NREL
Transforming ENERGY

Tools Assessing Performance (TAP) 2.0

Dmitry Duplyakin and the **entire TAP team**

PI: Heidi Tinnesand

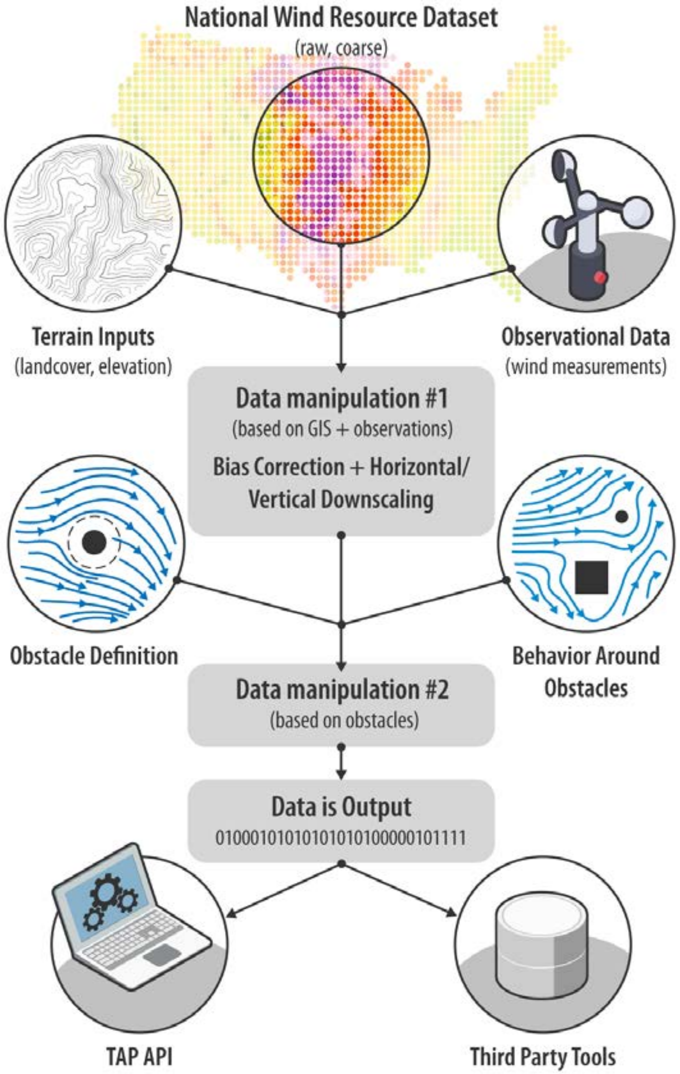
Feb. 28, 2023

Photo by Dennis Schroeder, NREL 55200

TAP Computational Pipeline

Design targets:

- Use of multiple inputs
- Customizable
- Open-source
- Efficient



TAP Computational Pipeline

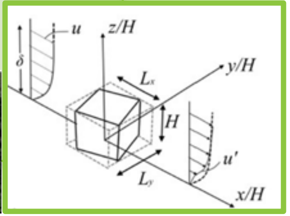
Inputs

(on NREL's high-performance computer or in the cloud)

WTK (2007–2013), 2-km res., hourly
--- or ---
WTK-LED (2001–2020), 2–4-km res., 5-min to hourly

Site analysis

1. Selection of (min, median, max) years for wind speed
2. Regional bias correction
3. Vertical and horizontal interpolation
4. Obstacle modeling



Estimates

1. **Wind speed**
2. **Wind direction**
3. Pressure
4. Temperature

(single point)

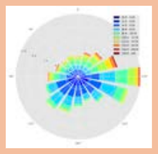
(single point)

(multiple points)

Visualizations

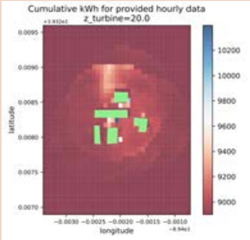
(produced locally or on NREL's high-performance computer or in the cloud)

