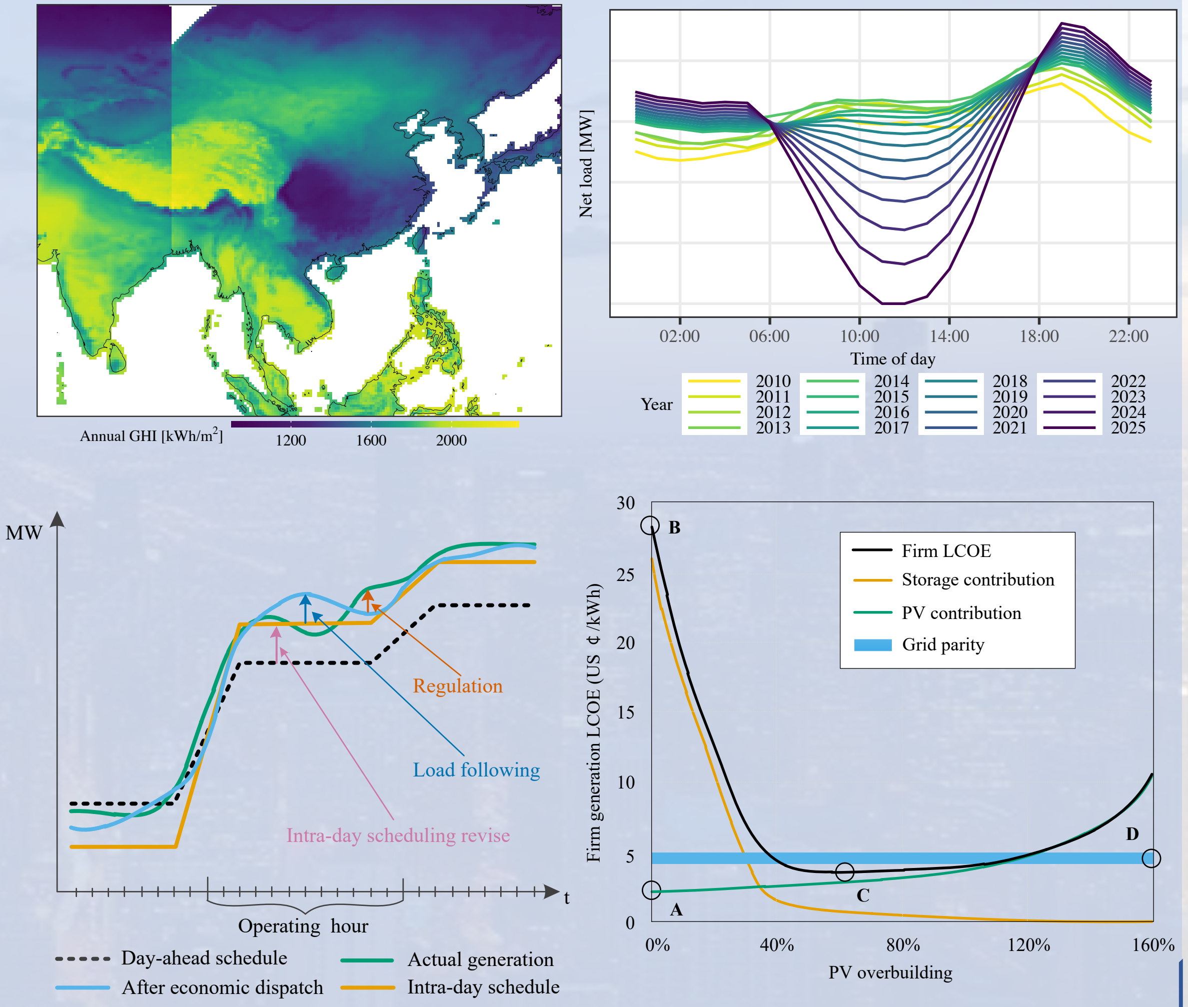
Materialization of values

Examine the value of forecasts based on the time scale, the spatial domain, and the market for which the forecasts are produced.

