PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading-Edge Erosion Solutions

NSF Global Centers Track 2: Enhanced Wind Turbine Blade Durability
#2329911

Partners: US (Cornell University), the UK (University of Lancaster), Canada (Wind Energy Institute of Canada), Norway (University of Bergen), Denmark (Technical University of Denmark and Orsted) and Spain (National Renewable Energy Center of Spain)

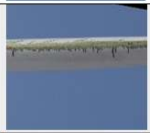
Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

US NSF 2329911

Blade leading edge erosion

Damage severity		Description	Action/Time to repair	Cost estimate $ *	Coating mass loss (%)	Laminate mass loss (%)	Turbine AEP loss (%)
0 (Inspection)			-	6200	0	0	0
1		Light pitting of coating	None	7000	<10	0	0
2		Small patches of missing coating	Repair if scheduled	7000	10-50	<10	0
3		Large patches of missing coating	Repair with 6 months	10000	50-100	10-50	1
4		Erosion of laminate	Repair within 3 months	42000	100	50-100	3
5		Complete loss of laminate	Repair immediately	3750000	100	100	5
6				5250000	100	100	?

*Data from: Lopez et al. Applied Energy 358 (2024) 122612, Maniaci et al. 2022 IEA Task 46

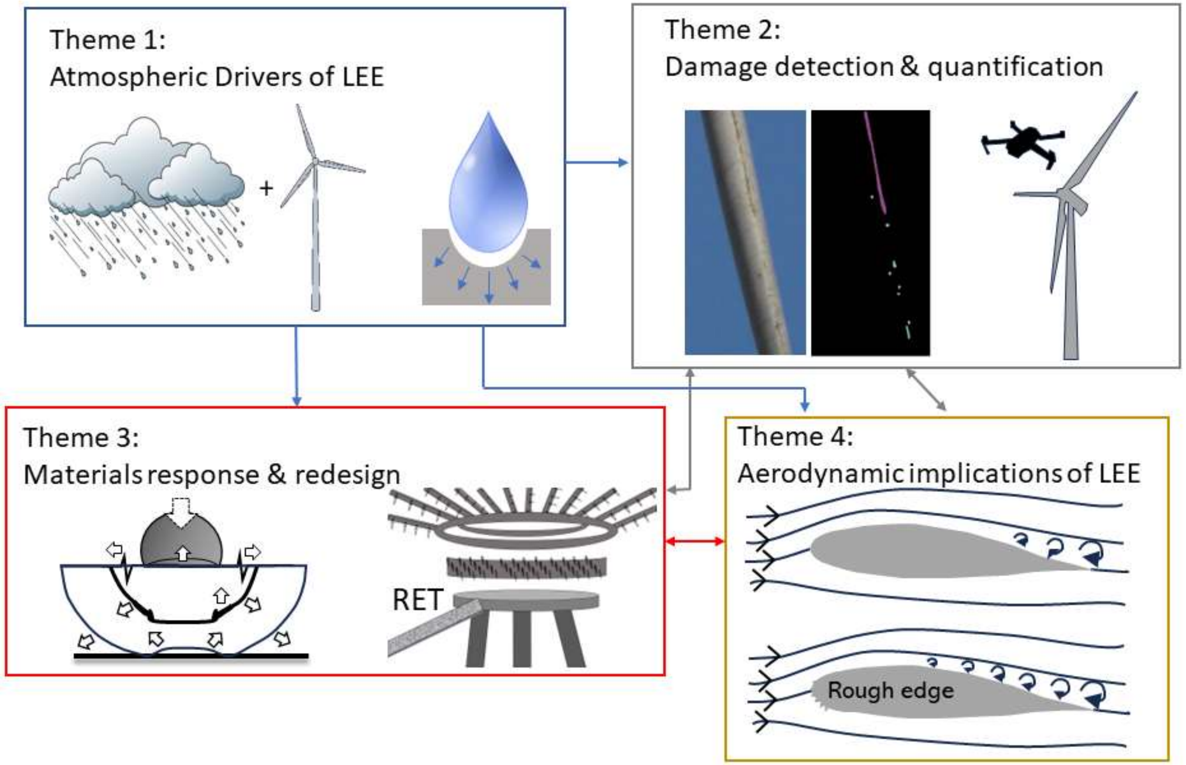
Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Objectives