Wind rose



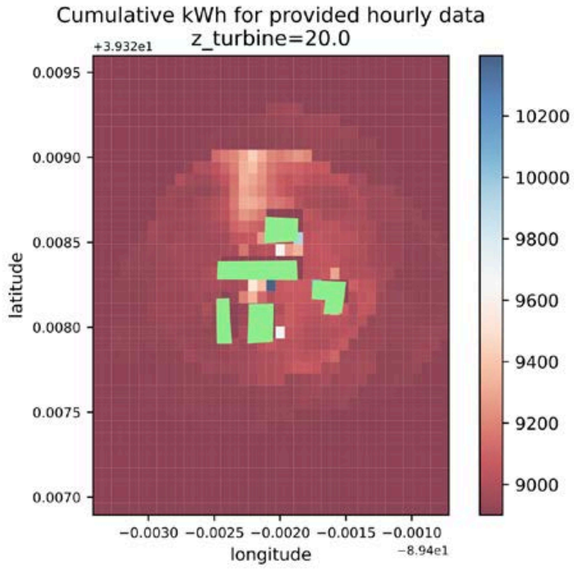
Cumulative energy

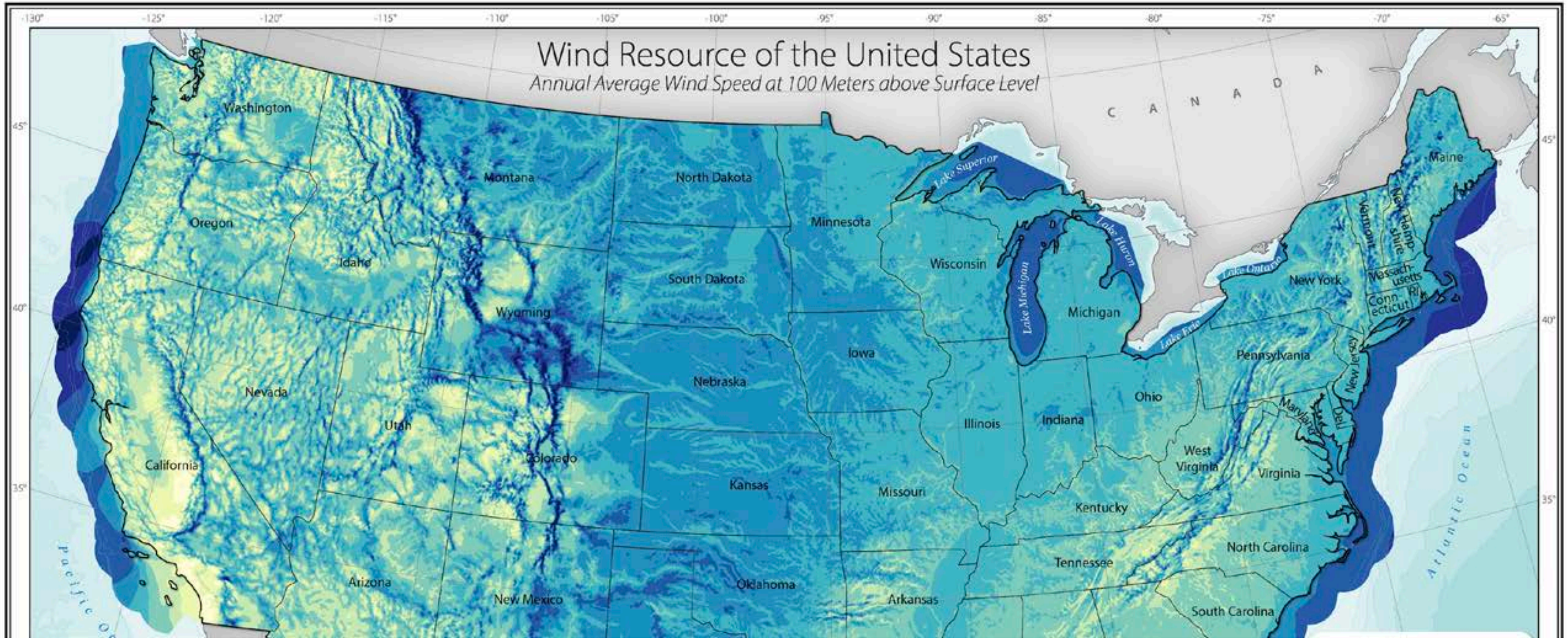
Site heat map



Presenting more on:

1. WTK, WTK-LED
2. Obstacle models
3. Recent results
4. Demo
5. Open questions





Current WIND Toolkit:

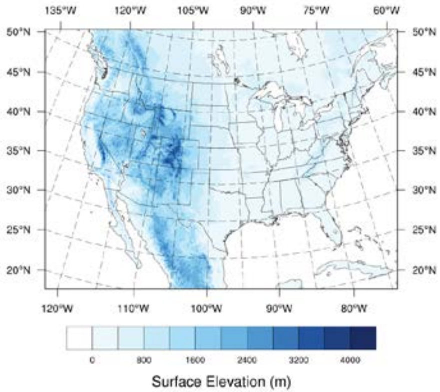
- Seven years (2007–2013)
- Deterministic data set
- Contiguous United States
- Developed as a grid integration data set to mimic forecast errors.