“First, it should be understood that forecasts possess **no intrinsic value**. They acquire value through their ability to **influence the decisions** made by users of the forecasts.”

--Allan Murphy

FIG. SOME CONSIDERATION FOR GRID INTEGRATION



SOLAR FORECASTING – VALUE / PENALTY EXAMPLE

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Post-Processing Probabilistic Forecasts

4 Chinese grid operators with different penalty triggers and penalty equations.
How to post-process dynamical ensemble forecasts into highest-value deterministic forecast?

Scoring Functions

Using the appropriate scoring functions can reduce forecast error by O(a few %), occasionally more.

TAB. PENALTY TERMS FOR 4 CHINESE GRID OPERATORS

zone	penalty trigger [dimensionless]	penalty [¥]	scoring function	consistent functional
CCG	$E = \frac{1}{96}\sum_{t=1}^{96}\frac{\lvert x_t - y_t\rvert}{\mathrm{Cap}} > 15\%$	$(E - 15\%) \times \mathrm{Cap[MW]} \times 1.5[\mathrm{h}] \times p^{\mathrm{avg}}[¥/\mathrm{MWh}]$	AE	median
CSG	$E = \frac{1}{\mathrm{Cap}}\sqrt{\frac{1}{96}\sum_{t=1}^{96}(x_t - y_t)^2} > 15\%$	$(E - 15\%) \times \mathrm{Cap[MW]} \times 1[\mathrm{h}] \times p^{\mathrm{avg}}[¥/\mathrm{MWh}]$	SE	mean
ECG	$E = \sqrt{\frac{1}{96}\sum_{t=1}^{96}\left(\frac{x_t - y_t}{y_t}\right)^2} > 20\%$	$(E - 20\%) \times \mathrm{Cap[MW]} \times 0.1[\mathrm{h}] \times \alpha \times p^{\mathrm{max}}[¥/\mathrm{MWh}]$	SPE	$\mathrm{med}^{(-2)}$
NEG	$E = \max\left(\left\lvert\frac{x_t - y_t}{x_t}\right\rvert\right) > 15\%, t = 1, \cdots, 96$	$\begin{cases}\int \lvert(1.15x_t - y_t\rvert dt[\mathrm{MWh}] \times 100[¥/\mathrm{MWh}] & \text{if } 1.15x_t < y_t \\ \int \lvert(0.85x_t - y_t\rvert dt[\mathrm{MWh}] \times 100[¥/\mathrm{MWh}] & \text{if } 0.85x_t > y_t\end{cases}$	RE	$\mathrm{med}^{(1)}$

TAB. 4 TYPES OF FORECAST ERRORS ASSOCIATED WITH USING DIFFERENT SCORING FUNCTIONS

Stn.	Scheme	RMSE	MAE	MRE	RMSPE
BON	mean	**111.3**	74.2	26.9	120.9
	median	113.1	**73.5**	26.9	120.9
	$\mathrm{med}^{(1)}$	116.5	75.9	**26.0**	133.3
	$\mathrm{med}^{(-2)}$	121.5	77.1	64.0	**89.5**
DRA	mean	**75.9**	47.5	13.3	58.5
	median	76.5	**47.1**	13.2	58.4
	$\mathrm{med}^{(1)}$	76.5	47.5	**12.9**	62.6
	$\mathrm{med}^{(-2)}$	82.6	49.6	19.2	**49.4**

