Environment and Natural Resources Trust Fund
2017 Request for Proposals (RFP)

Project Title: **ENRTF ID:** **133-E**

Compressed Air Energy Storage for Renewable Energies

Category: E. Air Quality, Climate Change, and Renewable Energy

Total Project Budget: $ 712,392

Proposed Project Time Period for the Funding Requested: 3 years, July 2017 - June 2020

Summary:

This project will develop a novel compressed air energy storage system for renewable energies that will solve the increasing challenge of integrating these intermittent energy sources into the electrical grid.

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Sponsoring Organization: U of MN

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Location

Region: Statewide

County Name: Statewide

City / Township:

Alternate Text for Visual:

Open accumulator CAES with an isothermal compressor/expander is a competitive energy storage approach that is cost-effective, efficient and increases revenue for wind/solar farms and stability for the electrical grid.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

_____ Extent of Impact _____ Innovation _____ Scientific/Tech Basis _____ Urgency

_____ Capacity Readiness _____ Leverage _______ TOTAL ______%

PROJECT TITLE: Compressed Air Energy Storage System for Renewable Energies.

I. PROJECT STATEMENT

This project will develop and demonstrate a novel, fuel-free, compressed air energy storage (CAES) system for renewable energies such as wind and solar. While Minnesota has excellent wind and solar resources, it is increasingly challenging to integrate more of these intermittent, variable and unpredictable energy sources into the electrical grid. Because these energy sources are not always available, backup power with capacity greater than the supplies' variability are required. Currently, these are served by natural gas power plants – known as "peaker" plants, which have large carbon footprints and are expensive to build, operate and maintain. Availability of an economical, grid scaled energy storage system that can respond rapidly to meet the changing disparity between supply and demand is key to resolving this issue. Such a system would allow excess energy to be stored when energy supply exceeds demand, and stored energy to be used when demand exceeds supply.

The proposed compressed air energy storage (CAES) system is unique in that it uses a special *open accumulator* (OA) architecture and a *near-isothermal* compressor/expander. The former allows the system to increase energy storage density by 5 times over existing systems by varying the air volume in the storage tank. The latter, through optimized heat transfer, enables the energy storage and regeneration processes to be efficient and powerful. These translate to an economically scalable system with target costs of $1000/kW and $150/kWh. Compared to electric batteries, the system is many times cheaper, can charge/recharge unlimited times, and does not require exotic materials nor have toxic chemicals. As compressed air can be stored in pressure vessels that can be located anywhere, it is not restricted by geographic locations like pumped-hydro or conventional CAES that require large reservoirs or underground salt caverns. Unlike conventional CAES that is used in conjunction with natural gas turbines, our system has no carbon footprint, is 50% more efficient and 5 times more energy dense. The proposed system can also be directly integrated with wind-turbines to store excess energy prior to generating electricity. In this case, the costly electrical generator and power electronics can be downsized for the mean power instead of the peak power to reduce capital expense. This is significant since the typical capacity factors of wind turbines are below 40% so that downsizing by 60% is possible. Furthermore, the proposed system has a rapid response time of 10ms-100ms, allowing it to stabilize the frequency and voltage variability of the electrical grid, preventing disastrous blackouts.

Prior research by the project team in the past 5 years, funded by the National Science Foundation (NSF), has established the feasibility of the proposed concept, and has validated the designs of critical elements. The goal of the present project is to design and construct a scaled (50kW, 25kWh) system prototype, to develop its control system and to demonstrate its capabilities. Such demonstration is necessary to transition from fundamental research to commercial adoption. Widespread deployment of the proposed system will make renewables much easier to integrate into the grid and financially much more attractive, thus making the goal of generating 25% of Minnesota's energy by 2025 and the proportionate reduction in carbon emission a reality.

II. PROJECT ACTIVITIES AND OUTCOMES

Activity 1: *Design and construct 50kW, 25kWh system prototype.* **Budget: $304,131**

A prototype of the proposed compressed air energy storage (CAES) system (Fig. 1) capable of capturing and delivering 50kW power and for storing 25kWh (30mins worth) energy will be designed, optimized and constructed. This size is small enough for the laboratory but large enough to have representative performance of a large-scale system. The high pressure (200bar/3000psi) liquid piston near-isothermal compressor/expander with optimized heat transfer is a critical custom design component that needs to be efficient and power dense.