WIND Toolkit Long-Term Ensemble Data Set (LED):

- Updated WRF version (4.1.3)
- 2-km, 5-min data set
- Twenty years (2001–2020)
- Regional bias guidance
- Uncertainty quantified (ensembles)
- Includes Alaska and Hawaii.

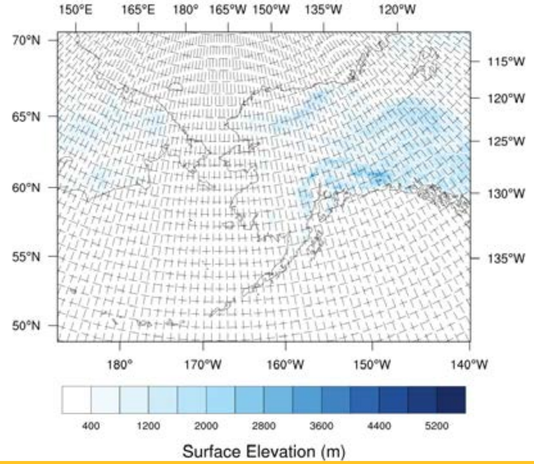
Work led by Caroline Draxl, NREL

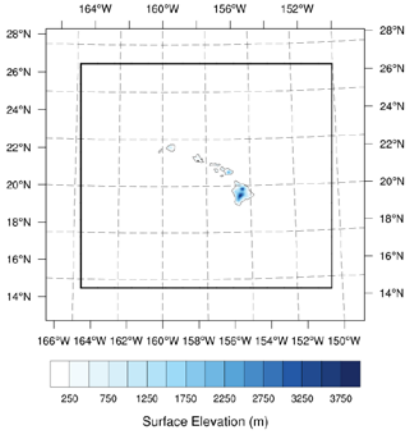
WRF Production Domains



CONUS:
2 km
5 min
3 years

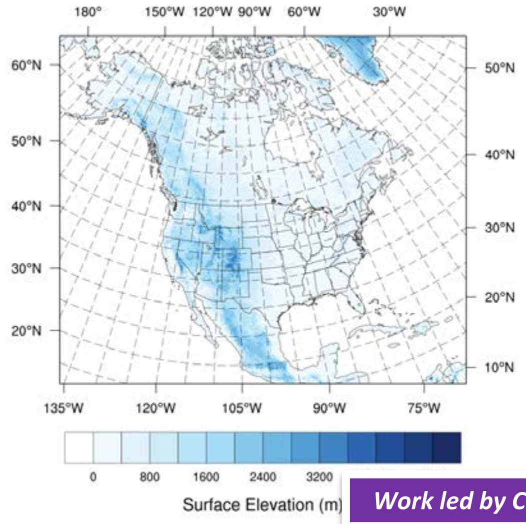
Alaska:
2 km
5 min
3 years





Hawaii:
2 km
5 min
20 years

North America:
4 km
Hourly
20 years



Work led by Caroline Draxl, NREL

Final WTK-LED Specifications

Variable	Height Levels (m)	Temporal Resolution
Wind Speed	10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250, 300, 500, 1000	2018–2020: 5-minute 2001–2020: Hourly and 4-km
Wind Direction	10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250, 300, 500, 1000	2018–2020: 5-minute 2001–2020: Hourly and 4-km
Temperature	2, 20, 40, 60, 80, 100, 200, 300, 500, 1000	Hourly
Virtual Potential Temperature	2, 20, 40, 60, 80, 100, 200, 300, 500, 1000	Hourly
Pressure	0, 100, 200, 500	Hourly
Turbulent Kinetic Energy	2, 20, 40, 60, 80, 100, 200, 300, 500, 1000	2018–2020: 5-minute
Vertical Windspeed	20, 40, 80, 120, 200, 500	Hourly
Cumulative Precipitation	0	Hourly
Inverse Monin-Obukhov Length	2	Hourly
Skin Temperature	0	Hourly
Latent Heat Flux	0	Hourly
Sensible Heat Flux	0	Hourly
Friction Velocity	2	Hourly
Boundary Layer Height	NA	Hourly

2001–2020:
2 km, 5 min

Stakeholders:
- Distributed and utility-scale wind industry
- Airborne wind energy
- Grid integration
- Power systems modeling
- Environmental modeling.

