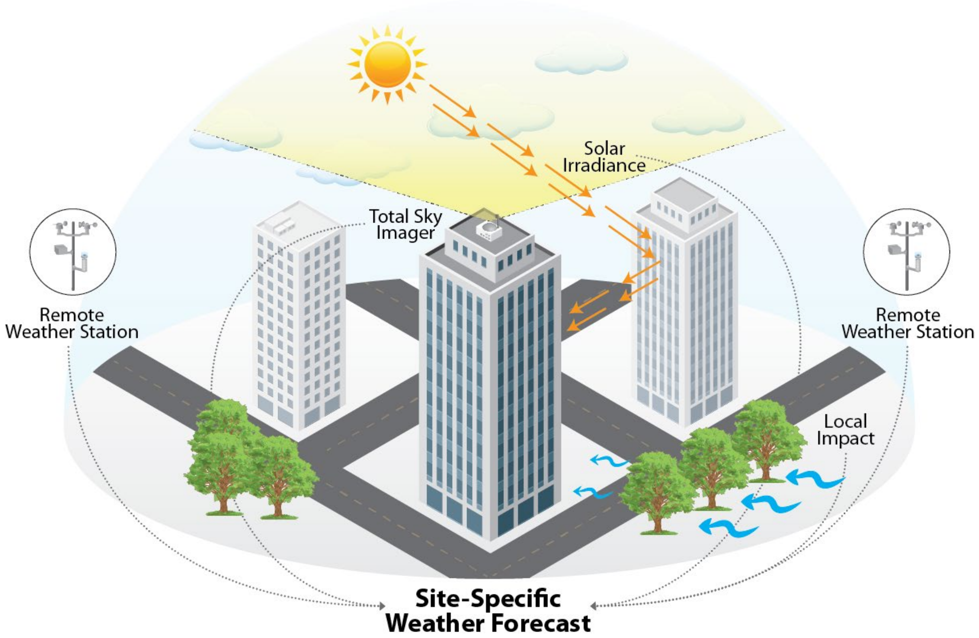
Machine-Learning-Driven, Site-Specific Weather Inference for Building Energy Forecasting



Performing Organization: National Renewable Energy Laboratory

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Xin Jin, Senior Research Engineer, 303-275-4360, Xin.Jin@nrel.gov

Project Summary

Timeline:

Start date: 10/01/2018

Planned end date: 09/30/2021

Key Milestones:

1. Achieved **≤20%** error on short-term forecasts of local weather conditions for the selected sites. **09/30/2019**
2. Achieved **≥5%** daily energy savings for selected buildings with MPC and site-specific weather forecasts. **09/30/2020**
3. Document site-specific weather forecasting methods and potential benefits for buildings. **09/30/2021**

Budget:

Total Project $ to Date:

- DOE: $750,000
- Cost Share: $0

Total Project $:

- DOE: $750,000
- Cost Share: $0

Key Partners:

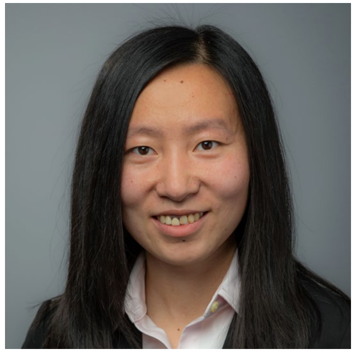
NREL Transforming ENERGY

EARTH NETWORKS

Project Outcome:

1. Advance fundamental building science on site-specific weather forecasting and its integration with advanced building controls.
2. Provide generalizable guidelines on the appropriate level of site-specific weather forecasting and its impact on building energy savings improvement.

Team



Rui Yang (PI)
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Site-specific weather forecasting

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Building control

Andrew Kumler
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Solar irradiance forecasting

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Jeff Maguire
Research Engineer
Building modeling

Rawad El Kontar
Research Engineer
Building analysis

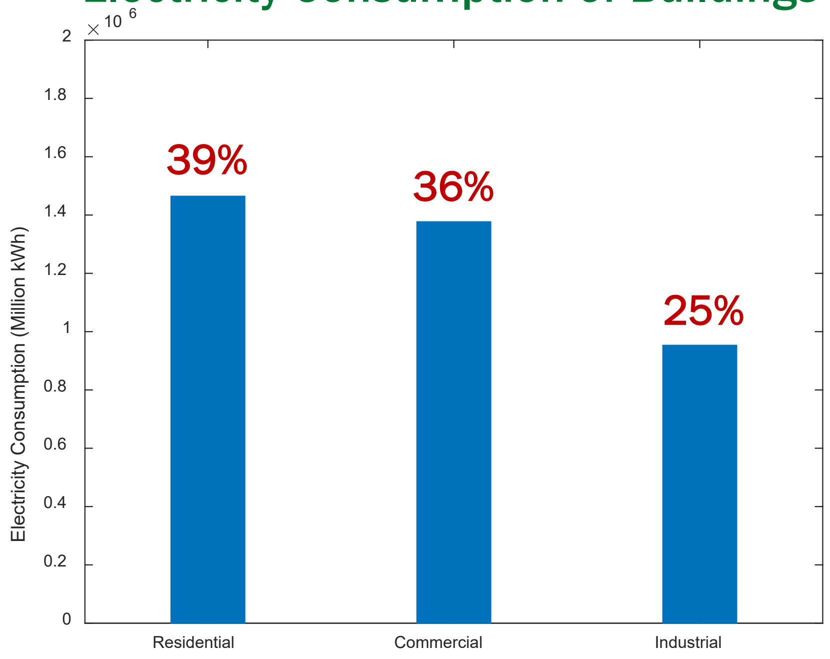
Yu Xie
Senior Research Scientist
Solar irradiance forecasting

Challenges

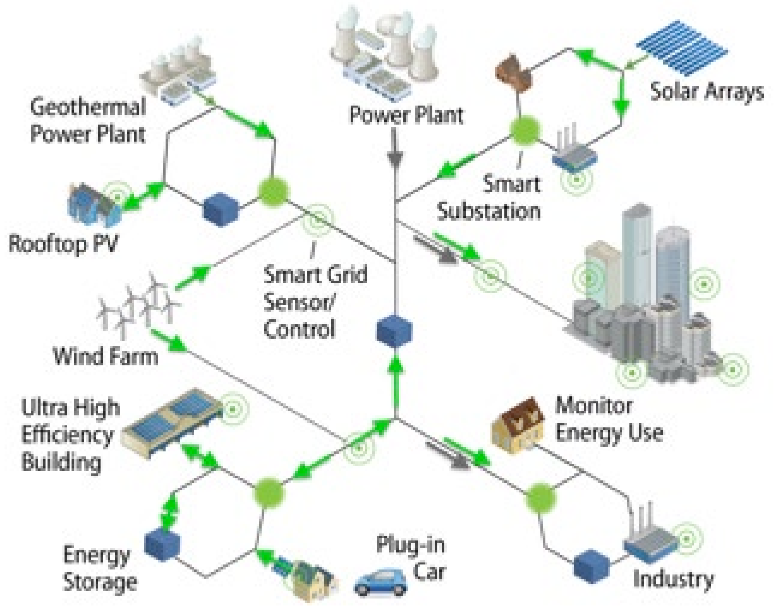
Accurate, site-specific weather forecasts are crucial for buildings