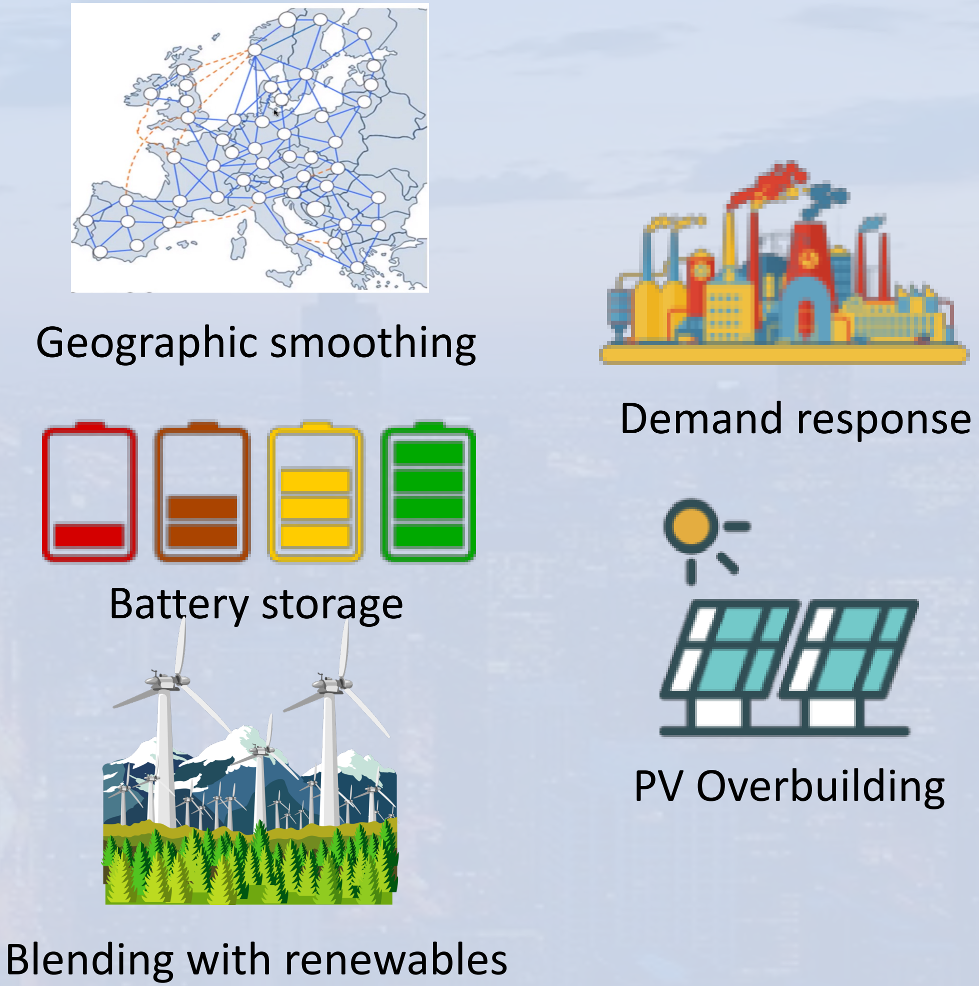
FIRM PV POWER

FIRM PV POWER ENABLERS

Firm PV Power Enablers

- Alleviate the volatility of PV power
- PV power can be thought of as *firm generator* when it is able to meet the required generation target with 100% certainty.
- Technologies that can help reduce or even remove variability are *firm power enablers* , which usually are summarized into five kinds.
- Each firm power enabler, while being attractive in its own respect, has disadvantages. For example, batteries are at present costly.

FIG. Firm PV Power Enablers



[1] Perez M, Perez R, Rábago K R, et al. Overbuilding & curtailment: The cost-effective enablers of firm PV generation. Solar Energy, 2019, 180: 412-422.

