

# Renewable Electricity for Minnesota's Future



**Xcel Renewable Development Fund  
Advisory Group Presentation  
November 8, 2016**

INSTITUTE ON THE  
**ENVIRONMENT**

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UNIVERSITY OF MINNESOTA  
**Driven to Discover<sup>SM</sup>**

# Agenda

- Renewable Electricity for MN Future's Advisory Board
- Project Presentations
- Impact
- Questions

# Renewable Electricity for Minnesota's Future

## Advisory Board

| First Name | Last Name     | Position                                                         | Organization                             |
|------------|---------------|------------------------------------------------------------------|------------------------------------------|
| Nina       | Axelson       | Vice-President, Public Relations                                 | Ever-green Energy                        |
| Bill       | Blazar        | Senior Vice-President of Public Affairs and Business Development | MN Chamber of Commerce                   |
| Dan        | King          | Program Director                                                 | Midwest Renewable Energy Tracking System |
| Holly      | Lahd          | Director of Electricity Markets                                  | Fresh Energy                             |
| Paul       | Lehman        | Manager of Community Energy Partnerships                         | Xcel Energy                              |
| Laureen    | McCalib       | Manager, Resource Planning and Regulatory Affairs                | Great River Energy                       |
| Rolf       | Nordstrom     | President and CEO                                                | Great Plains Institute                   |
| Kelly      | Schwinghammer | Executive Vice-President                                         | BlueGreen Alliance                       |
| Will       | Seuffert      | Executive Director                                               | Environmental Quality Board              |
| Doug       | Shoemaker     | Vice-Chairperson                                                 | MN Renewable Energy Society              |
| Kaya       | Tarhan        | Chief Development Officer                                        | SolarStone                               |

# Program Funding

| Total Budget | Total Disbursed | Expenses | Encumbrances | Unencumbered Funds |
|--------------|-----------------|----------|--------------|--------------------|
| 3,000,000    | 1,000,000       | 347,893  | 283,013      | 64,880             |

Project Funding Start Date: 5/30/2016



# Project Presentations

- **Richard James & Bharat Jalan:** *The direct conversion of heat to electricity using fast switching of ferroelectric oxides*
- **Ned Mohan:** *Research on Power Electronics and Control: Grid-Interface for Renewables, Storage and Green Micro-Grids*
- **Chris Leighton:** *Pyrite  $\text{FeS}_2$ : A Low-Cost Earth-Abundant Photovoltaic Solution for Renewable Electricity in Minnesota*
- **Lian Shen:** *Simulation, Measurement, Modeling, and Control of Wind Plant Power*

# Project 1

- **Richard James & Bharat Jalan:** *The direct conversion of heat to electricity using fast switching of ferroelectric oxides*

# Introduction

**The direct conversion of heat to electricity  
using fast switching of ferroelectric oxides**

## Senior Personnel

- Prof. Richard James, Aerospace Engineering and Mechanics, UMN
- Prof. Bharat Jalan, Chemical Engineering and Materials Science, UMN

## Post Doctoral Fellows

- Dr. Paul Plucinsky, PhD from Caltech, Start Date: May 2017
- Dr. Ryan Haislaier, PhD from Penn State, Start Date: Dec 2016

## Graduate Students

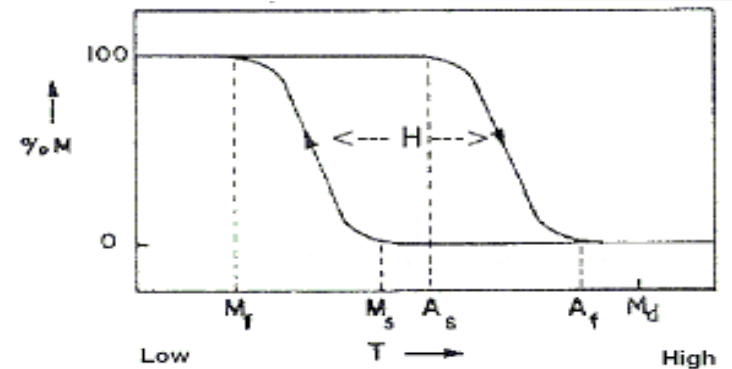
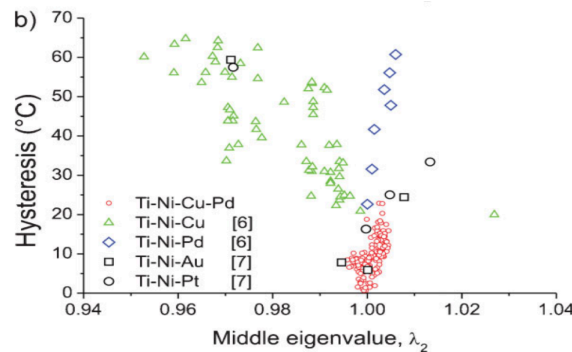
- Ms. Hanlin Gu, 3<sup>rd</sup> year
- Mr. William Nunn, 2<sup>nd</sup> year

# Sources of heat at small temperature differences

- **Waste heat** rejected in **exhaust systems** of automobiles, and **power plants**
- Waste heat from **air conditioning systems\***
- Waste heat from **laptop** and **desktop computers** and **supercomputer clusters**
- **Handheld electronic devices** (phones, videogames), **watches**, **stand-alone sensors**
- **Major environmental sources:** solar thermal plants, temperature difference between air and sub-ice water in winter, accumulate heat in attics in summer

## Key Technological Breakthrough

A strategy for minimizing hysteresis ( $\lambda_2$  to 1). Near zero hysteresis demonstrated