- **Input for advanced building control**
  - Predictive optimization
  - Improve energy efficiency
  - Reduce energy cost
- **Enabling technology for GEBs**
  - GEB service capabilities
  - GEB renewable energy integration
  - Optimal demand side management

Electricity Consumption of Buildings

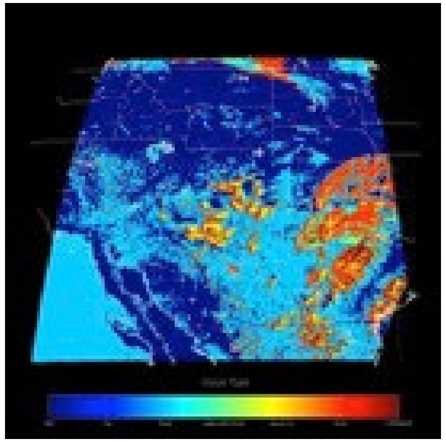


Buildings as Controllable Resources in Power Grids

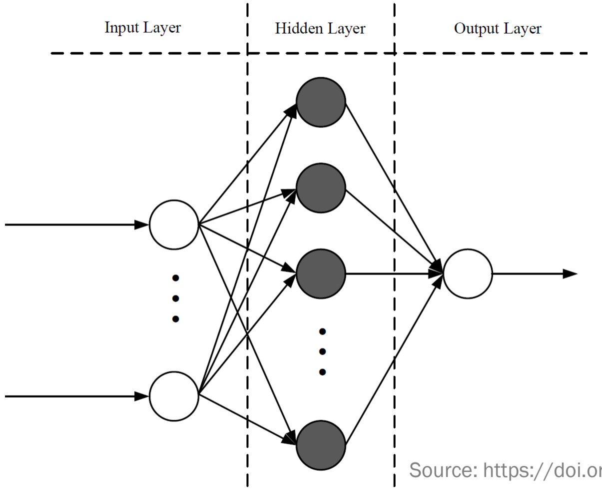


Challenges

- **Physics-based approaches**
  - Numerical weather prediction (NWP) models
  - Down to 4km^2
  - Lack the capability to further scale down to finer resolutions



- **Data-driven approaches**
  - Promising accuracy for short-term forecasts
  - Use time-series weather data
  - Not employed to provide site-specific forecasts



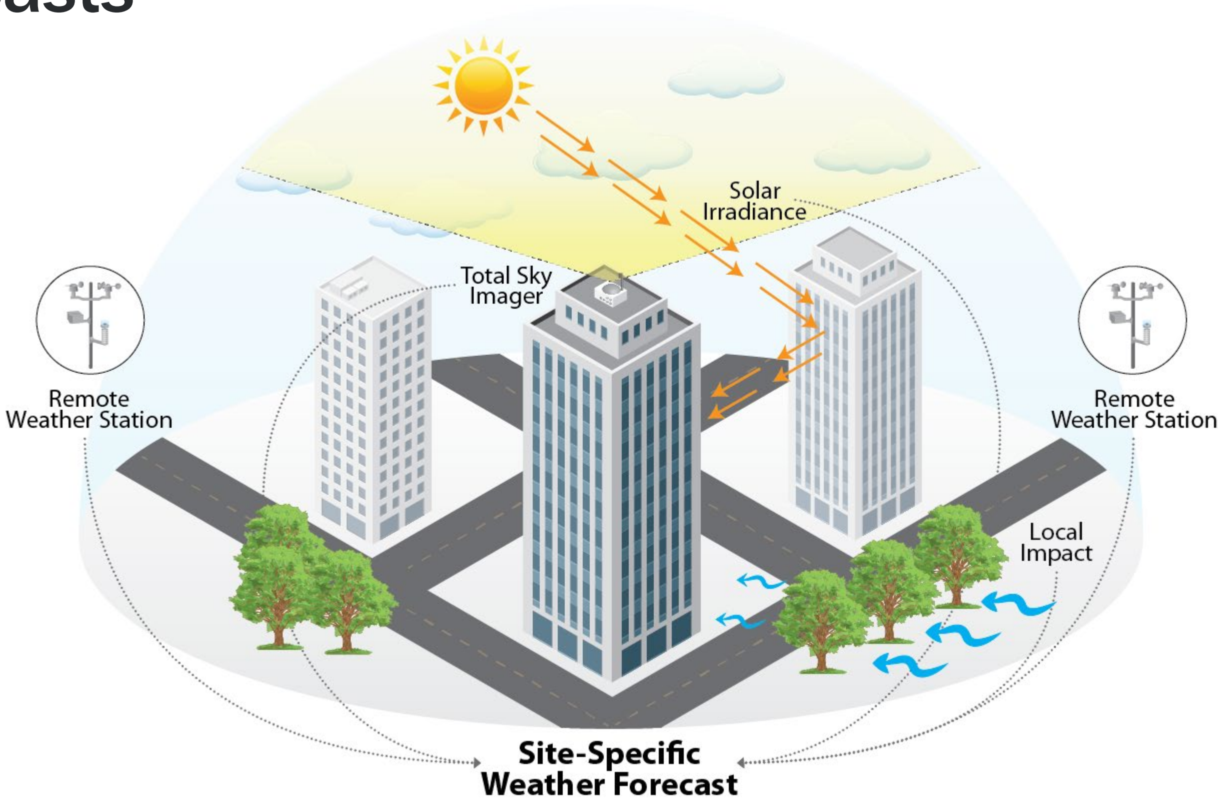
Source: https://doi.org/10.1109/PESGM.2016.7741933