Outcome	Completion Date
1. *Optimal design of the liquid piston near-isothermal compressor/expander*	End of month 9
2. *Construction of near-isothermal compressor/expander.*	End of month 12
3. *Complete construction of the balance of plant*	End of month 15

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Activity 2: *Develop control system for the prototype* **Budget: $204,131**

Control system is needed for 3 aspects: 1) plant level control for the low level operation; 2) supervisory control to determine when energy should be stored and regenerated to maximize utility of the energy; 3) grid integration control to support the electrical grid in the event of frequency or voltage fluctuation.

Outcome	Completion Date
1. Plant level control developed	End of month 18
2. Supervisory control developed	End of month 21
3. Grid integration control developed	End of month 24

Activity 3: *Testing and evaluation* **Budget: $ 204,131**

The prototype will be tested for 1) nominal power and efficiency; 2) ability to meet variable power demand; 3) ability to respond to grid fluctuations

Outcome	Completion Date
1. Power and efficiency evaluation	End of month 30
2. Demand tracking performance evaluation	End of month 33
3. Grid stabilization performance evaluation	End of month 36
4. System demonstration to potential commercialization partners	End of month 36

III. PROJECT STRATEGY

A. Project Team/Partners

Project manager Perry Li and investigators Terry Simon and Jim Van de Ven are Mechanical Engineering professors at the U. of Minnesota. Their collective expertise in control systems (Li), fluid power (Li and Van de Ven), machine design (Van de Ven) and heat transfer/fluid mechanics (Simon) is the basis for the proposed high efficiency, high energy density, fast responding CAES. In the present project, Li will manage the overall project and lead the control effort; Van de Ven will lead the prototype design and manufacturing effort; and Simon will lead the heat transfer / fluid mechanics efforts. Three Mechanical Engineering PhD students will carry out the design, control and testing responsibilities.

B. Project Impact and Long-Term Strategy

Increasing adoption of renewable energy is a necessity for a sustainable environment and economy. Availability of a cost effective grid scale energy storage system removes the greatest challenge of integrating intermittent renewable energy into the electric grid by replacing the expensive natural gas "peaker" plants. With the proposed system, renewable energy producers can benefit from lower capital expenditure (through downsizing components) and increased revenue (through price arbitrage and selling reliable power that is more valuable and ancillary services to stabilize the grid). These incentivize the development of the renewable energy resources of Minnesota and beyond. Consumers will benefit from lower cost clean electricity and a more reliable electric grid. Besides being useful for land based wind and solar farms, the proposed system is well suited for off-shore wind and wave energies of which Lake Superior is a good resource. The long term goal is to commercialize and widely deploy the proposed system. This can be through the establishment of a startup company, or in partnership with commercial, State or non-profit entities. The prototype and the demonstration of its capability established by this project will provide the data to convince investors and other commercial entities to partner with us.

C. Timeline Requirements

The project is planned for 3 years over the period 7/1/2017-6/30/2020. Roughly, year 1 will focus on design and construction of the prototype; year 2 will focus on control design; and year 3 will focus on testing and evaluation. During the project duration, we will continue to actively seek industry and state partners, to plan for the development of a large-scale field demonstration and to commercialize the technology.

2017 Detailed Project Budget

Project Title: Compressed Air Energy Storage for Renewable Energies

INSTRUCTIONS AND TEMPLATE (1 PAGE LIMIT)

Attach budget, in MS-EXCEL format, to your "2017 LCCMR Proposal Submission Form".

(1-page limit, single-sided, 10 pt. font minimum. Retain bold text and DELETE all instructions typed in italics. ADD OR DELETE ROWS AS NECESSARY. If budget item row is not applicable put "N/A" or delete it. All of "Other Funds" section must be filled out.)

IV. TOTAL ENRTF REQUEST BUDGET *3* **years**

BUDGET ITEM *(See "Guidance on Allowable Expenses", p. 13)*	**AMOUNT**
Personnel:	$ -
Perry Y. Li, Project Manager, control and fluid power expert (75% salary, 25% benefits), 8.3% FTE for all years	$ 58,020
Terrence W. Simon, Co-Investigator, heat transfer expert (75% salary, 25% benefits), 8.3% FTE for all years	$ 76,498
James D. Van de Ven, Co-Investigator, machine design expert, (75% salary, 25% benefits), 8.3% FTE for all years	$ 47,196
3 Graduate Research Assistants, design, control and demonstration (60% salary, 40% benefits), 50% FTE for all years	$ 429,178
Professional/Technical/Service Contracts:	
Equipment/Tools/Supplies:	
Compressed Air Energy Storage System prototype (50kW, 30min) Custom components (liquid piston compressor/expander, heat exchanger, liquid piston pump/motor, high speed valves): materials and construction $71000 Off-the-shelf hydraulic components (pump/motors, fittings): $5000 Instrumentations (sensors and data acquisition): $5000 Composite accumulator (storage): $5000 Induction Generator: $7000 Electric load bank: $7000	$ 100,000
Lab supplies: hydraulic oil, misc electronics, mechanical and hydraulic parts	$ 1,500
Travel:	
Additional Budget Items: In this column, list any additional budget items that do not fit above categories. List by item(s) or item type(s) and explain how number was determined One row per type/category.	$ -
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST	$ 712,392