- To advance fundamental understanding of the processes that cause LEE
- To advance effective solutions

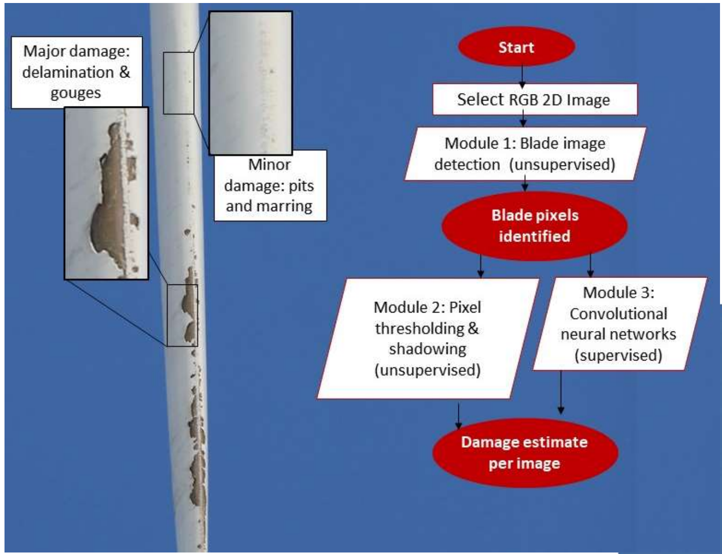


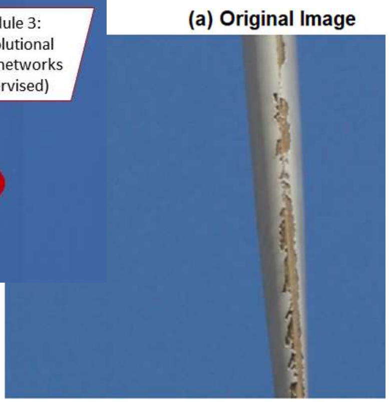
Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

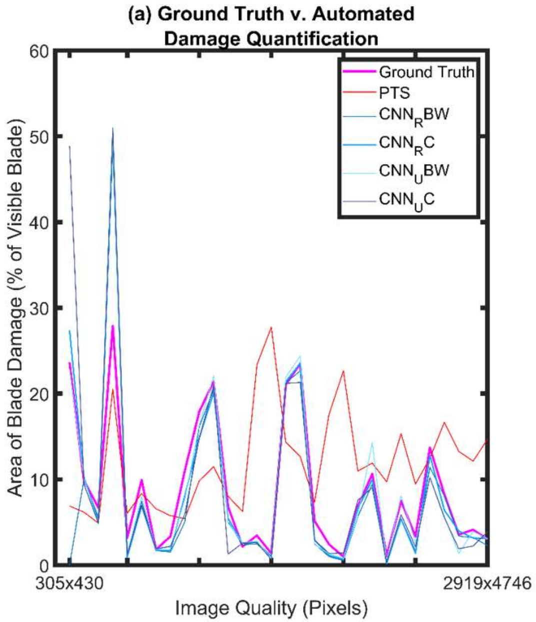
PIRT analyses for LEE

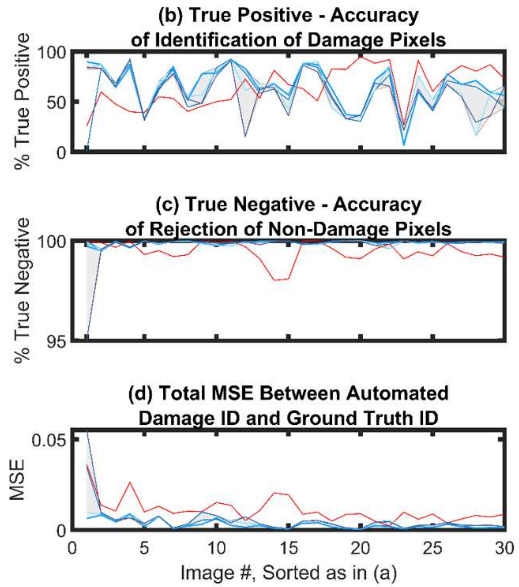
R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Damage detection & quantification