No site-specific weather forecasts available for individual buildings

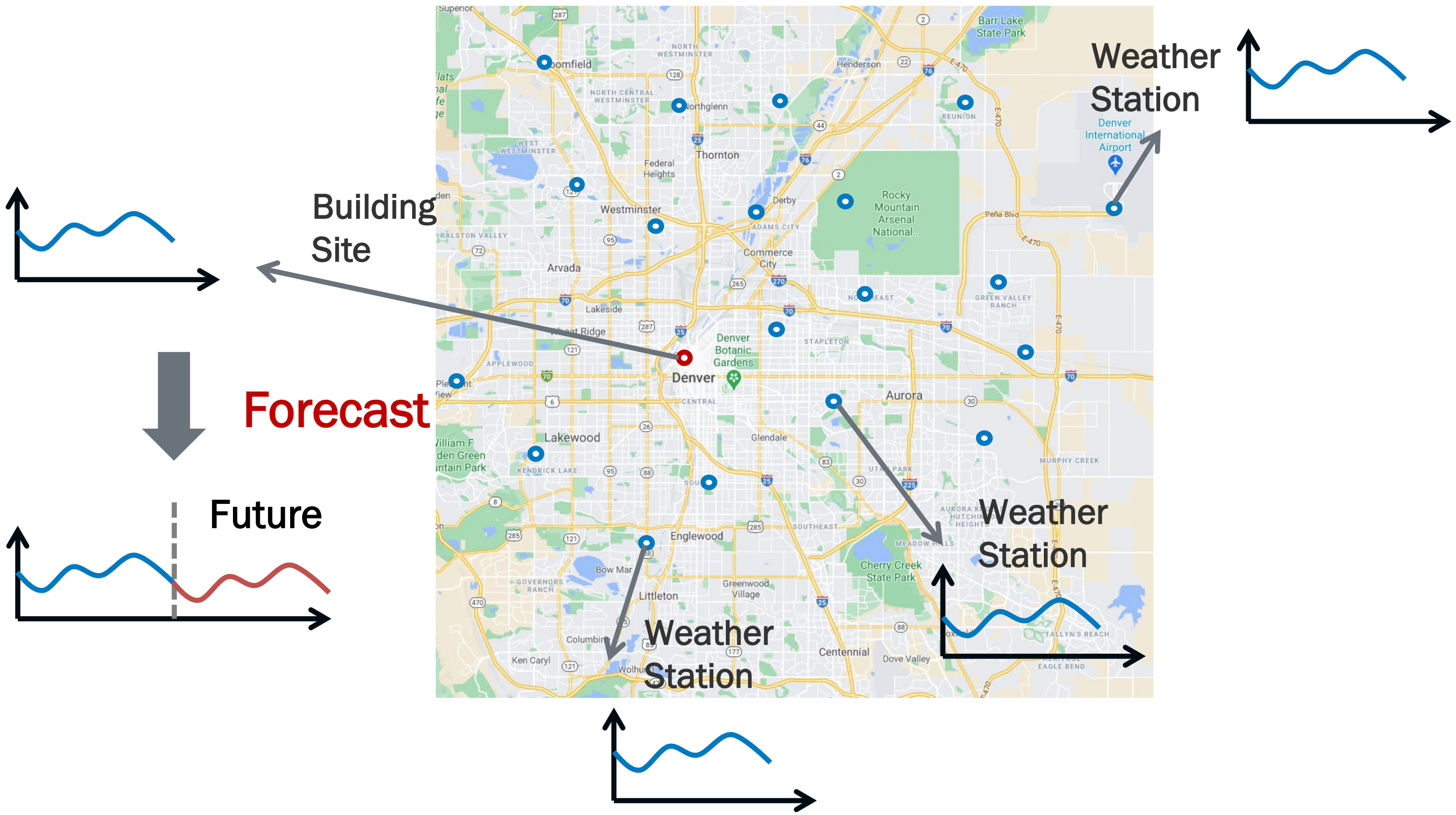
Approach

- **Develop a foundational platform to provide site-specific weather forecasts**
  – Low-cost total sky imagers (TSIs)
  – Weather station data

- **Incorporate site-specific weather forecasts in building controls**
  – Advanced control technologies
  – Co-simulation with EnergyPlus



Approach: Weather Forecasting



Historical weather station measurements

Map

Current and future weather conditions at the building site

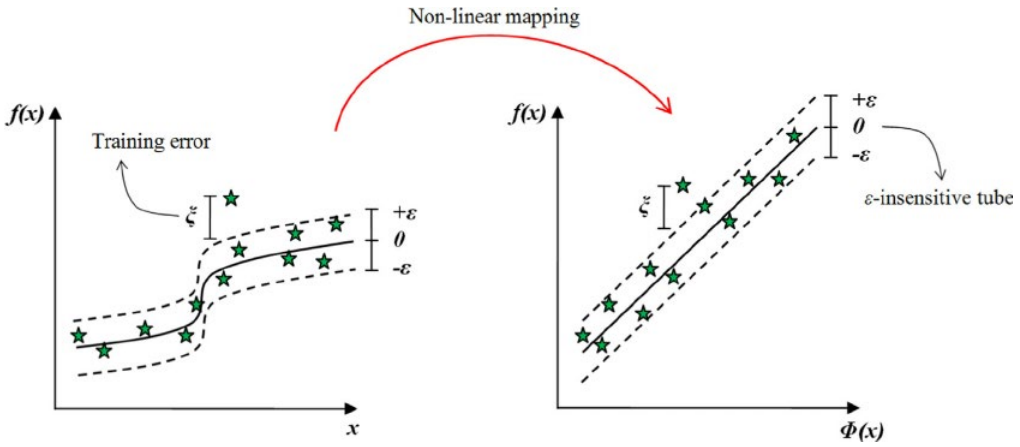
Machine Learning

Learn the spatiotemporal correlation between weather conditions at nearby weather stations and the building site

Publication #1: R. Yang, H. Jiang, J. Hao, and X. Jin, “Machine-Learning-Driven, Site-Specific Weather Forecasting for Grid-Interactive Efficient Buildings,” *2020 ACEEE Summer Study on Energy Efficiency in Buildings*, Aug. 2020.