- \*Collaboration with Daikin Applied, 13600 Industrial Park Blvd., Plymouth, MN •

# The Goal

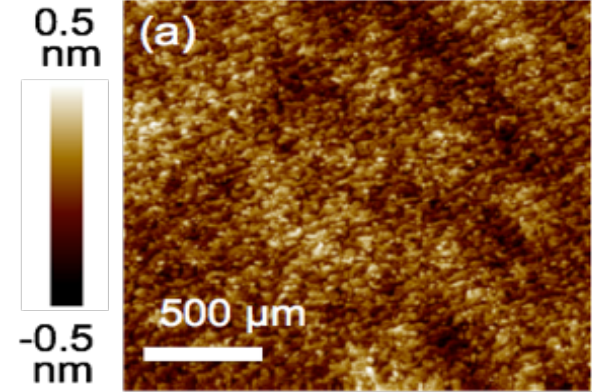
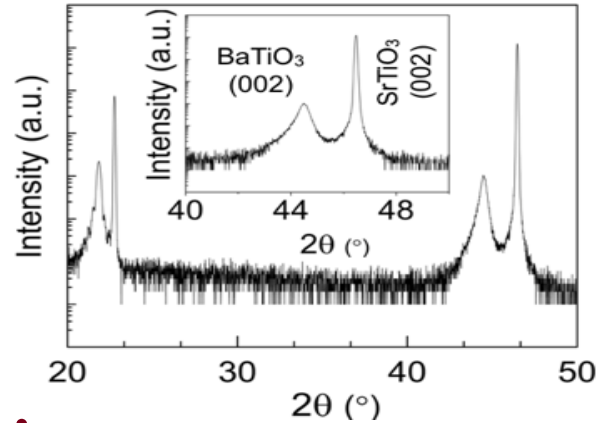
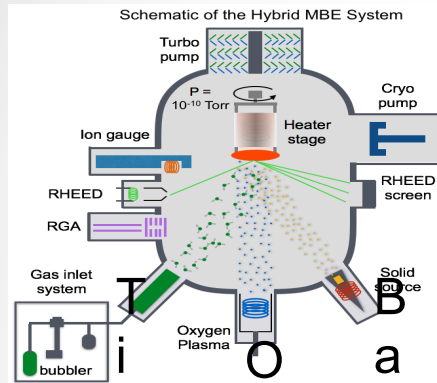
To develop energy conversion devices based on phase transformation in ferroelectric films through the establishment of molecular beam epitaxy (MBE) growth and the computational design.

## Key Deliverables

- Development of an Oxide Film with a  $\lambda_2 = 1$  Interface
- Development of a Switch
- Modeling of Thermo-Electro-Dynamics of Ferroelectric Energy Conversion
- Construction and Testing of a Prototype
- Scale-up

# Preliminary results and plans

Synthesis of excellent quality Ferroelectric BaTiO<sub>3</sub> films using hybrid MBE



## Plans for the coming year

- Identify 3-4 candidate  $\lambda_2 = 1$  ferroelectric oxides with a suitable phase transformation temperature and dielectric behavior
- Characterize bulk or film samples of these candidates. Downselect
- Develop growth procedures for the selected  $\lambda_2 = 1$  ferroelectric oxide
- Develop a predictive thermo-electro-dynamic model for ferroelectric energy conversion, including analysis of thermodynamic cycles, heat transfer, efficiency and power density

# Project 2

- **Ned Mohan:** *Research on Power Electronics and Control: Grid-Interface for Renewables, Storage and Green Micro-Grids*



# Objective: Grid-Parity of Utility-Scale Renewables

## Team:

Ned Mohan (ECE)  
William Robbins (ECE)  
Murty Salapaka (ECE)  
Peter Seiler (AEM)  
Sairaj Dhople (ECE)  
Chris Henze (Consultant)

## Industrial Partners:

Brad Palmer (Cummins Power)  
Dakshina Murthy-Bellur  
(Cummins Power)

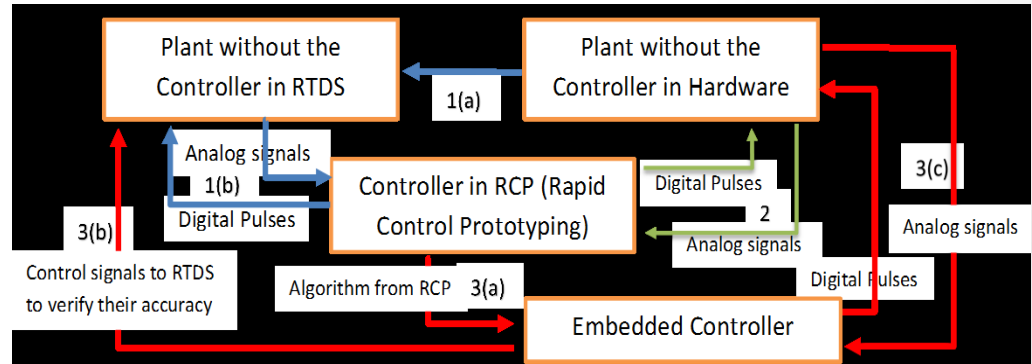
## External University Collaborator:

Daniel Opila (U.S. Naval  
Academy)