V. OTHER FUNDS *(This entire section must be filled out. Do not delete rows. Indicate "N/A" if row is not applicable.)*

SOURCE OF FUNDS	**AMOUNT**	**Status**
Other Non-State $ To Be Applied To Project During Project Period:	N/A	
Other State $ To Be Applied To Project During Project Period:	N/A	
In-kind Services To Be Applied To Project During Project Period: The foregone federally negotiated ICR funding constitutes the University's cost share to the project. The total cost share is $348,189 and has been determined using the federal IDC rate of 52% with appropriate exclusions for equipment and academic year tuition and benefits.	$ 348,189	*Pending*
Funding History: $2,000,000 - NSF #1038294 "EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage" 9/2010-8/2016.	$ 2,000,000	Ending
Remaining $ From Current ENRTF Appropriation:	N/A	

Cost effective grid scale compressed air energy storage solves problem of integrating intermittent renewable energies

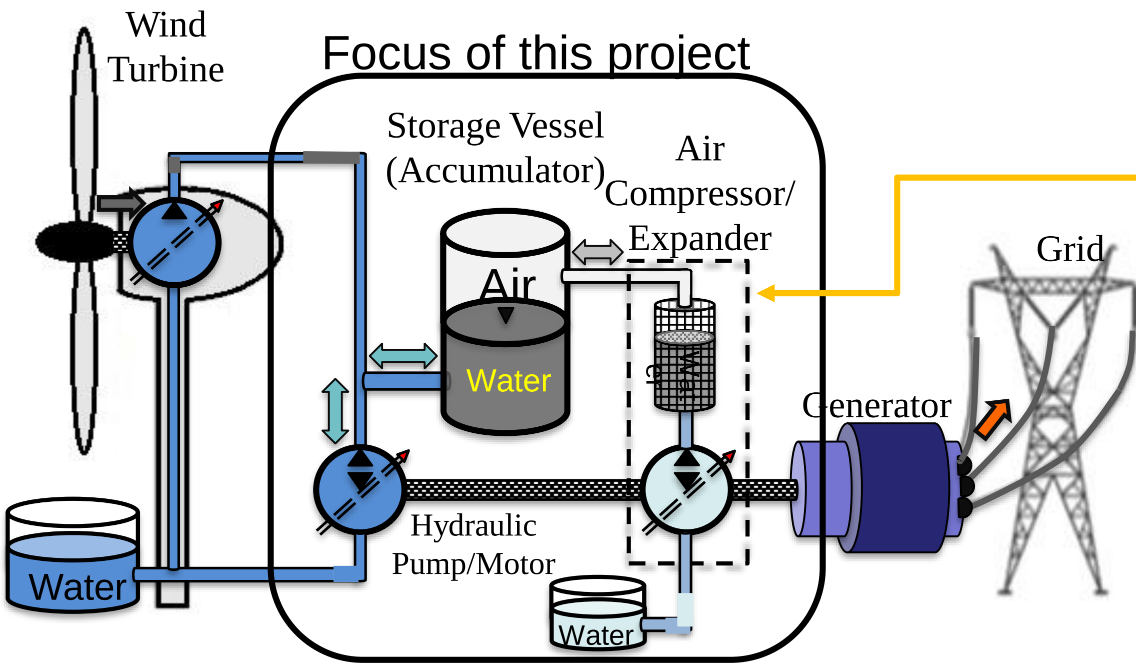

Fig.1 Open accumulator isothermal CAES integrated with a wind turbine

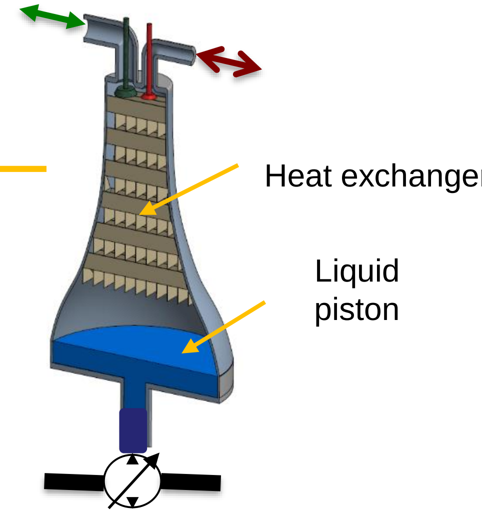

Fig. 2: Liquid piston high pressure air compressor/expander optimizes heat transfer to achieve high efficiency and power density