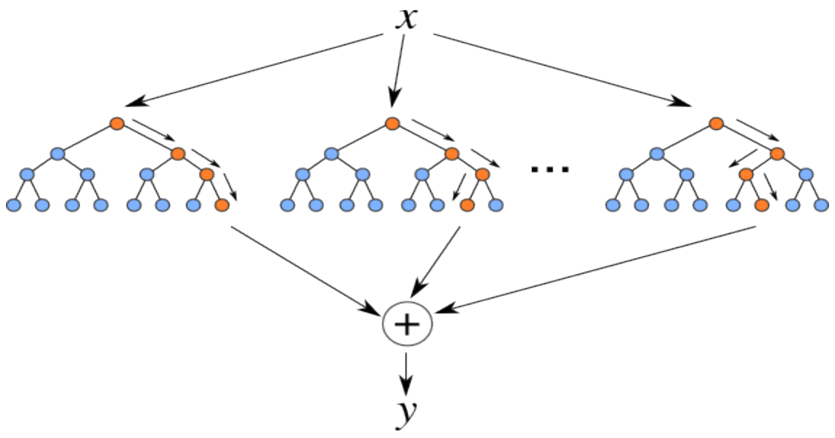
Approach: Weather Forecasting

Support Vector Regression

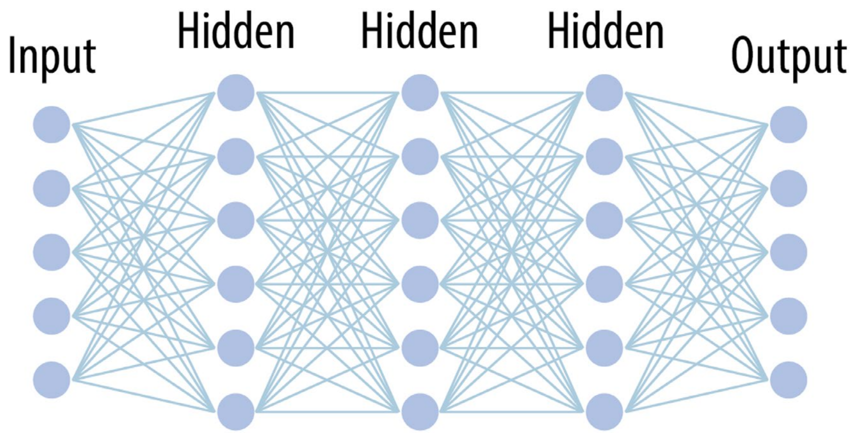


Source: https://doi.org/10.1016/j.ijrmms.2014.09.012

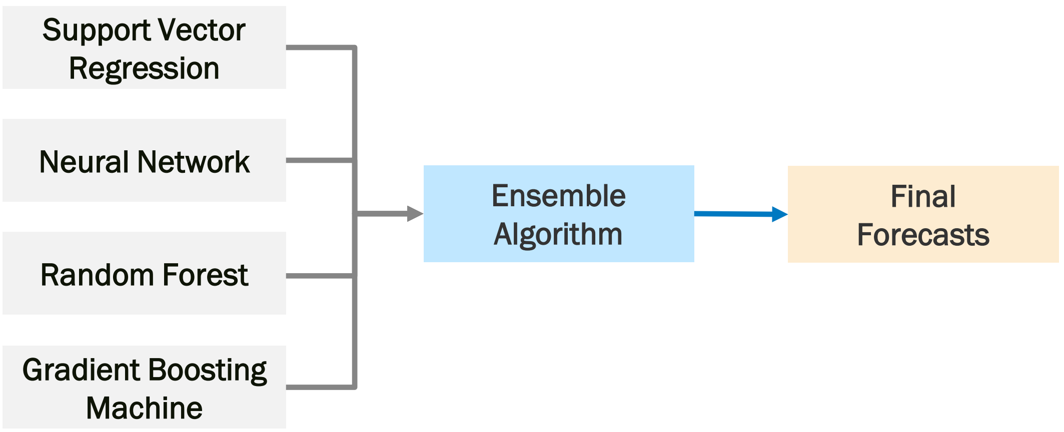
Decision Tree-Based Methods



(Deep) Neural Networks

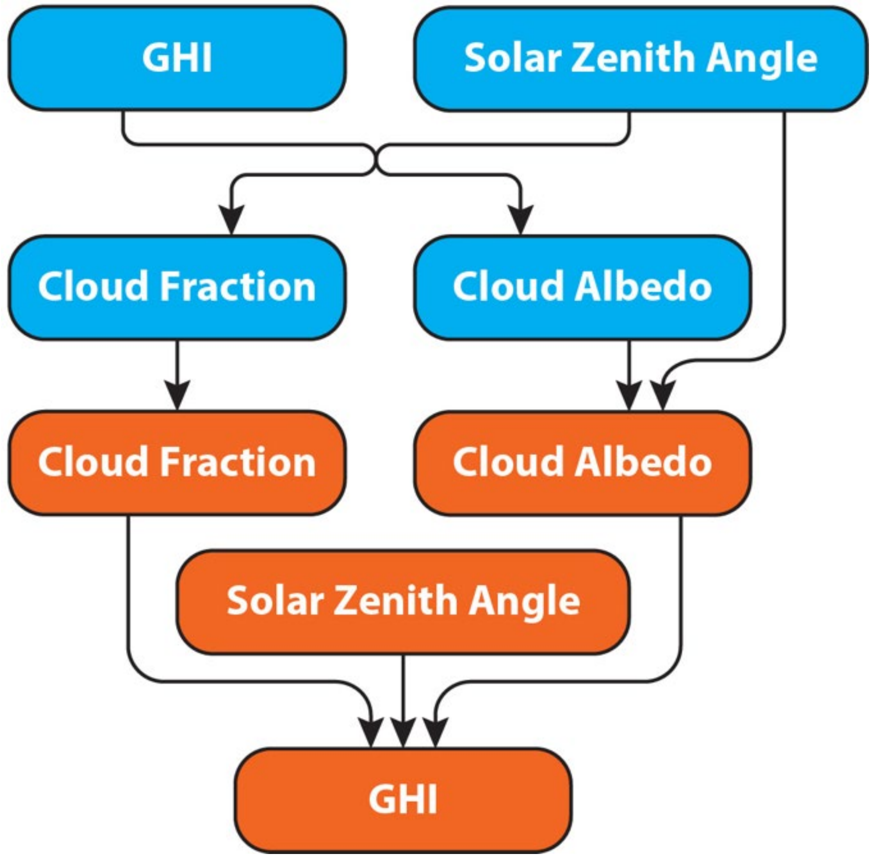


Ensemble Learning



Approach: Solar Forecasting

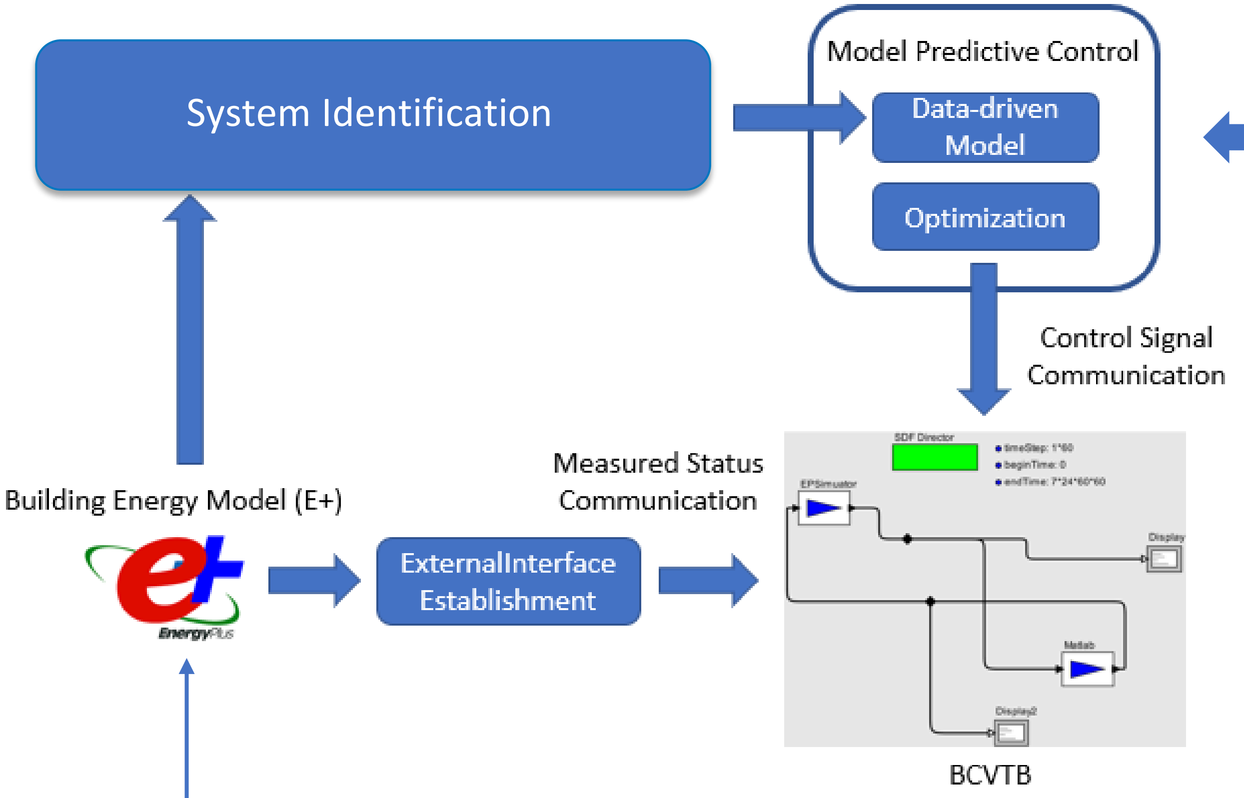
- **Physics-based, smart persistence model for intra-hour solar forecasting (PSPI)**
  - Utilize radiative transfer physics
  - Break down global horizon irradiance (GHI) into various physical components
  - Allow forecasting of separate variables
  - Integrate surface-based observations of cloud fraction from TSI
  - Investigate time-series and machine learning methods for forecasting of cloud fraction and cloud albedo



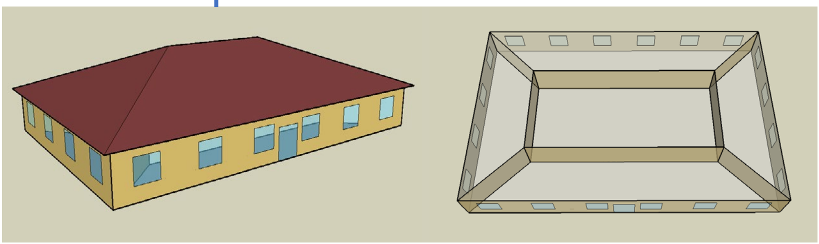
Publication #2: A. Kumler, Y. Xie, Y. Zhang, R. Yang, X. Jin, M. Sengupta, and Y. Liu, "Integration of Total Sky Imager Data with a Physics-based Smart Persistence Model for Intra-hour Forecasting of Solar Radiation (PSPI)," *American Meteorological Society Meeting*, Boston, MA, Jan. 2020.