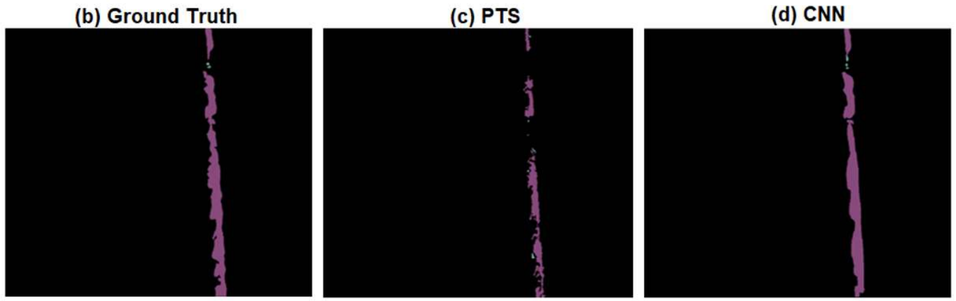








1. Unsupervised (PTS—pixel intensity thresholding & shadow ratio)
2. Supervised (CNN)



- ~65% of total damage area
- better quantifying deep damage
- CNN better for shallow damage

Aird, J.A.; Barthelmie, R.J.; Pryor, S.C. Automated Quantification of Wind Turbine Blade Leading Edge Erosion from Field Images. *Energies* **2023**, *16*, 2820.

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Materials response

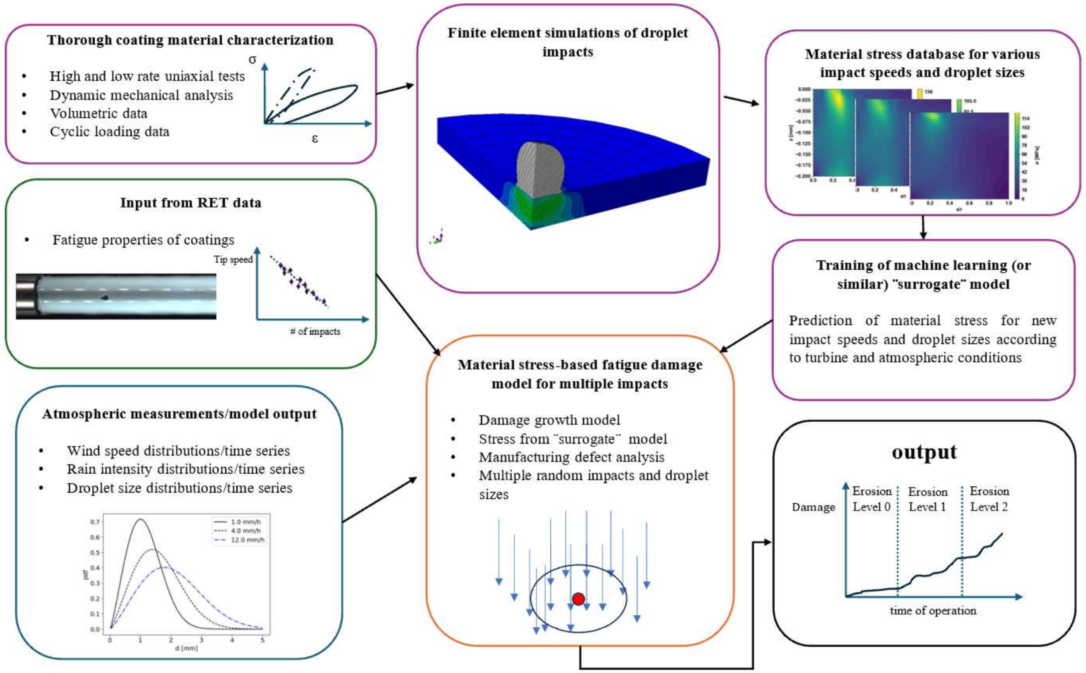
https://www.youtube.com/watch?v=DT-w1rihJjl