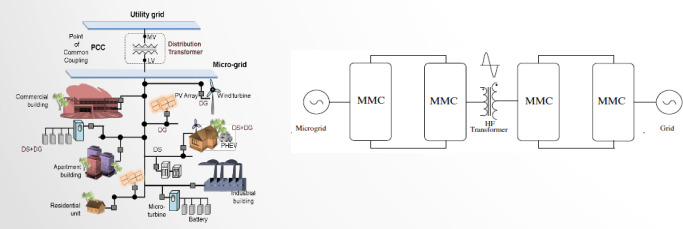
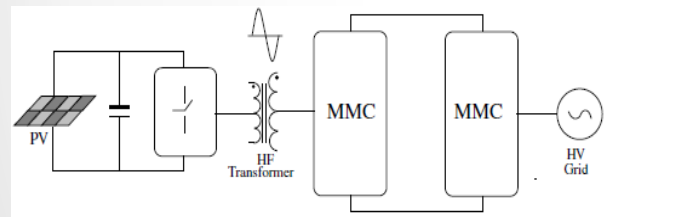
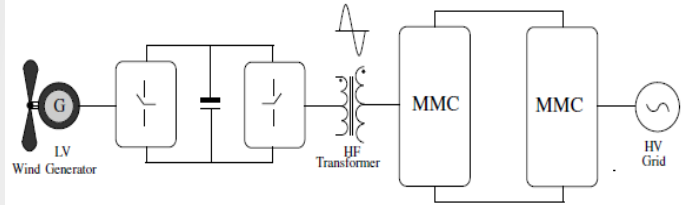
## People Hired:

1. Abhijit Kshirsagar (Post-Doc)
2. Vishnu Narayan Vipin (RA)
3. Anushree Ramanath (RA)
4. Sourav Kumar Patel (RA)

Submitted a Proposal to the Office of Vice President for Research (110 k\$ total) for “Real-Time Digital Simulator with Rapid-Control Prototyping features”



### Nanocrystalline High Frequency Transformers Are Over 150 Times Lighter And Significantly Smaller



1. Kartik Ayer and Ned Mohan "A High-Frequency AC-Link Single-Stage Asymmetrical Multilevel Converter for Grid Integration of Renewable Energy Systems"

1. Ashish Sahoo and Ned Mohan, "Analysis and Experimental Validation of a Modular Multilevel Converter with 3-Level T-Type submodules"
2. Ashish Sahoo and Ned Mohan, "Modulation and Control of a Single-Stage HVDC/AC Solid State Transformer Using Modular Multilevel Converter"

1. Ruben Otero and Ned Mohan, "A Highly Modular Grid Interface for Utility Scale Renewables: MMC with High Frequency Link Sub-Modules"

1. Ashish Sahoo and Ned Mohan, "MODULAR CONVERTER WITH MULTILEVEL SUBMODULES"

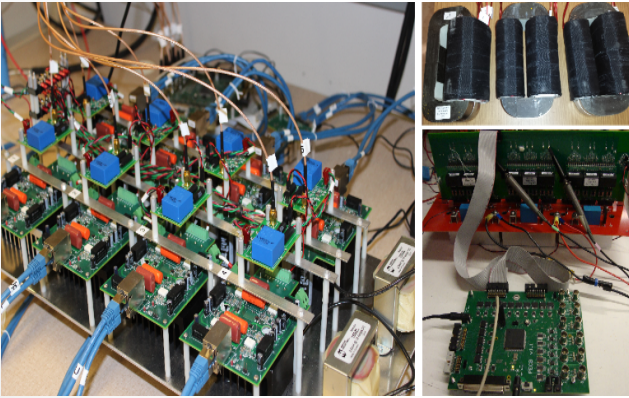
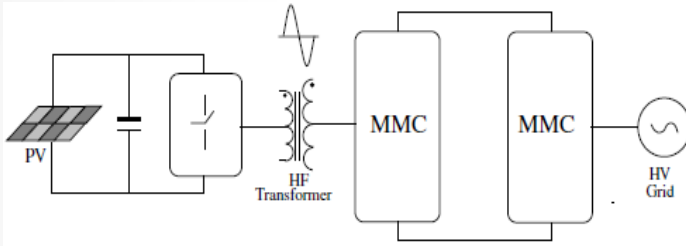
The diagram illustrates a power system architecture. On the left, three power sources are shown: a PV Simulator (represented by a solar panel icon), a Battery (represented by a battery icon), and a DC Source (represented by a DC voltage source icon). Each source is connected to a bidirectional DC-DC converter (represented by a square with a diagonal line). These converters are controlled by a common 'Control' signal, indicated by red arrows labeled 'Control'. The outputs of these converters are connected to a central 'DC Link'. The DC Link is connected to a set of 'Emulated Loads'. These loads include a 'DC Link' capacitor, a 'Deferrable' load (represented by a switch and a capacitor), a 'Non-Deferrable' load (represented by a capacitor), and a 'Controllable' load (represented by a switch and a capacitor). The DC Link is also connected to a ground symbol.

# Project Goals After Three Years (Deliverables):

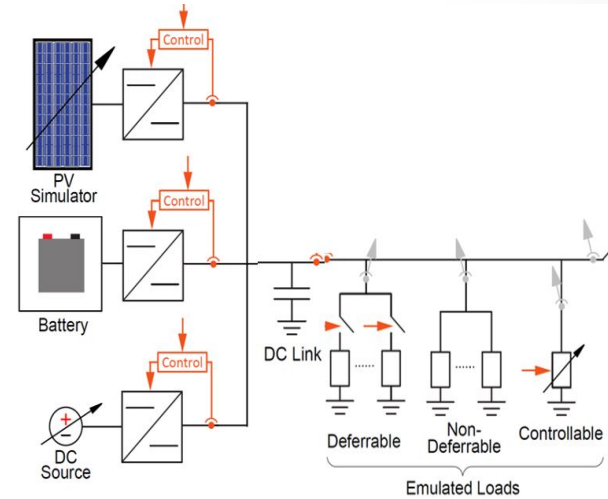
1. Technology Transfer: Analyze, design, fabricate and test a Modular Power Electronic Transformer in the laboratory for Technology Transfer
2. Control of green micro-grids with the main grid and with other micro-grids