FIRM PV POWER: OVERBUILDING AND STORAGE

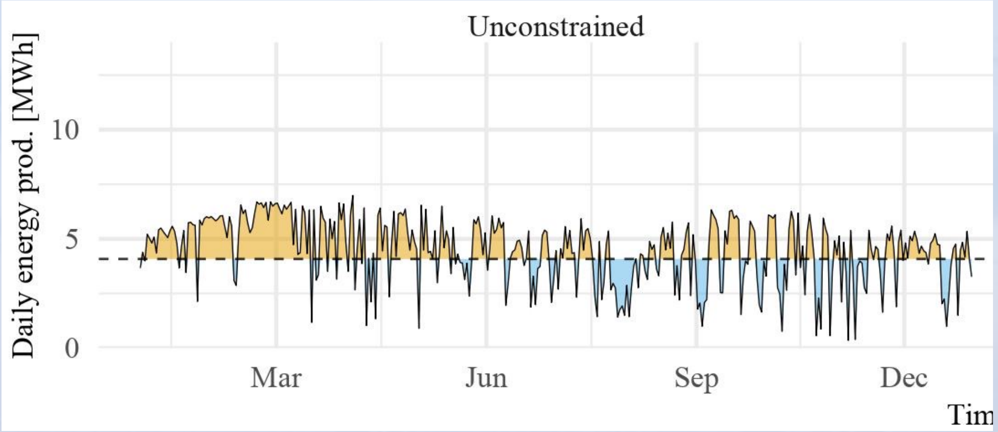
Overbuilding and Storage Example: 2x

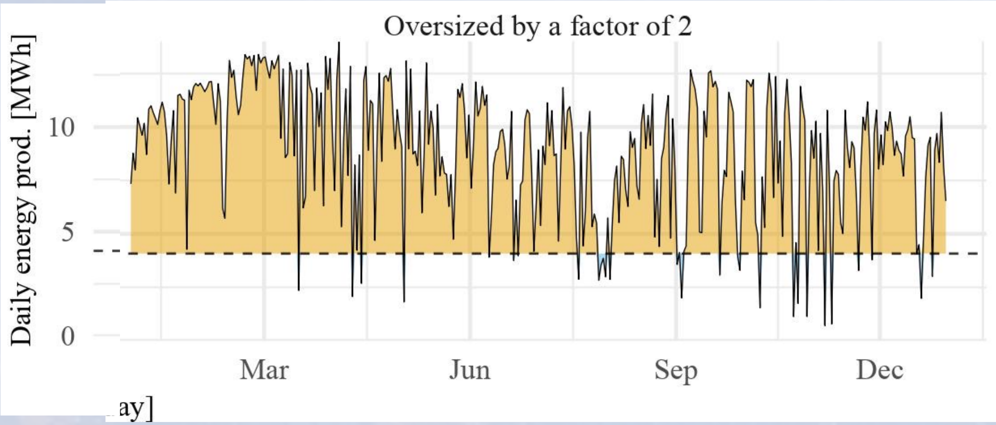
- For the non-oversized PV plant, much energy deficit is seen, which needs to be supplied through electric storage
- For the 2x overbuilt PV plant, the energy deficit is substantially reduced. Clearly, a combination of these enablers is attractive.
- We study firm power delivery through battery storage and PV overbuilding.
- Metric: Firm kWh premium

$$\text{Firm kWh premium} = \frac{\text{Firm PV generation LCOE}}{\text{Unconstrained PV LCOE}}$$