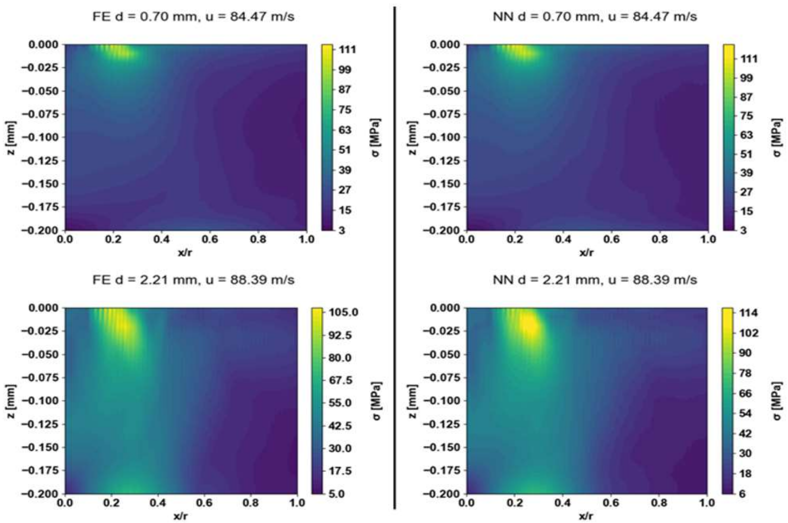
Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Materials response



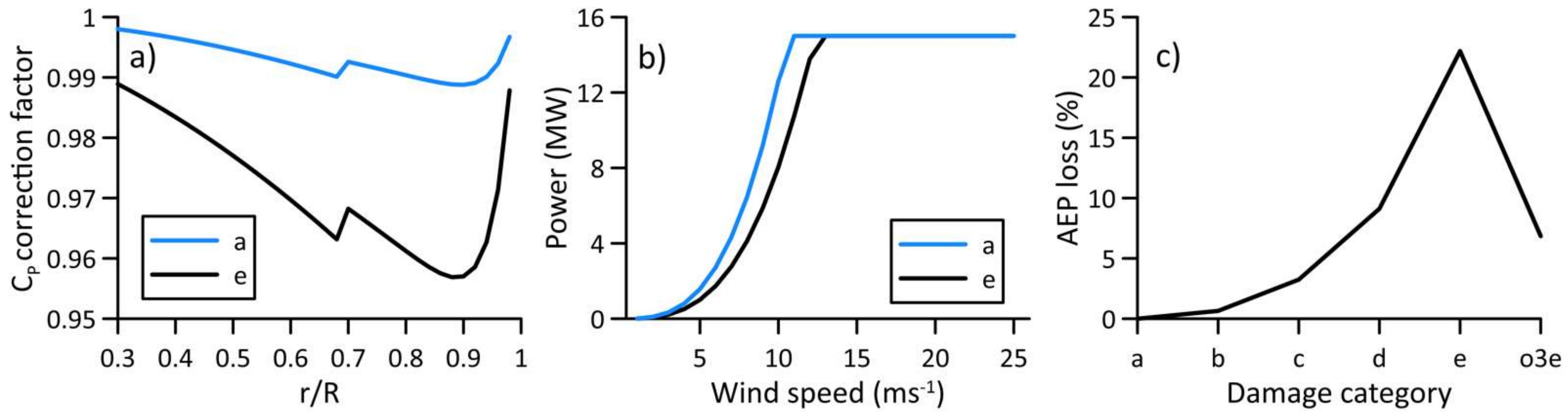


Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Aerodynamic response



Simplified Aerodynamic Loss Tool (SALT) model
https://gitlab.windenergy.dtu.dk/lercat/salt