Approach: Building Controls

Co-simulation with EnergyPlus via BCVTB



- Flexible workflow for evaluating different types of weather forecasts, building control systems, and building types.
- Model predictive control is the only control method that can take full advantage of accurate, intra-day weather forecasts.



- Small office building from the DOE reference building library
- 5 zones: 4 perimeter zones and 1 core zone
- IECC 2009 Code
- Floor area: 511 m^2

Impacts: Support DOE Missions and Benefit Stakeholders

- **Net-zero emissions by 2050 and carbon-free electricity sector by 2035**
- **Energy justice for disadvantaged communities**
- **Energy, Emission and Equity (E3) Initiative**

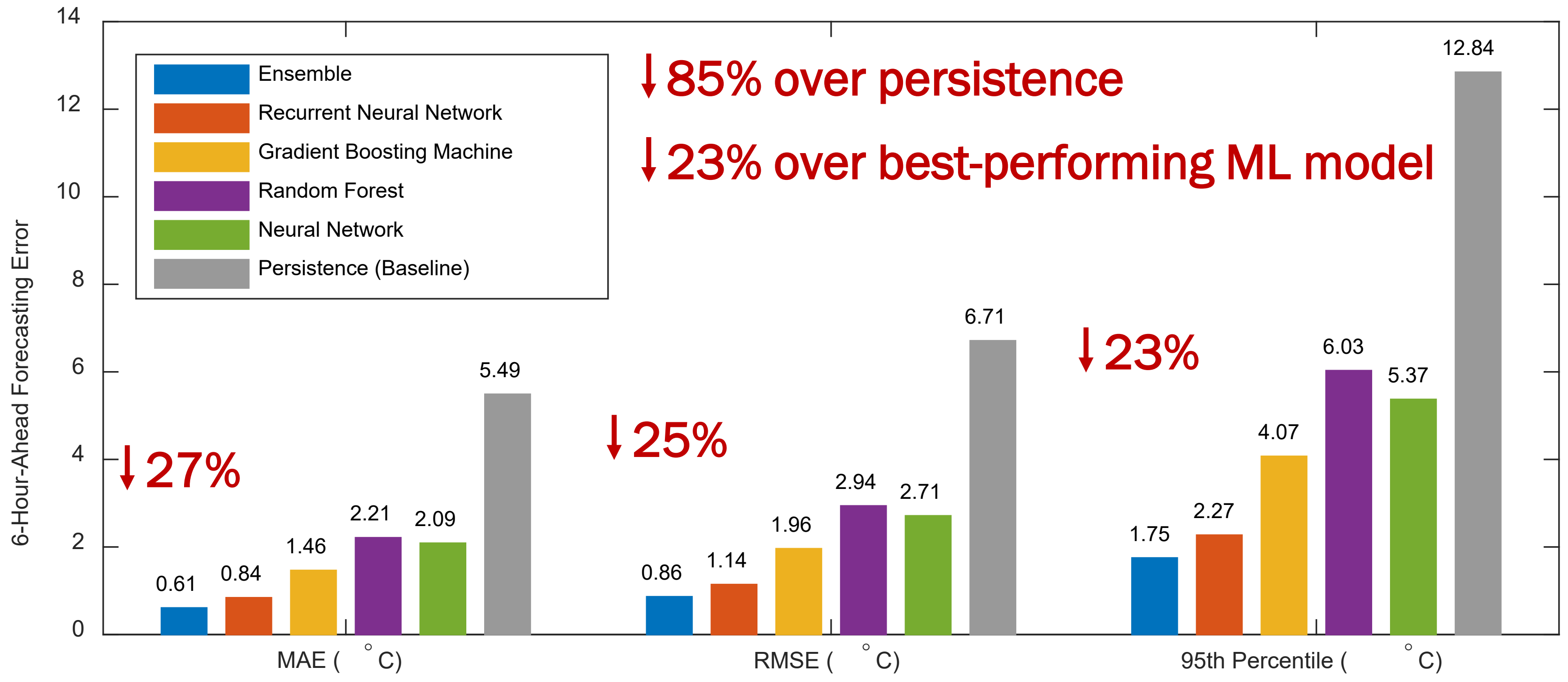
Audience/Customers	How audience will use the results
Building Owners/Operators	• Better understanding of the **microclimate** and its impact to building energy use; • Drive efficiency upgrades or adjustments of building control strategies for **better energy savings**; • Leverage solar irradiance forecasts to **reduce energy cost** for buildings with rooftop photovoltaics.
Equipment Manufacturers	• Incorporate the site-specific weather forecasts in their product; • Improve pre-cooling and pre-heating, leverage natural ventilation; • Save energy and improve efficiency.
Weather Service Providers	• Provide more accurate forecasts that are specific to a building site instead of a large area.
Buildings Researchers	• Use the site-specific forecasts to improve simulation accuracy and reliability of techno-economic analysis.