Work led by Caroline Draxl, NREL

Data Availability

- **WTK**
  - Available on Eagle (NREL's high-performance computing machine)
  - Available in the cloud; more on how to access it can be found here: https://github.com/NREL/hsds-examples/blob/master/notebooks/01_WTK_introduction.ipynb.
- **WTK-LED**
  - Available on Eagle
  - Soon will be available in the cloud
  - The tools we develop will leverage WTK-LED in the future.

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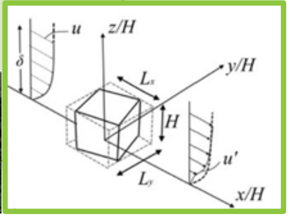

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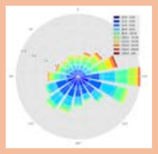
(single point)

Wind rose

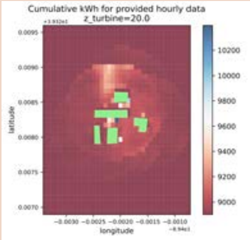


(single point)

Cumulative energy

(multiple points)

Site heat map



Integration of Obstacle LOMs

Inputs

(on NREL's high-performance computer or in the cloud)

WTK (2007–2013), 2-km res., hourly
--- or ---
WTK-LED (2013–2020), 2–4-km res., 5-min to hourly

Site analysis

1. Selection of (min, median, max) years for wind speed
2. Regional bias correction
3. Vertical and horizontal interpolation
4. Obstacle modeling

QUIC
- or -
PILOWF

1. Atmospheric data

[5]:

	datetime	ws	wd	temp	pres	inversemoninobukhovlength_2m
0	2007-01-01 00:00:00	7.744876	232.969856	282.541870	98493.965337	0.011512
1	2007-01-01 12:00:00	9.165510	278.610485	272.009949	99037.753033	0.001730
2	2007-01-02 00:00:00	5.667914	294.372393	275.522644	100177.180992	0.042600
3	2007-01-02 12:00:00	1.196242	199.775672	272.208313	100652.980804	0.048113
4	2007-01-03 00:00:00	6.783602	194.172807	276.606049	100410.263947	0.047254
...	...	...	...	...	...	...
726	2007-12-30 00:00:00	3.874950	176.357785	272.583710	99716.562444	0.108205
727	2007-12-30 12:00:00	4.888072	152.960520	271.582703	99367.990863	0.015526
728	2007-12-31 00:00:00	6.975717	191.885982	275.272369	98836.610143	0.056662
729	2007-12-31 12:00:00	4.802318	227.441046	270.859406	98993.799386	0.027217
730	2008-01-01 00:00:00	7.361367	303.598820	272.241882	98926.921183	0.010325