# Plans for this Year:

Complete the design and fabrication of the complete system shown below:



Continue Research on Micro-grid Controllers:



# Project 3

- **Chris Leighton:** *Pyrite  $\text{FeS}_2$ : A Low-Cost Earth-Abundant Photovoltaic Solution for Renewable Electricity in Minnesota*

# Project Team



**Chris Leighton**  
(Chem Eng & Mat Sci)

electronic and magnetic  
properties of materials



**Laura Gagliardi**  
(Chemistry)

theoretical chemistry;  
electronic structure  
computation



**Eray Aydil**  
(Chem Eng & Mat Sci)

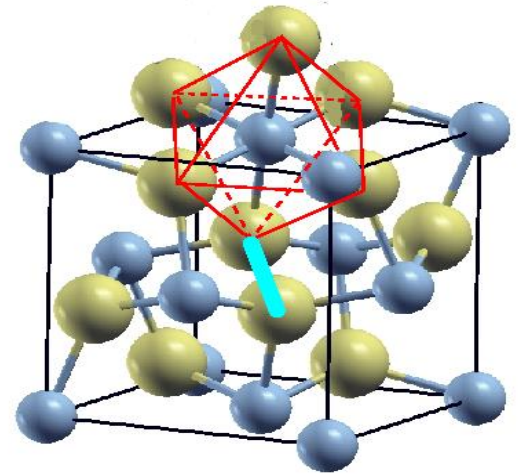
solar cells;  
materials for energy  
applications

**TenK Solar:** Bloomington-based commercial solar installation company

**PHI (Physical Electronics):** Eden-Prairie-based materials analysis company

# Background / Motivation

- Current PV market: Si, CdTe, CuInGaSe<sub>2</sub> (CIGS)
- Si builds on established technology, but requires costly, thick, crystalline wafers
- CdTe and CIGS are *thin film* technologies, but require low abundance, toxic, costly elements
- **Grand challenge:** High performance PV materials from earth-abundant, cheap, non-toxic constituents; wide-scale deployment of solar-to-electric power
- The semiconductor FeS<sub>2</sub> (pyrite, fool's gold (!!)) is a high-potential candidate:
  - > Outstanding abundance and cost
  - > Extraordinary light absorption
  - > Theoretical efficiency > 30 %
  - > Current record: 2.8 %!!
- **GOAL:** Remove barriers to FeS<sub>2</sub> usage in solar cells





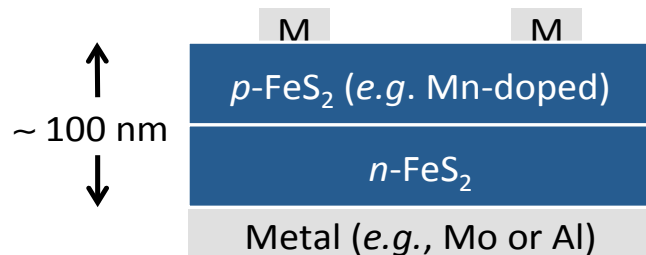
# Overall (Long Term) Project Goals

- Main open issues with  $\text{FeS}_2$ :

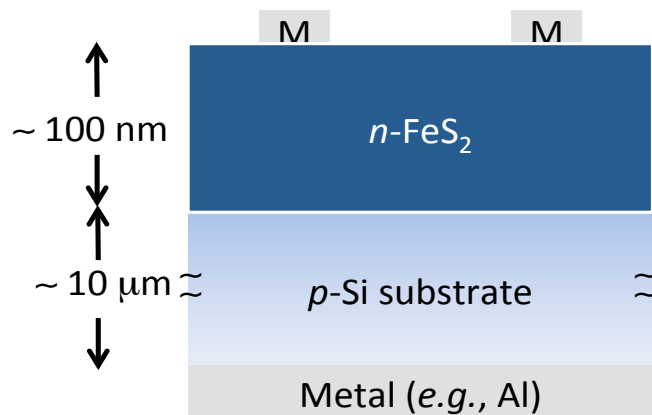
Surface conduction  
Doping control

- What is the *origin* of these surface effects?  
How can they be *mitigated*?  
Thus armed, can we *build better solar cells*?
- Can we understand and control *doping*?  
Can we intentionally *p-dope*?  
Can we make the *first  $\text{FeS}_2$  p-n solar cell*?
- Two main thrusts:
  - A: *p-n “homojunction” solar cells*
  - B: “ $\text{FeS}_2$ -sensitized” Si solar cells

## Thrust A: Thin film *p-n* $\text{FeS}_2$ homojunction



## Thrust B: Si/ $\text{FeS}_2$ *p-n* heterojunction





# Short Term (12 Month) Project Goals

- What we have under control:

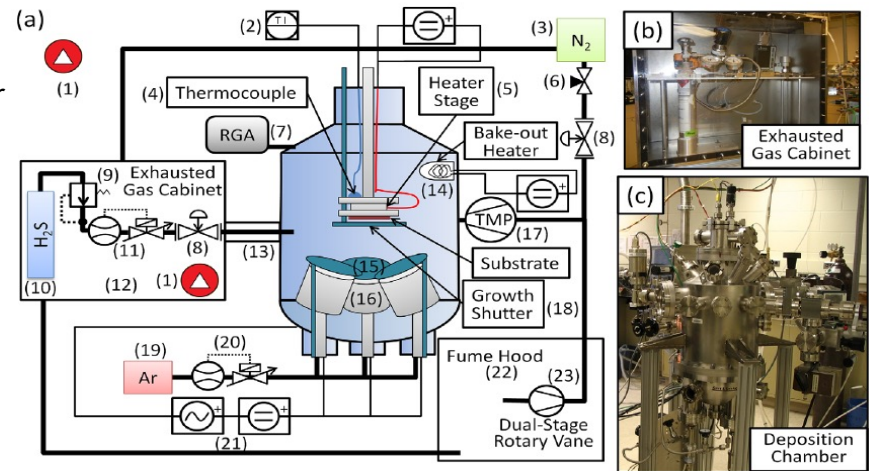
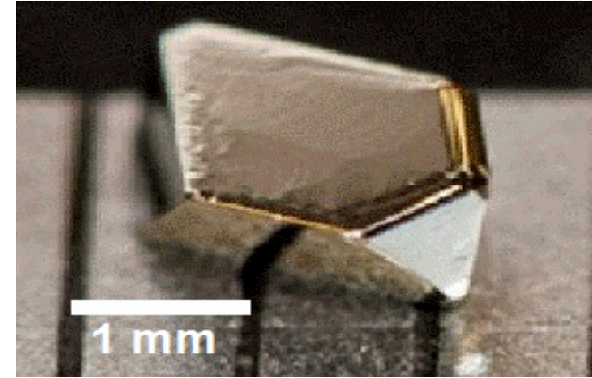
- > Synthesis of high quality  $\text{FeS}_2$  crystals
- > Synthesis of  $\text{FeS}_2$  thin films
- > Surface conduction confirmed
- >  $n$ -doping understood

- What we are currently working on (experiment and theory):

- > Proving that sulfur vacancies cause  $n$ -doping
- > Developing phosphorous as a  $p$ -dopant (or Mn?)

- What we plan:

- >  $p$ - $n$  homojunctions in crystals
- > Understanding the origins of surface conduction



# Project 4

- **Lian Shen:** *Simulation, Measurement, Modeling, and Control of Wind Plant Power*



# Project Team

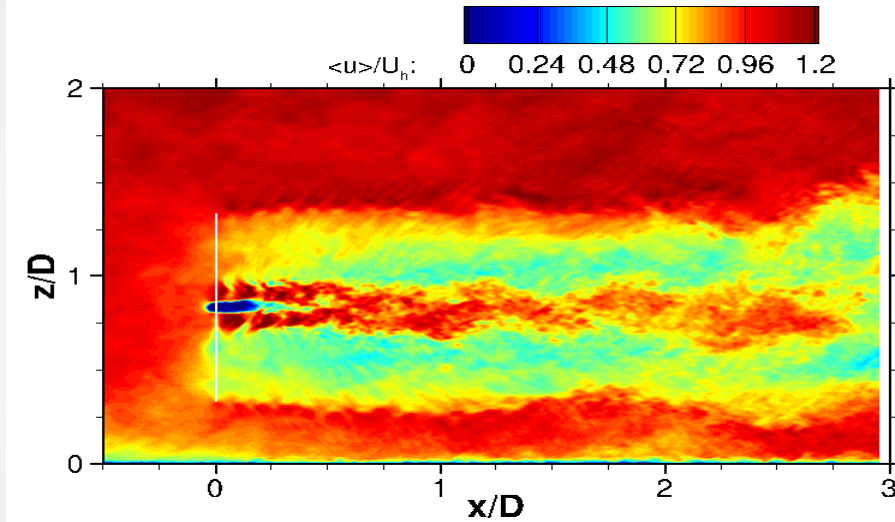
PI: Lian Shen - Associate Director for Research, St. Anthony Falls Laboratory  
shen@umn.edu

## Co-Principle Investigators

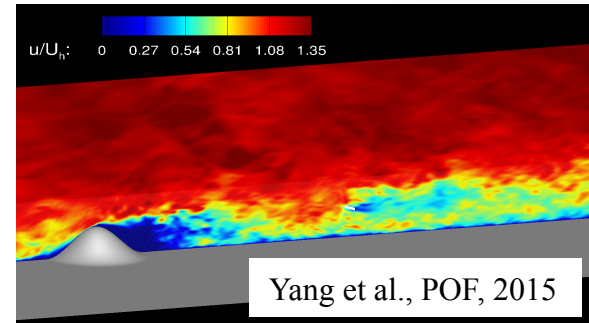
- Michele Guala, Department of Civil, Environmental and Geo- Engineering & St. Anthony Falls Lab
- Jiarong Hong, Department of Mechanical Engineering & St. Anthony Falls Lab
- Jeffery Marr, St. Anthony Falls Lab
- Joseph Nichols, Department of Aerospace Engineering and Mechanics
- Peter Seiler, Department of Aerospace Engineering and Mechanics & St. Anthony Falls Lab

Hired three graduate research assistants and one post-doc. Additional student researchers will be hired in the next quarter.