Technology Impact

- Cost-effective & scalable ($150/kWh, $1000/kW) [cf. Li Ion batteries: $5000/kWh, $1300/kW]
- Downsize elec. components for wind turbines → → 17% less CAPEX
- Reliable, on-demand green energy
- Replace "peaker plants" → ease grid integration
- Stabilize grid frequency/voltage fluctuations

- Prior research established feasibility
  - 5x improved energy density
  - 200x increase in power density
  - ➔ cost-effectiveness, efficiency

This project:

- Develop system prototype & control
- Demonstrate capabilities

➔ Commercialization and deployment

PROJECT TITLE: Compressed Air Energy Storage for Renewable Energies

I. PROGRAM MANAGER QUALIFICATIONS

Program Manager, Perry Y. Li, is Professor of Mechanical Engineering at the University of Minnesota. He received his PhD in Mechanical Engineering from the University of California, Berkeley, MS in Biomedical Engineering from Boston University, and M.A. in Electrical and Information Sciences from Cambridge University, UK. His expertise is in control systems, fluid power and robotics. He was the founding Deputy Director for the Center for Compact and Efficient Fluid Power (CCEFP), a NSF funded national Engineering Research Center, with the responsibility of coordinating the research across the many research groups within the center. At the University of Minnesota, he directs the Fluid Power Controls Laboratory and the Mechatronics and Intelligent Machines Laboratory. He is the Principle Investigator of the prior $2M, NSF funded project on compressed air energy storage that is the precursor to the present application. In this role, he managed the multidisciplinary research team of 20 faculty members, post-doc researchers and graduate students. He and his research group has invented the open accumulator energy storage architecture that increases fluid power energy storage by an order of magnitude; and the liquid piston high pressure near-isothermal compressor/expander that incorporates optimal control, heat transfer and hydraulic power take-off to increase power density of such a device by 2 orders of magnitude without sacrificing efficiency. Both inventions are used in the proposed compressed air energy storage system. Through a DOE/ARPA-E grant, he and investigator Simon, have applied a similar compressor approach to develop a low cost CNG refueling system for vehicles. Besides researching energy storage for renewable energies, his other current research topics include novel energy efficient fluid power components, design and control of hydraulic hybrid vehicles and human scale fluid power robots. He has several patents related to these topics.

II. ORGANIZATION DESCRIPTION

Department of Mechanical Engineering, is part of the College of Science and Engineering at the University of Minnesota Twin Cities Campus, serves the state and nation as a leading center of education, research, and innovation. The Department has 42 active faculty, 30 staff members, 300 graduate students, 50 postdoctoral associates, research associates and visitors, and about 550 undergraduate students. The department has a variety of professional and student machine shops, workshops and computer laboratories with a full range of machine tools, 3D printers and high performance computing facilities. Two research labs, **the Fluid Power Controls Lab.**, directed by Program Manager Li, and the **Mechanical Energy and Power Systems Lab.**, directed by investigator, Van de Ven, are equipped with state-of-the-art equipment for conducting fluid power research. The department is well known internationally for its fundamental and applied heat transfer research. Investigator, Simon, is currently the Eckert Chair Professor of Heat Transfer.

Center for Compact and Efficient Fluid Power (CCEFP), is a National Science Foundation funded Engineering Research Center, founded in 2006, to transform how fluid power is researched, applied and taught. The center, which is headquartered at the University of Minnesota, consists of 38 faculty members from 7 leading US universities and over 50 industrial sponsors. Its research goals are to create fluid power that is efficient, compact and can be used everywhere. Since founding, the CCEFP has significantly increased and transformed the research of Fluid Power in the U.S.. The proposed project will be an associated project within the CCEFP. Program manager Li was the founding Deputy Director and investigator Van de Ven is the current Education Director. The CCEFP has enabled a strong and direct relationship to the major fluid power companies, and a well-established education and outreach program that this project can make use of.