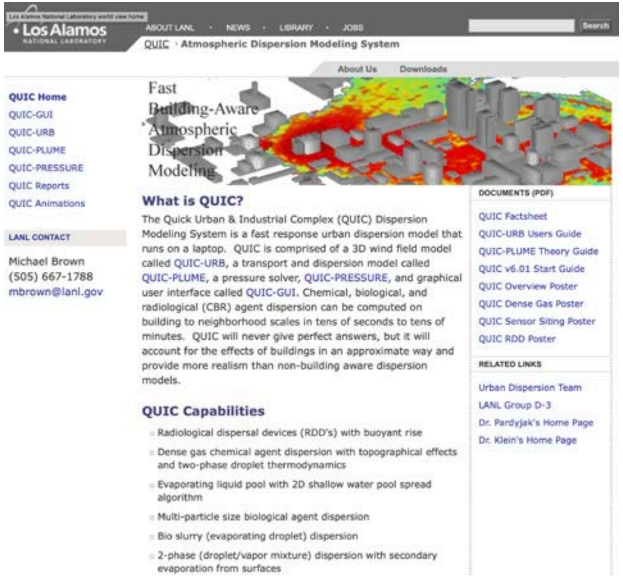
2. Obstacle data

3. Site specs:

```
lat=39.3
lon=-89.4
hub_height=40
```

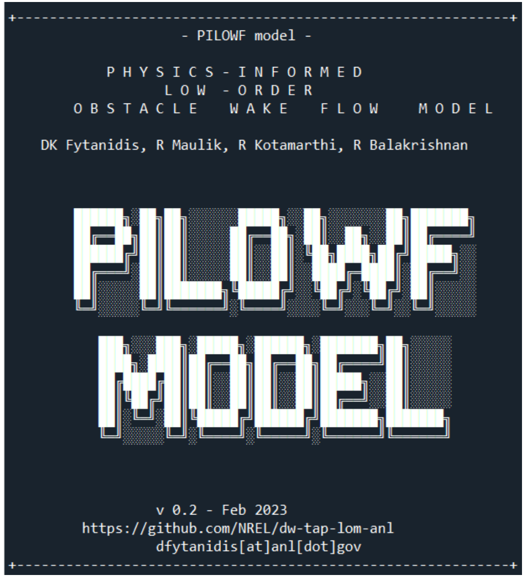
Obstacle Models

QUIC by LANL



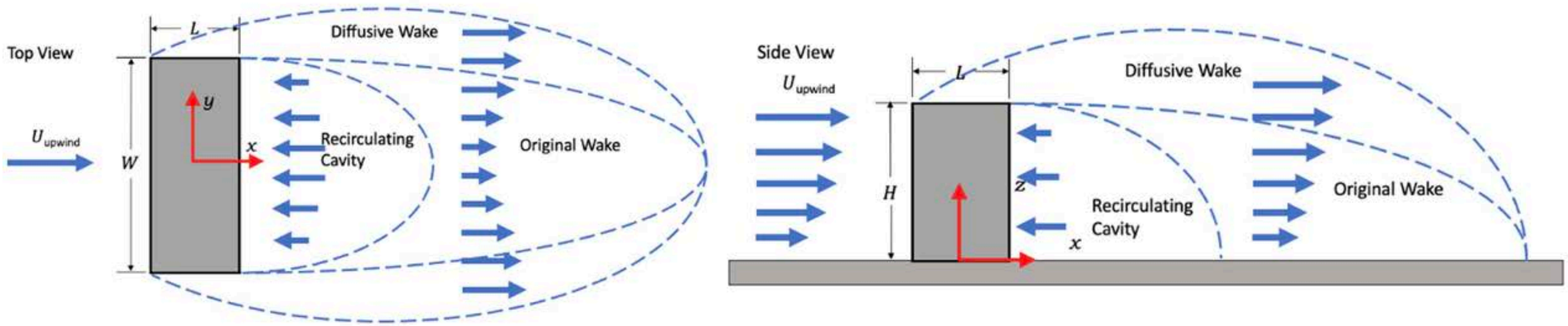
More at : https://www.lanl.gov/projects/quic/

PILOWF by ANL



More at : https://doi.org/10.2172/1782670

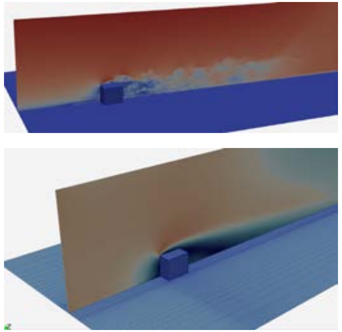
QUIC Model



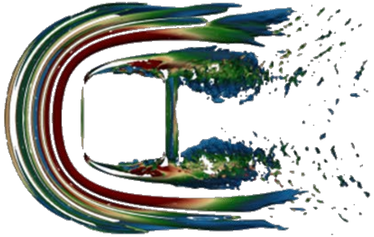
- QUIC-URB: empirical diagnostic wind solver
- Diffusive wake: modeled using machine learning techniques applied to time-averaged high-fidelity LES
- **Recent milestone: developed and started testing Python's interface for QUIC-URB**
  - Required inputs: atmospheric data, obstacle description (latitude, longitude, height) for points of interest

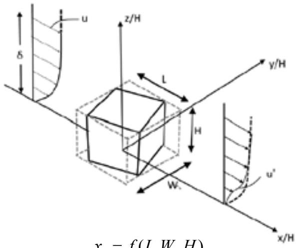
Work led by Matt Nelson and LANL team

PILOWF Model



Data from RANS, LES, DNS simulations using NEK5000



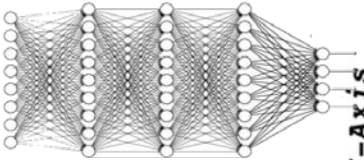


$$f = \frac{\Delta u}{U_H} = 1 - \alpha \left[\frac{W}{\lambda_y}\right]\left[\frac{H}{\lambda_z}\right]^2 f(\xi)h(\eta)$$