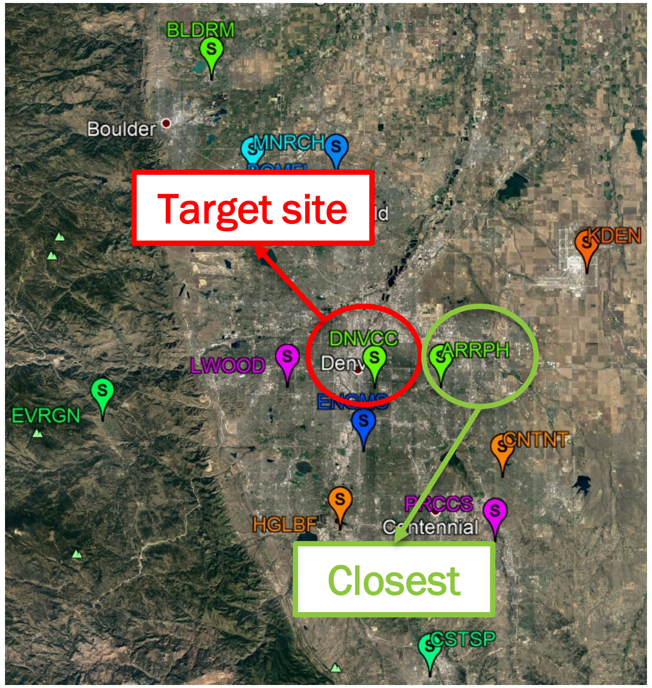
Progress: Weather Forecasting

Representative Results in Denver

Data from 13 stations in 2017
- 274 days for training
- 91 days for testing

6-Hour-Ahead Temperature Forecasting Error Comparison

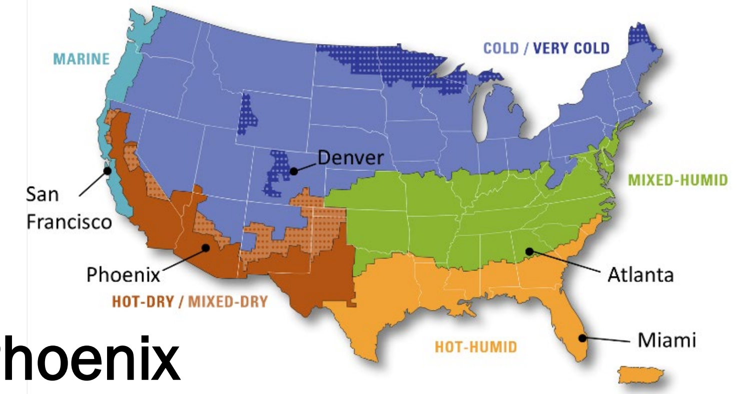




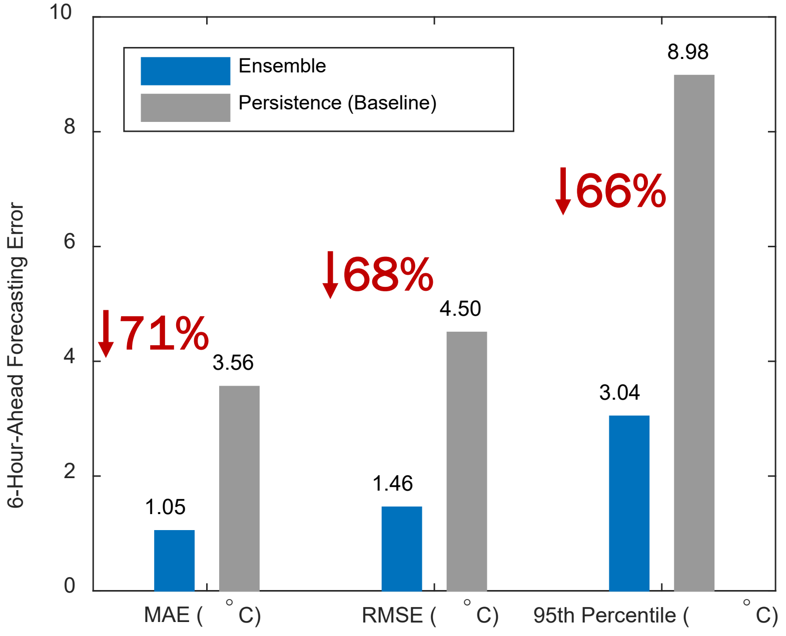
Superior accuracy using machine-learning-based forecasting methods

Progress: Generalization

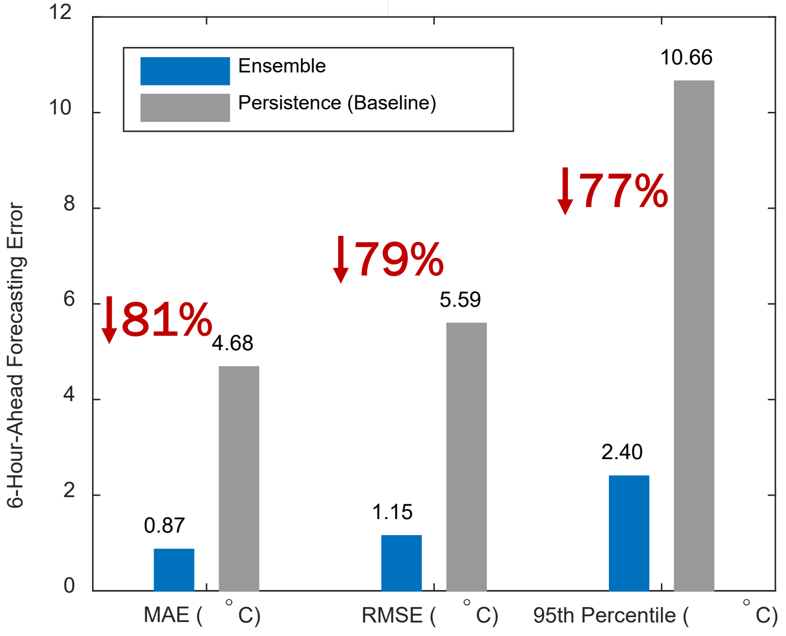
- **Generalization to different climate zones**
  - Same model trained in the Denver metro area
  - Using 91 days of data for calibration, the rest 274 days for testing



Atlanta



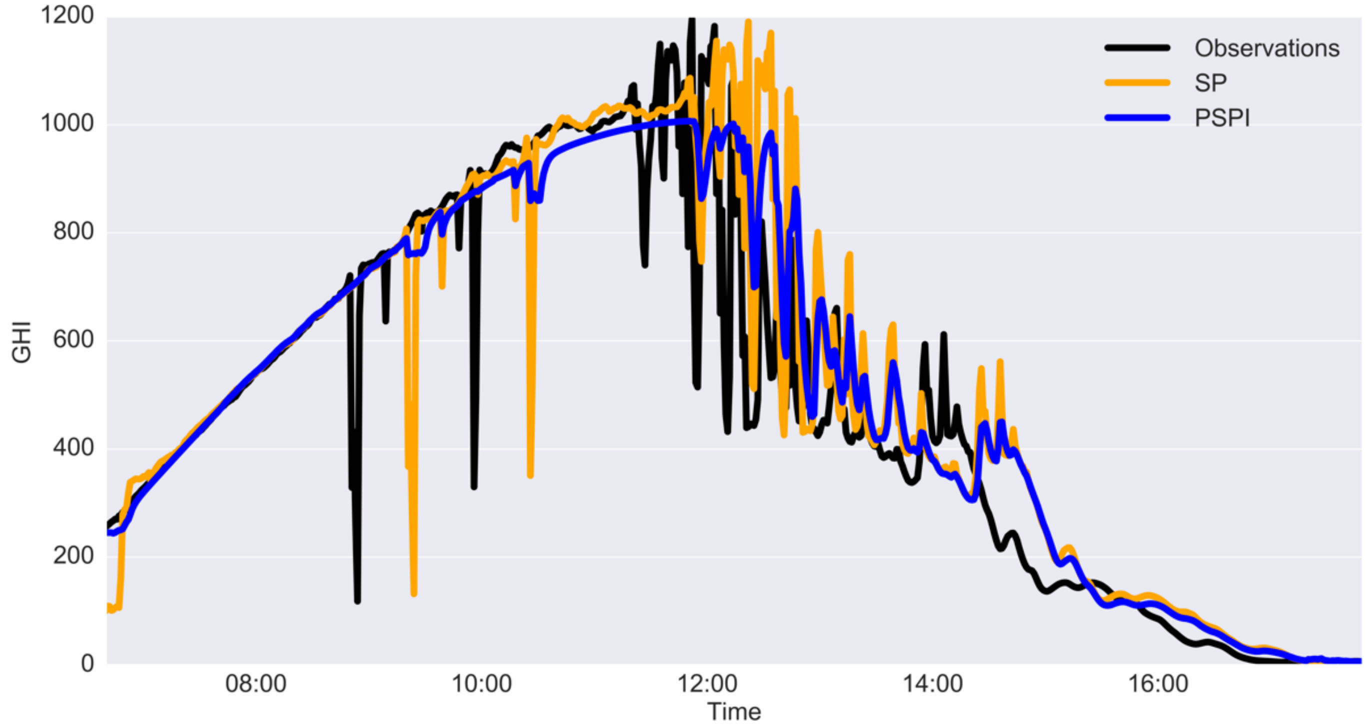
Phoenix



Machine-learning-based forecasting methods can generalize to different climate zones