# Research Importance



Measuring only 1 turbine is typical



Measuring hills has not been done extensively



# Research Methods: Lab Wind Tunnel

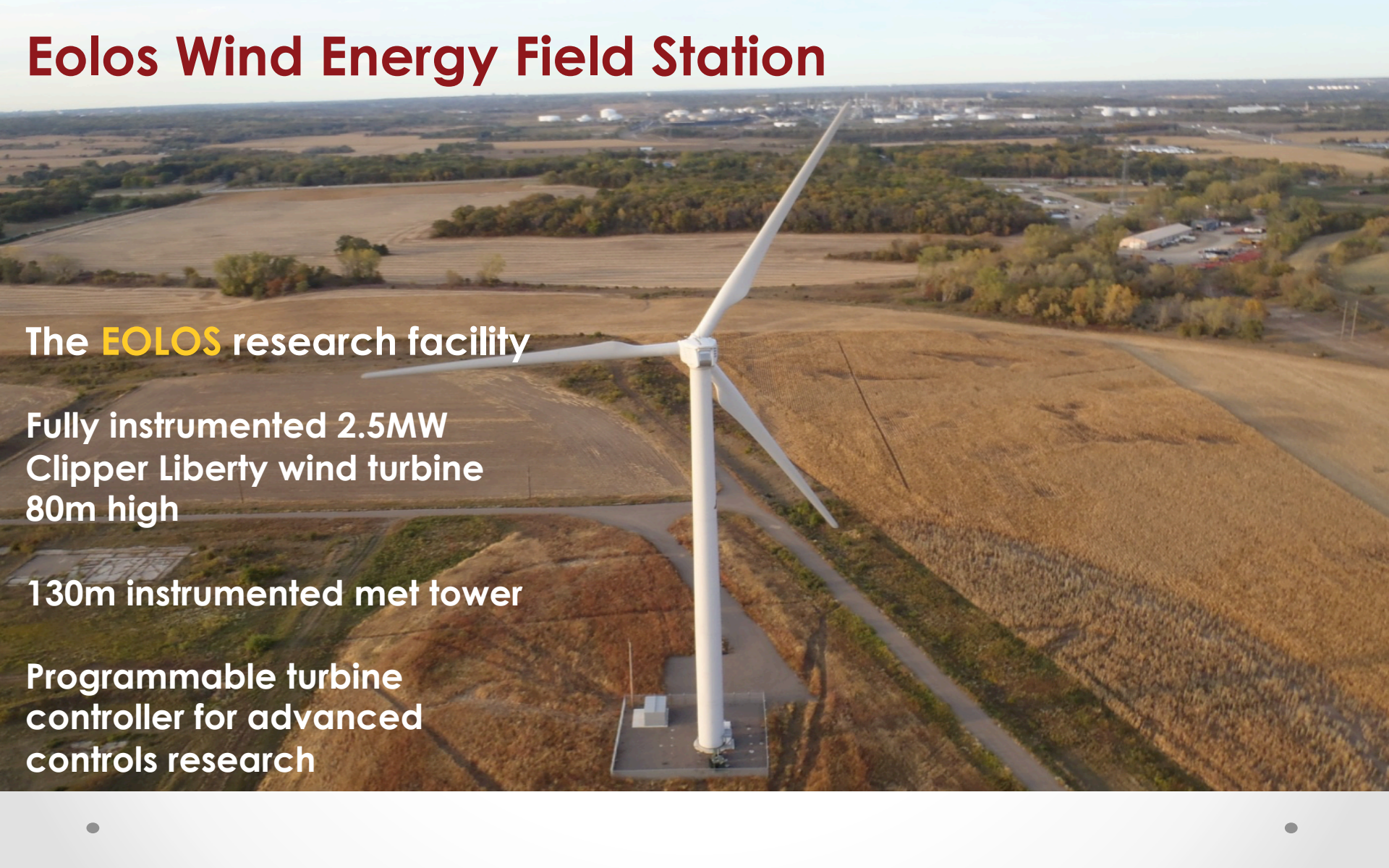


St. Anthony Falls has a large-scale wind tunnel. The tunnel is powered by at 200 hp fan and can reach speeds up to 148 ft/second (45 meters/second).





# Eolos Wind Energy Field Station

An aerial photograph of a large white wind turbine standing in a rural landscape. The turbine is the central focus, with its three blades extending outwards. The surrounding area consists of dry, brownish-yellow fields and some scattered trees. In the background, a small town or industrial area is visible under a clear sky.

The **EOLOS** research facility

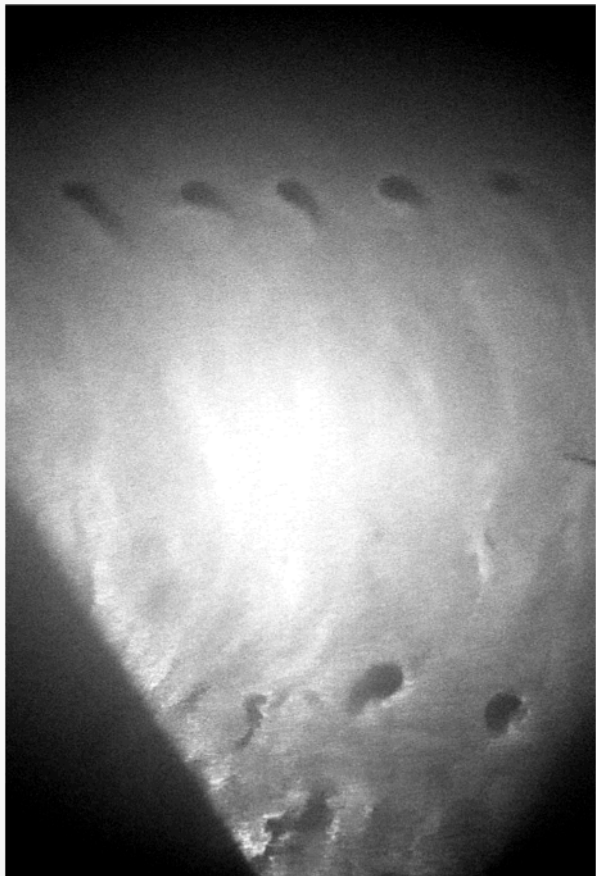
Fully instrumented 2.5MW  
Clipper Liberty wind turbine  
80m high