LCOE: Levelized Cost of Energy

FIG. Firm PV Power With and Without Overbuilding





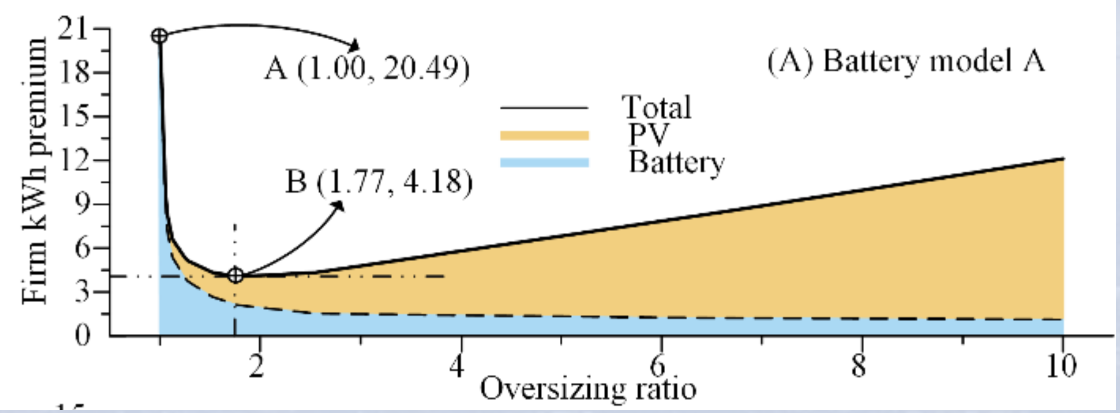
FIRM PV POWER: RESULTS

Firm kWh Premium Versus Oversizing

- When X_s = 1, i.e., no oversizing, a high firm kWh premium of 20 is obtained. However, with just a small fraction of overbuilding, there is a drastic decrease in the firm kWh premium---when X_s = 1.8, the firm kWh premium sees a five-fold reduction, reaching just 4.2. As more PV is overbuilt, the premium starts to increase quasi-linearly.

Par.	Value	Par.	Value
c_b	137 $/kWh	c_s	833 $/kW

FIG. Firm kWh premium versus oversizing ratio

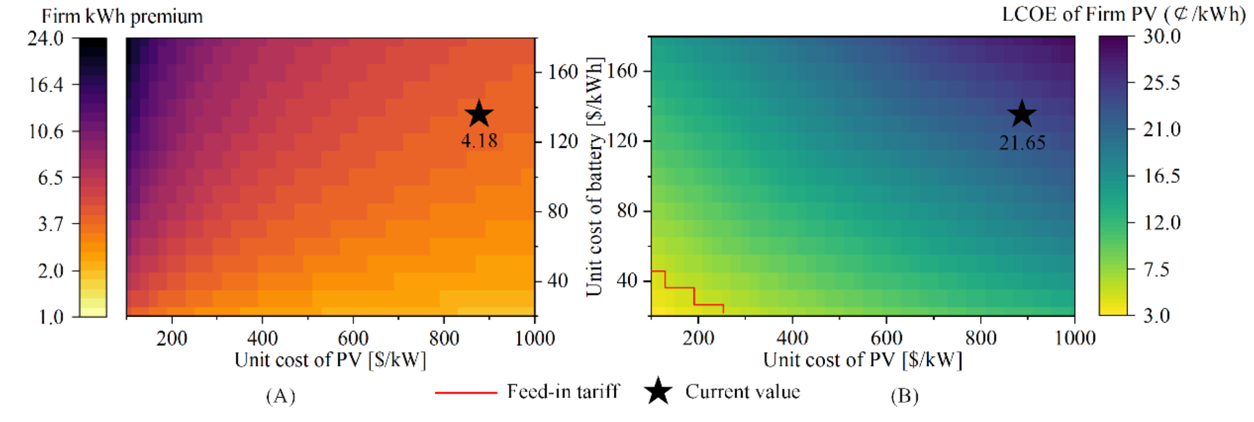


FIRM PV POWER: CONCLUSIONS

Firm PV Power Conclusions

- ☐ The lowest firm kWh premium occurs when the PV cost is high and battery cost is low, with c_s = 1000 \$/kW and c_b =20 \$/kWh, the premium is just 1.88.
- ☐ The lowest firm kWh premium under the present-day cost structure at the northern China location is around 4.18, which is still too high.
- ☐ To drop the LCOE of firm PV below grid parity, the unit investment costs of PV and battery need to be lower than 250 \$/kW and 40 \$/kWh, respectively.

FIG. Firm kWh premium sensitivity to PV and battery costs



THANK YOU!