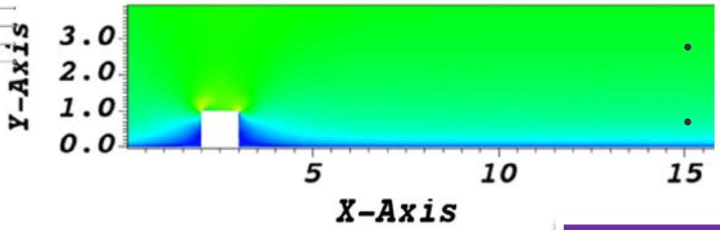
$$f' = \left.\frac{\Delta u}{U_H}\right|_{\text{due to HV}} = \Gamma y' h x \left(\frac{1}{\left(y'^2 + h^2 + z^2\right)^2 - 4z^2h^2} \right)$$

Analytical model

$x_o = f(L,W,H)$
$\alpha = f(L,W,H)$
$D_y = f(L,W,H,x,y,z)$
$D_z = f(L,W,H,x,y,z)$
$\Gamma = f(L,W,H)$
$y_v = f(L,W,H)\ (y' = y - y_v)$
$h = f(L,W,H)$



Data-driven techniques

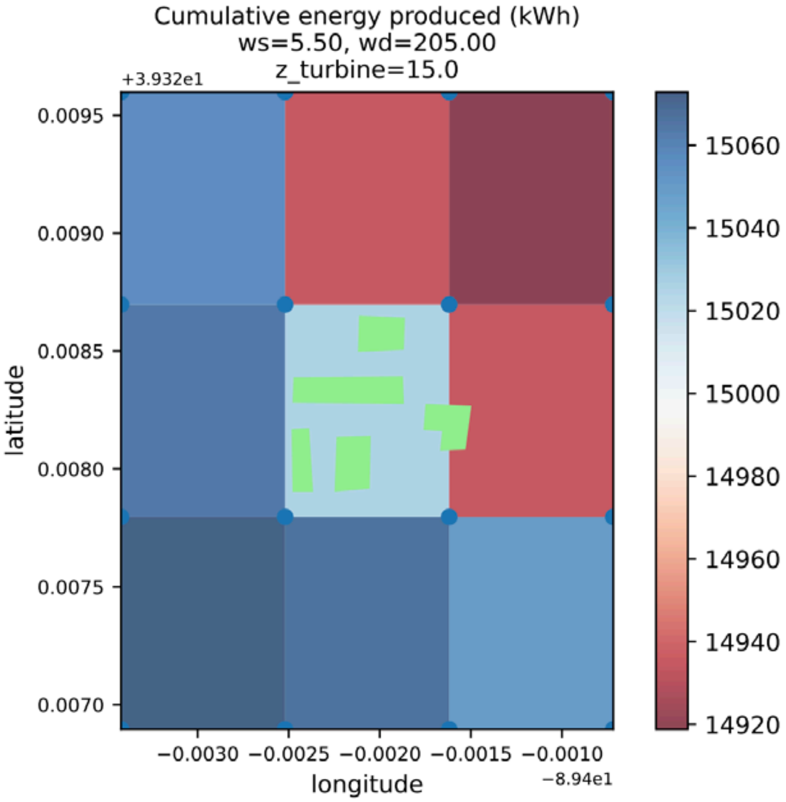


- Classic artificial neural networks to train the parameters (x_o, α, D_y and D_z , Γ, y_v, h) of the LOM. All these parameters have physical meaning:
  - x_o : virtual origin of the wake's Gaussian
  - D_y and D_z: spanwise and vertical diffusivities of the wake (eddy viscosities)
  - α: strength of the wake
  - Γ: circulation at x = 0 for the horseshoe vortex correction f'
  - h, y_v: distances to the center of the horseshoe vortex
- The parameters x_o, α, Γ, y_v, and h were assumed to be functions of enclosing cuboids' aspect ratio (H, L, and W), while the eddy diffusivities, D_y and D_z, were assumed to be functions of H, L, and W and x, y, and z.
- The number of layers/neurons/activations and optimization hyperparameters were manually tuned to improve the robustness and accuracy of the LOM.
- Positivity preserving constraints were embedded in the model as per the physical range of parameters (e.g., eddy viscosities D_y and D_z ; cannot get negative values).
- 70% of the data were used for training and validation of the model and 30% were used for testing of the model.
- Tested and validated against real world EAZ data in the Netherlands (Phillips et al. 2022).

Phillips et al. 2022. "Evaluation of obstacle modelling approaches for resource assessment and small wind turbine siting: Case study in the northern Netherlands." *Wind Energy Science* 7 (3): 1153-1169.