130m instrumented met tower

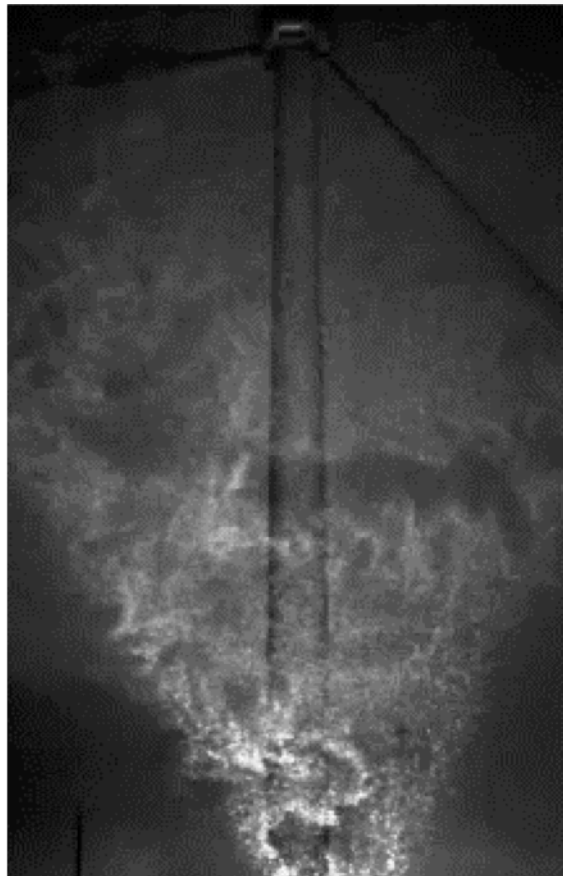
Programmable turbine  
controller for advanced  
controls research

# Samples of flow measurements with natural snow

Side View



Plan-view



Complex flow structures revealed for the first time around utility-scale wind turbine.

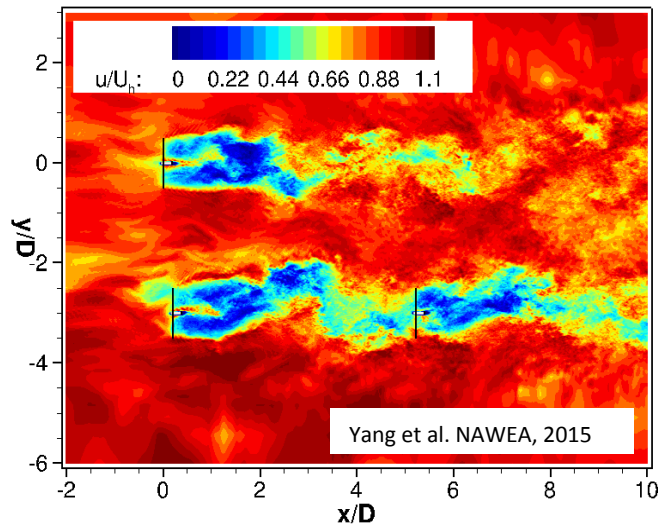


# Wind Farm Simulations

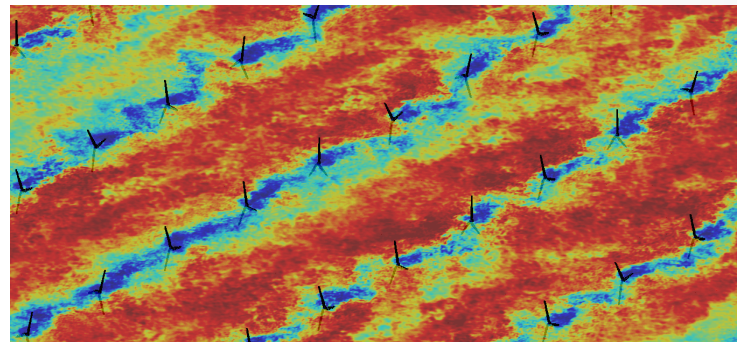


The DOE/SNL SWiFT Facility  
in Lubock, TX

SWiFT turbine simulation in  
collaboration with Sandia  
National Laboratories



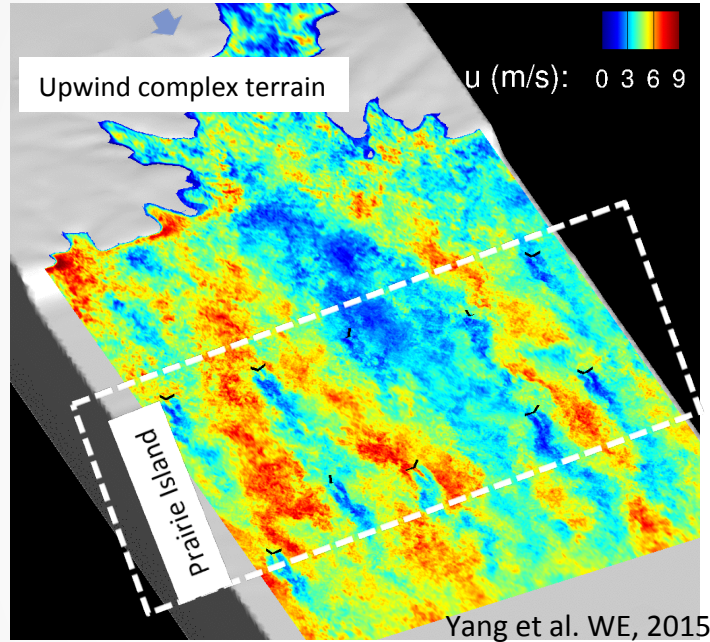
Horns Rev 3  
Offshore Wind  
Farm Simulation