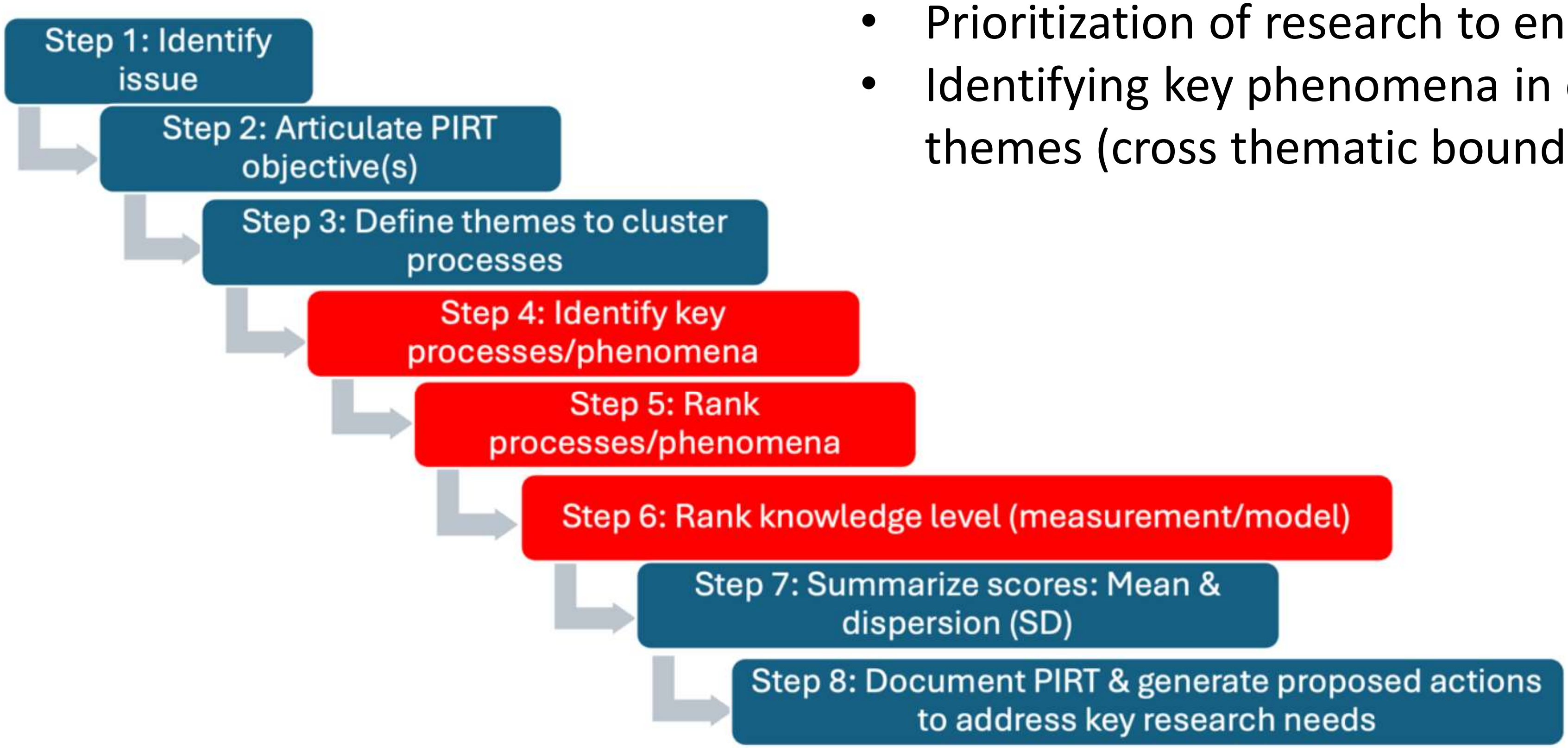
Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Phenomena Identification and Ranking Tables (PIRT) Workflow

- Systematic way of gathering information
- Ranking importance to meet objective
- Prioritization of research to enhance TRL
- Identifying key phenomena in each of LEE themes (cross thematic boundaries)



Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT1: Atmospheric drivers

Objective: Identify phenomena/processes that have high importance and where critical knowledge gaps preclude full treatment of those phenomena/processes in models, measurements or data analysis tools. Advancing knowledge for these topics is most likely to enhance TRL for LEE solutions.