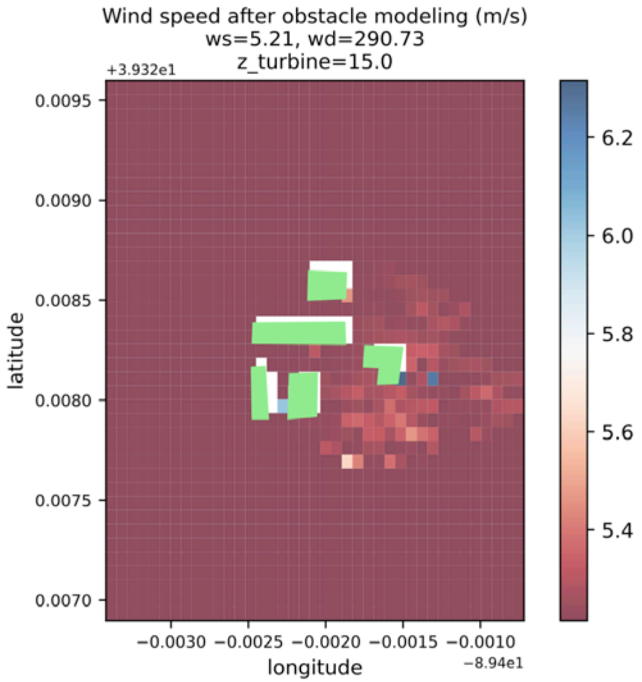
Work led by Dimitrios K. Fytanidis and ANL team

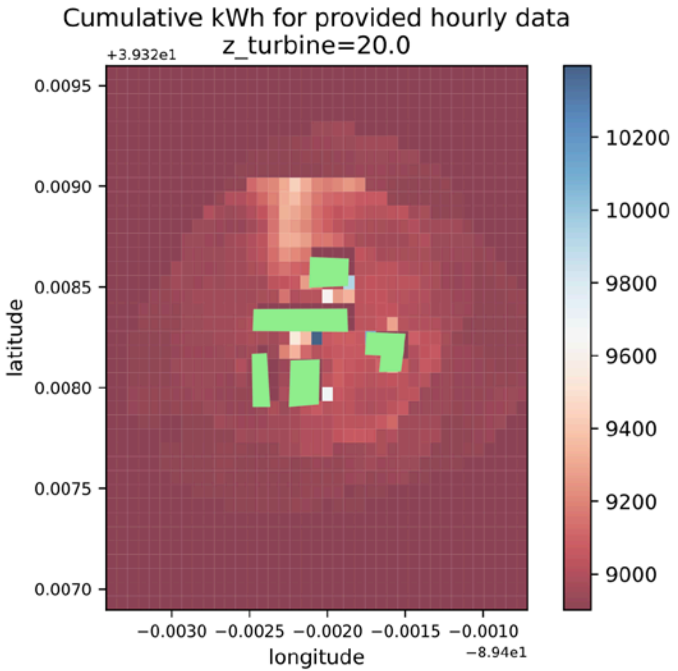
Results (QUIC)



- Studied 16 points near an existing DW site in IL, USA
- Modeled the impact of five buildings
- Estimated cumulative energy produced over a period of 1 year using an actual power curve

Results (PILOWF)