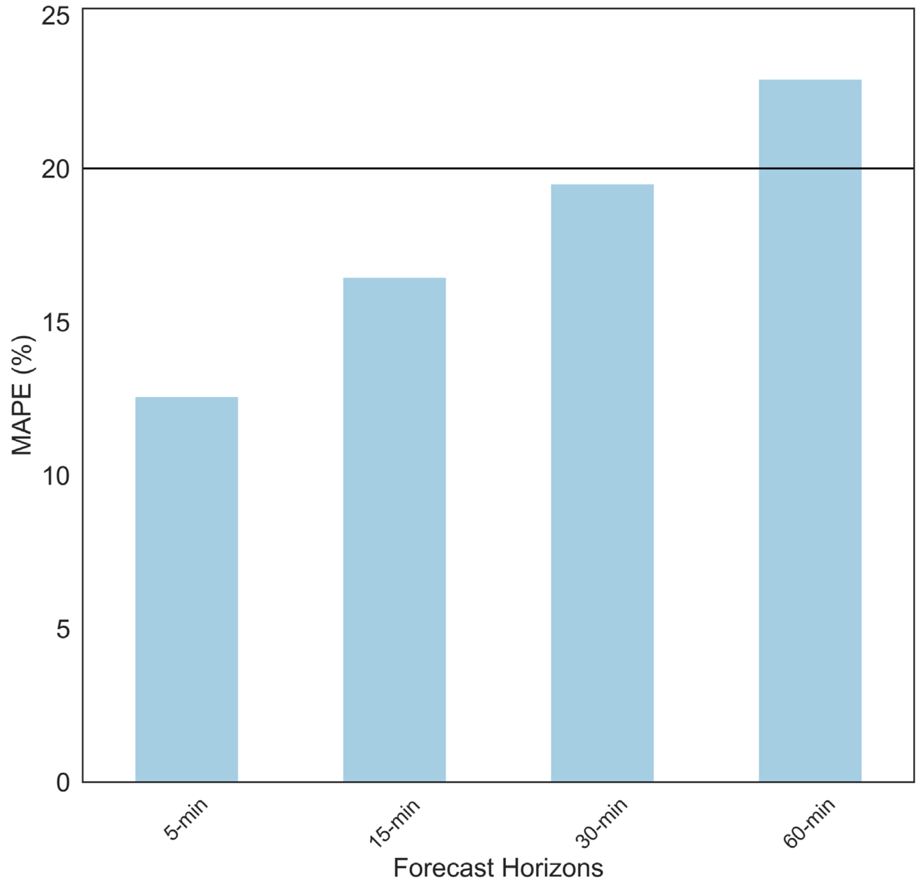
Progress: Solar Forecasting

One Example Day



30-minute forecasts for 2014-04-23

MAPE for PSPI + TSI

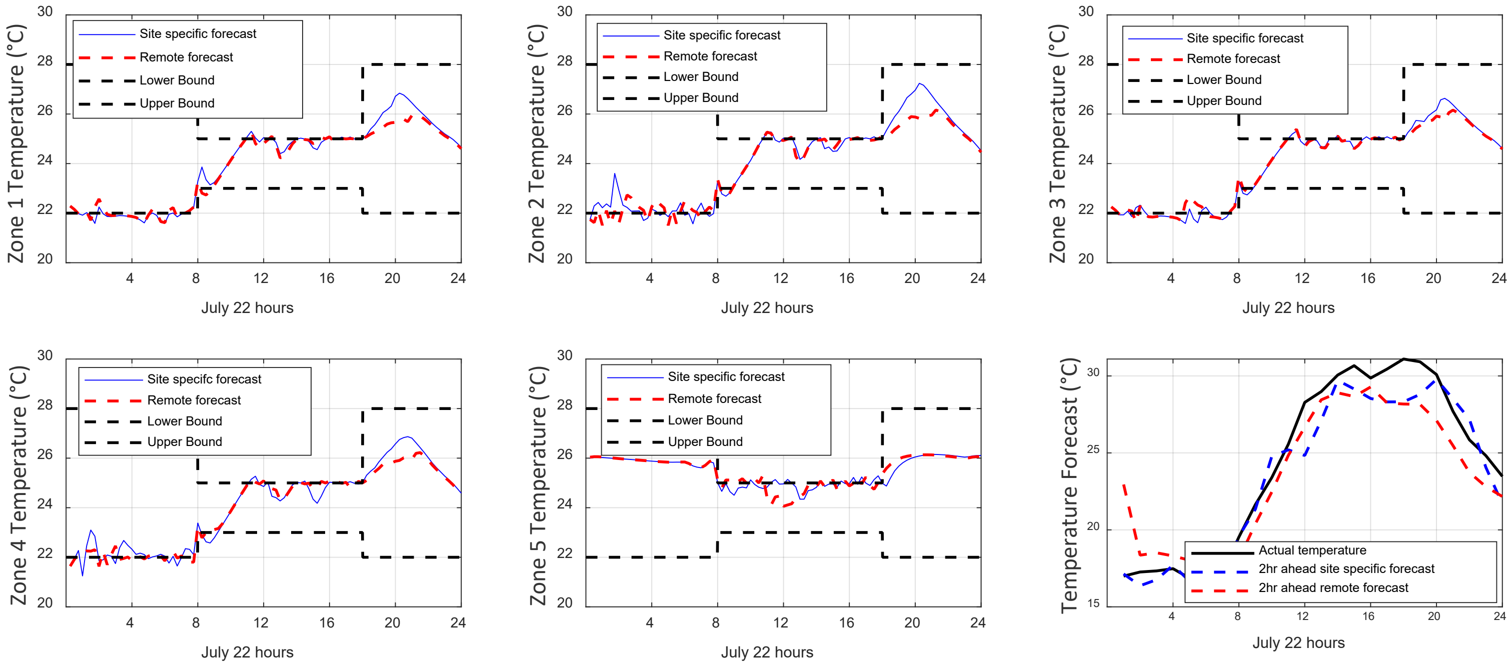


Evaluation for 2014-2018

Accurate intra-hour solar irradiance forecasts with TSIs

Progress: Buildings

Site-specific weather forecasts improve energy cost savings while maintaining thermal comfort



Indoor temperature of the small office reference building in a typical summer day in Denver

Under time-of-use rate, MPC with site-specific forecasts achieved:

- 15.6% cost savings compared to the baseline case without MPC
- 5.4% cost savings compared to the case with remote forecasts and MPC
- Comparable thermal comfort levels

Similar results were observed during other days in the summer and in other scenarios with different rate structures.

Key findings:

- MPC is tolerant of weather forecast errors because it uses receding horizon and buildings act as low-pass filters.
- Site-specific forecasts can generate higher energy cost savings in mild days when the cooling load is relatively low.
- Standard weather services can still be used to drive MPC as long as the forecast error is smaller than 2°C.