	Process/Phenomena Importance Level	
Theme 1: Atmospheric Drivers	Mean	SD
Hub-height wind speeds: existing wind farms		
Hub-height wind speeds: prospective wind farms		
Hydrometeor size distribution		
Hydrometeor phase (rain/hail/other)		
Hydrometeor fall velocities		
Impinged water (blade capture efficiency as a function of droplet diameter)		
Real-time data for 'erosion safe mode'		
Space/time variability in hydroclimate conditions		
Non-hydrometeor weathering stressors (e.g. UV radiation, icing, thermal expansion, aerosols (incl. dust & pollution))		
Reanalysis/gridded product data quality		

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT1: Atmospheric drivers

Is the following variable/process important to blade leading edge erosion?
Strongly agree/Agree/Neither agree nor disagree/Disagree/Strongly Disagree
Do not rank everything as ‘Strongly agree’

https://www.surveymonkey.com/r/Y26NNXY

5 mins to complete!

	Process/Phenomena Importance Level	
Theme 1: Atmospheric Drivers		
Hub-height wind speeds: existing wind farms		
Hub-height wind speeds: prospective wind farms		
Hydrometeor size distribution		
Hydrometeor phase (rain/hail/other)		
Hydrometeor fall velocities		
Impinged water (blade capture efficiency as a function of droplet diameter)		
Real-time data for 'erosion safe mode'		
Space/time variability in hydroclimate conditions		
Non-hydrometeor weathering stressors (e.g. UV radiation, icing, thermal expansion, aerosols (incl. dust & pollution))		
Reanalysis/gridded product data quality		

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT1: Atmospheric drivers

	Process/Phenomena Importance Level		Measurement		Modeling	
Theme 1: Atmospheric Drivers	Mean	SD	Mean	SD	Mean	SD
Hub-height wind speeds: existing wind farms	0.92	0.19	1	0	0.73	0.26
Hub-height wind speeds: prospective wind farms	0.91	0.2	0.82	0.25	0.68	0.25
Hydrometeor size distribution	0.86	0.32	0.27	0.41	0.2	0.26
Hydrometeor phase (rain/hail/other)	0.91	0.3	0.36	0.39	0.14	0.23
Hydrometeor fall velocities	0.58	0.36	0.41	0.38	0.32	0.34
Impinged water (blade capture efficiency as a function of droplet diameter)	0.55	0.44	0.15	0.34	0.1	0.21
Real-time data for 'erosion safe mode'	0.68	0.25	0.18	0.34	0.46	0.33
Space/time variability in hydroclimate conditions	0.64	0.23	0.59	0.2	0.59	0.2
Non-hydrometeor weathering stressors (e.g. UV radiation, icing, thermal expansion, aerosols (incl. dust & pollution))	0.55	0.27	0.18	0.25	0.27	0.34
Reanalysis/gridded product data quality	0.44	0.17	0.67	0.25	0.81	0.26

Mean	Importance	Process understanding
Black	>0.8	>0.5
Red	>0.8	<0.5
Blue	0.5-0.8	<0.6
Green	<0.5	

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT2: Damage detection and quantification