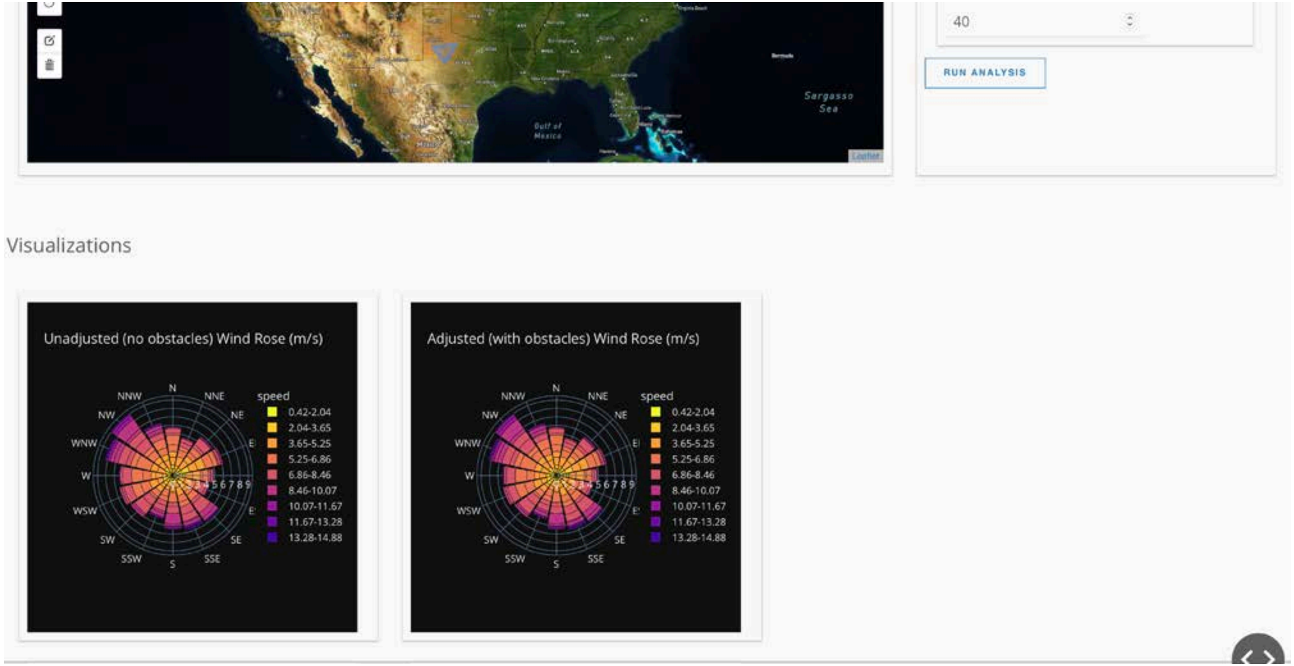


- Same site
- Much faster analysis and finer resolution
- **Left**: impact of buildings on wind speed for a single moment in time
- **Right**: impact of buildings on the cumulative energy produced over a period of time

Upcoming Validation

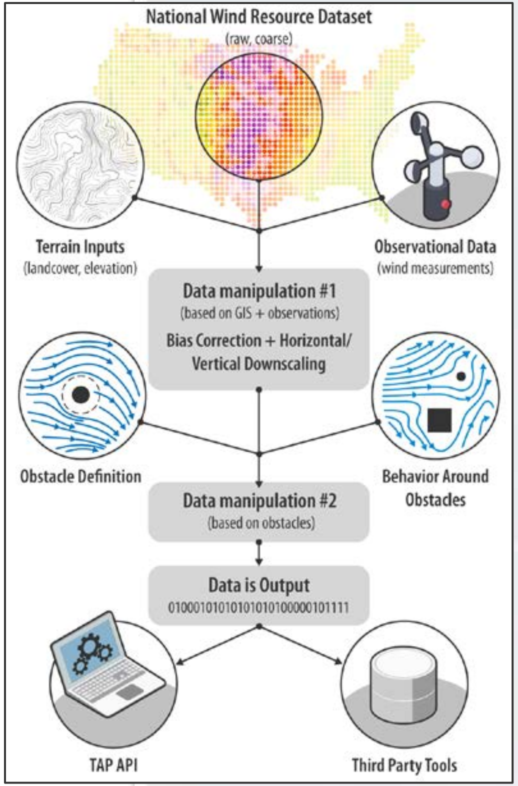
- Selected a number of actual DW sites across the United States
- Plan to evaluate the entire TAP pipeline as well as individual components, studying both wind speed estimates and energy produced estimates
- Plan to evaluate the quality of our estimates as a function of turbine location, number of nearby obstacles, hub height, and use of obstacle models.

Demo


40
RUN ANALYSIS
Sargasso Sea
Gulf of Mexico
Visualizations
Unadjusted (no obstacles) Wind Rose (m/s)
Adjusted (with obstacles) Wind Rose (m/s)
N
NNE
NE
E
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
speed
0.42-2.04
2.04-3.65
3.65-5.25
5.25-6.86
6.86-8.46
8.46-10.07
10.07-11.67
11.67-13.28
13.28-14.88

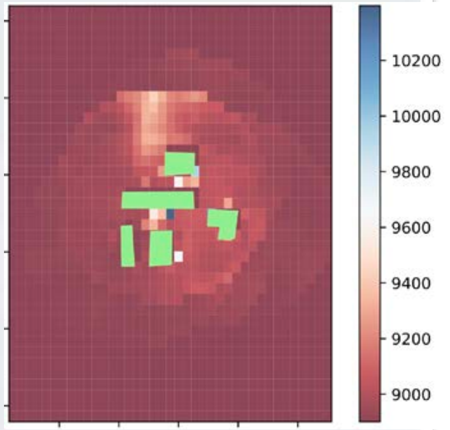
Open Questions

- What are the key questions the community wants to see answered as part of the described analysis and validation effort?
- What additional data should be included in this work?
- What are the market segments in which this research can be most impactful?



Thank you!

NREL/PR-2C00-85406



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