Stakeholder Engagement

- **Technical advisory group**
  - Regular meetings with advisory group
- **Dissemination**
  - 1 conference paper published
  - 2 conference presentations
  - 1 journal paper finalized
- **Potential adoption**
  - Active discussion with partner for industry adoption
  - Potential implementation in a microgrid

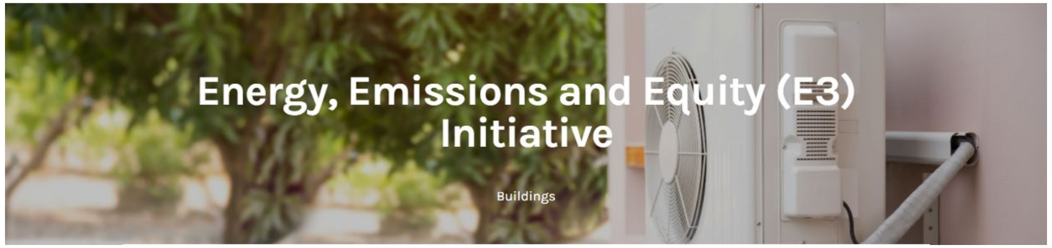
Remaining Project Work

Remaining Project Work

1. **Wrap up building simulations to demonstrate values of site-specific weather forecasts**
   – Complete simulations for 3 use cases
2. **Document and close out project**
   – Complete the final report of the project
   – Organize a technical advisory group webinar
3. **Complete in-progress publications:**
   – Transfer learning-based generalization of site-specific weather forecasting method
   – Value analysis of site-specific weather forecasts with MPC for buildings

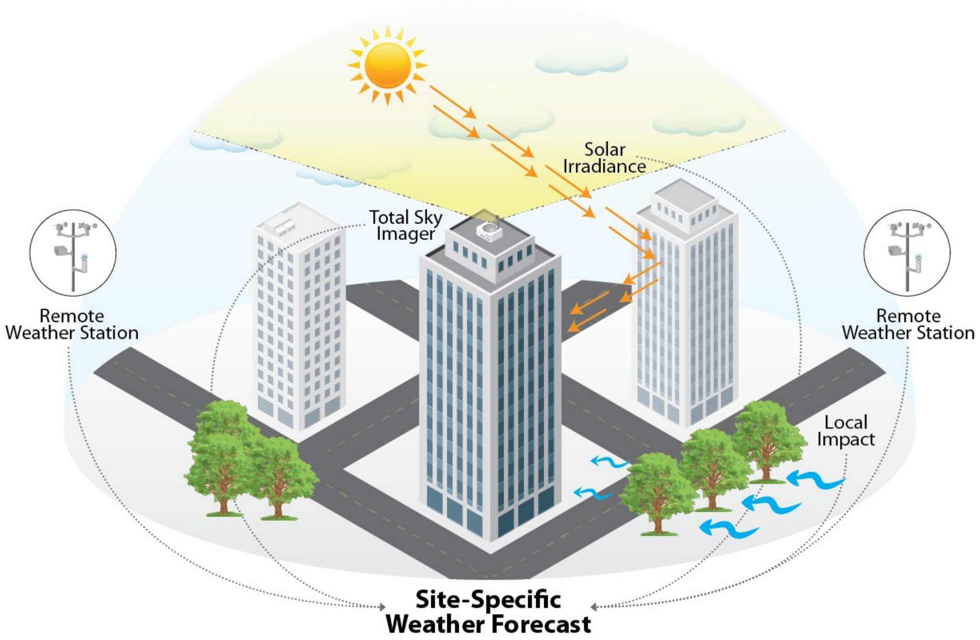
Future Research Topics

- **Energy justice**
  – Explore the impact of microclimate on disadvantaged neighborhoods
  – Inform future urban planning and policy making
- **Supporting E3 Initiative**
  – Improve the efficiency and reduce emissions of heat pumps
  – Better understand microclimate's impact on heat pump efficiency and operational limit



Source: DOE

Thank You



Performing Organization: National Renewable Energy Laboratory

Principal Investigators: Rui Yang, Senior Research Engineer, 303-275-4336, Rui.Yang@nrel.gov

Xin Jin, Senior Research Engineer, 303-275-4360, Xin.Jin@nrel.gov

REFERENCE SLIDES

Project Budget

Project Budget:

Variances: No variances.
Cost to Date: $665,226.
Additional Funding: None.

	DOE
FY19	$250,000
FY20	$250,000
FY21	$250,000
Total	**$750,000**

Budget History					
FY 2019 – FY 2020 (past)		FY 2021 (current)		FY 2022 (project concluded)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500,000	$0	$250,000	$0	N/A	N/A

Project Plan and Schedule

Legend: Past work · Current work · ▲ Completed milestone · ★ Completed Go/No-Go · ★ End-of-project goal

Task	Description	FY 2019 Q1	FY 2019 Q2	FY 2019 Q3	FY 2019 Q4	FY 2020 Q1	FY 2020 Q2	FY 2020 Q3	FY 2020 Q4	FY 2021 Q1	FY 2021 Q2	FY 2021 Q3	FY 2021 Q4
1	Develop site-specific weather inference using weather station data	Past work	Past work										
2	Develop solar irradiance forecasting method using TSIs			Past work	Past work								
3	Evaluate the impact of different weather conditions on building energy consumption			Past work	Past work								
4	Improve the site-specific weather forecasting methods					Past work	Past work	Past work					
5	Develop building energy models with predictive controllers					Past work	Past work						
6	Quantify the impact of building-specific variables to energy consumption						Past work	Past work					
7	Evaluate the energy savings impact of site-specific weather forecasts and predictive controller							Past work	Past work				
8	Develop ensemble learning method to improve site-specific weather forecasting methods									Past work	Past work		
9	Demonstrate the potential values of site-specific weather forecasts for buildings										Past work	Past work	
10	Disseminate the project results											Current work	Current work

M	Description	FY 2019 Q1	FY 2019 Q2	FY 2019 Q3	FY 2019 Q4	FY 2020 Q1	FY 2020 Q2	FY 2020 Q3	FY 2020 Q4	FY 2021 Q1	FY 2021 Q2	FY 2021 Q3	FY 2021 Q4
M1	Identify potential members for a technical advisory group	▲											
M2	Summarize site-specific weather inference method and results		▲										
M3	Summarize the impact analysis results of different weather conditions on building energy consumption			▲									
M4	Deliver a technical report on the developed site-specific weather forecasting method and results				▲								
GNG-1a	Strong correlation between the weather differences and building energy consumption				★								
GNG-1b	Achieve less than 20% error on short-term forecasts of local weather conditions				★								
M5	Summarize the validation results of the weather forecasting methods					▲							
M6	Summarize the building model and controller development efforts and outcomes						▲						
M7	Summarize the impact of building-specific variables to building energy consumption							▲					
GNG-2	Achieve at least 5% daily energy savings with MPC and site-specific weather forecasts								★				
M8	Demonstrate the site-specific weather forecasting methods can generalize to different climate zones									▲			
M9	Validate the site-specific weather forecasting methods in different climate zones										▲		
M10	Quantify the potential benefits of site-specific weather forecasts for buildings											▲	
EPG	Deliver a final report and present the work to the technical advisory group in a webinar												★