	Process/Phenomena Importance Level	Measurement	Modeling			
Theme 2: Damage detection and quantification	Mean	SD	Mean	SD	Mean	SD
Availability of blade images & methods to quantify damage	0.83	0.25	0.54	0.33	0.5	0.33
Damage characterization from varying image types & methods to translate to damage classification	0.88	0.23	0.58	0.29	0.44	0.3
Methods for 3-D characterization of damage morphology & rate of progression	0.71	0.26	0.25	0.26	0.18	0.25
Translating water impingement to materials loss/stress (e.g. metrics: Kinetic Energy, Springer-ADF, VN curves)	0.86	0.23	0.27	0.26	0.36	0.23
Quantification of materials loss	0.71	0.26	0.5	0.39	0.27	0.26
Quantification of equivalent surface roughness for aerodynamic loss	0.75	0.26	0.41	0.3	0.45	0.27
Microplastic loss for environmental impacts	0.5	0.21	0.21	0.26	0.27	0.26

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT3: Materials response

	Process/Phenomena Importance Level	Measurement	Modeling			
Theme 3: Materials response	Mean	SD	Mean	SD	Mean	SD
Rain erosion tester reliability & reproducibility	0.92	0.19	0.59	0.3	0.4	0.21
Rain erosion tester representation of atmospheric conditions: hydrometeors: phase (e.g. rain and hail), size distributions & collision velocities	0.83	0.25	0.5	0.33	0.28	0.26
Rain erosion tester representation of atmospheric conditions: flow field (e.g. impact velocities)	0.71	0.33	0.45	0.28	0.28	0.36
Methodologies to translate lab experimental data (incl. rain erosion tester) to field conditions & failure modes	0.88	0.23	0.35	0.24	0.3	0.26
Damping and energy dissipation properties of LEPs/coatings (single/multilayer)	0.67	0.25	0.32	0.25	0.45	0.16
Linking mechanical and viscoelastic properties to failure mechanisms/modes	0.73	0.26	0.32	0.25	0.4	0.32
Coating adhesion & mechanics of multi-layer materials	0.75	0.26	0.45	0.44	0.55	0.28
Material response to non-hydrometeor weathering stressors (e.g. UV radiation, icing, thermal expansion, aerosols (incl. dust))	0.64	0.23	0.36	0.32	0.35	0.24

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

PIRT4: Aerodynamic implications of LEE

	Process/Phenomena Importance Level	Measurement	Modeling			
Theme 4: Aerodynamic implications of LEE	Mean	SD	Mean	SD	Mean	SD
Quantification of damage and surface roughness progression through time	0.95	0.16	0.4	0.32	0.45	0.28
Attribution of AEP loss to LEE (via effective surface roughness)	0.88	0.23	0.35	0.34	0.5	0.24
Attribution of AEP loss to application of LEP measures	0.75	0.26	0.4	0.39	0.55	0.28
Quantifying evolution of power curve through time (incl. post deployment)	0.75	0.26	0.3	0.42	0.3	0.42
Optimization of damage repair solution/timing	0.9	0.21	0.35	0.34	0.5	0.33

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* **17**, 6285 doi: 10.3390/en17246285

PIRT analyses for LEE

R.J. Barthelmie and S.C. Pryor Cornell University (rb737@cornell.edu)

Conclusions

- Multidisciplinary topic/specific model/measurement needs
- PIRT analysis to help frame the research needed to address LEE
- Some phenomena are important and well-understood, modeled and measured e.g. hub-height wind-speed, damage characterization, rain erosion testers
- A large number of phenomena are important but not well-measured or modeled e.g. hydrometeor size distributions, water impingement or impacts to damage, translating RET results to field conditions, understanding damage progression over time
- Second phase expand PIRT phenomena
- Propose open call for experts to participate (through IEA Task 46)

Acknowledgement: Funding from US NSF 2329911

Pryor S.C., Barthelmie R.B., Coburn J.J., Zhou X., Rodgers M., Norton M., Campobasso M.S., Lopez B.M., Hasager C.B., and Mishnaevsky Jr L. (2024): Prioritizing Research for Enhancing the Technology Readiness Level of Wind Turbine Blade Leading Edge Erosion Solutions. *Energies* ***17***, 6285 doi: 10.3390/en17246285