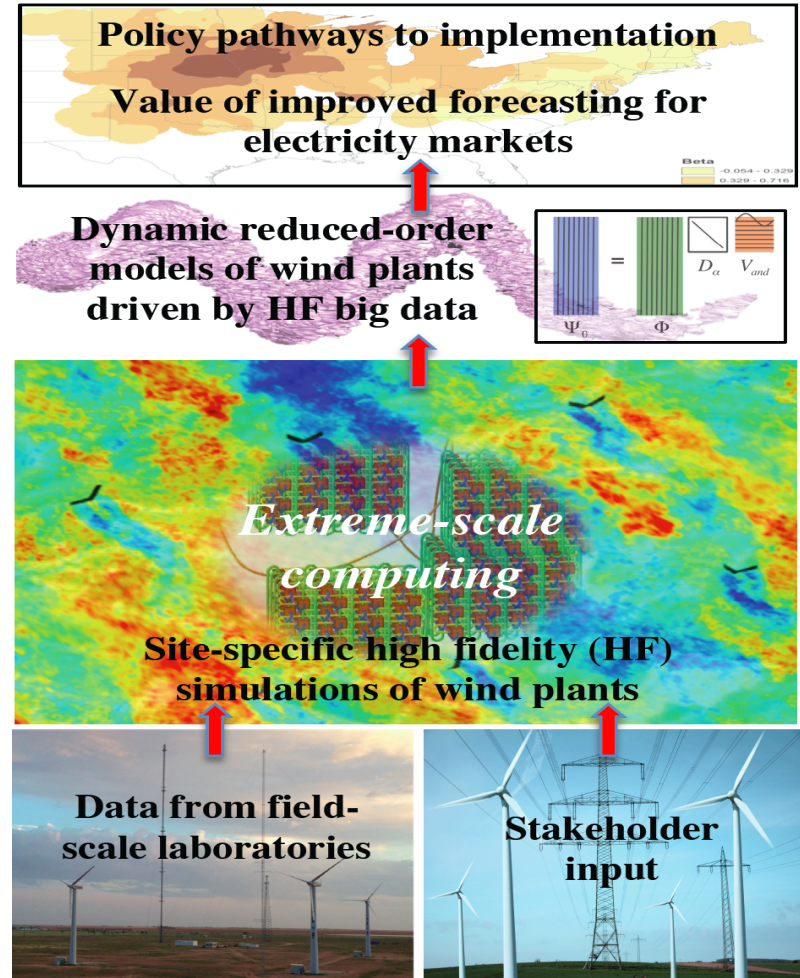


# 2017 Plan

## High Fidelity Simulation + Reduced Order Modeling



Wind over hypothetical  
installed wind turbines in  
Prairie Island, MN



# 2017 Action

## Reduced Order Modeling for Wind Power Optimization

**Goal:** Obtain (low-order) models suitable for control from high-fidelity LES models.

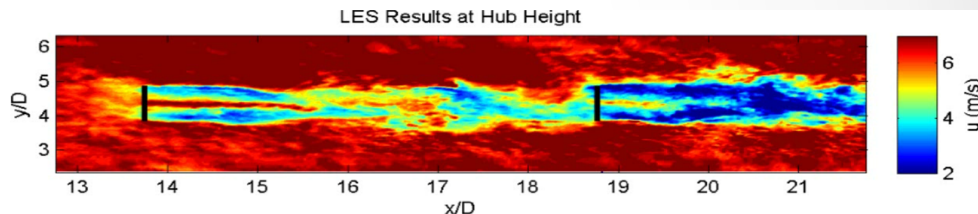
**Issues:** Ideal approach should:

- Handle  $> 10^5$  states
- Handle inputs and outputs
- Be adjoint free
- Have reduced states with physical meaning
- Handle varying wind condition

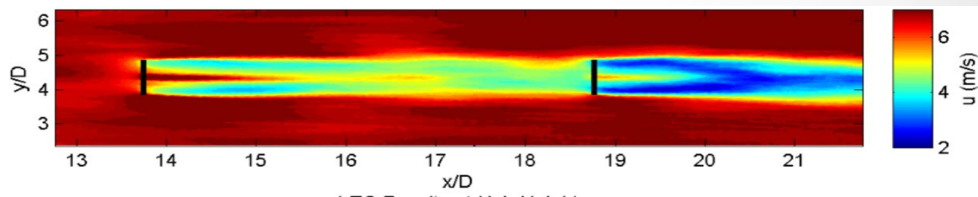
**Approach:** Construct reduced-order models with inputs & outputs (IOROMs) by combining:

- Subspace Identification
- Proper Orthogonal Decomposition
- Linear Parameter-Varying Modeling

Hub Height Speed: 20 State IOROM



Hub Height Speed: Full LES



# Project Benefits

- Xcel
  - Research leading to future development
- U of M
  - Top notch post-docs
  - Enhancing UMN research stature through Xcel part
- Minnesota
  - Enhanced connections between the University and the private sector
  - Economic opportunities for future industry



# QUESTIONS?

Lewis Gilbert – Managing Director / COO  
[legilber@umn.edu](mailto:legilber@umn.edu)

Christov Churchward – Energy Programs Coordinator  
[rdfinfo@umn.edu](mailto:rdfinfo@umn.edu)

