Environment and Natural Resources Trust Fund
2020 Request for Proposals (RFP)

Project Title: **ENRTF ID:** 179-E

Power Electronics Circuits for Minnesota's Renewable Energy Future

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

Sub-Category:

Total Project Budget: $ 472,647

Proposed Project Time Period for the Funding Requested: June 30, 2023 (3 yrs)

Summary:

Our project involves engineering techno-economic solutions that will propel pertinent stakeholders in Minnesota to the forefront of advances in next-generation ultra-wide-bandgap power-electronics circuits for renewable (solar) energy applications.

Name: Steven Koester

Sponsoring Organization: U of MN

Job Title: Professor

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Location:

Region: Metro

County Name: Hennepin

City / Township: Minneapolis

Alternate Text for Visual:

We will engineer techno-economic solutions for efficient and reliable solar energy conversion. The primary deliverable will be a residential-scale inverter that converts solar energy to electricity with industry-leading efficiency & reliability specifications built with MN-made ultra-wide-bandgap devices.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

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

_____ Capacity Readiness _____ Leverage _______ TOTAL ______%

PROJECT TITLE: Power-electronics Circuits for Minnesota's Renewable Energy Future

I. PROJECT STATEMENT:

The electrical power system in Minnesota is witnessing unprecedented transitions in form and function with the integration of renewable resources of energy (e.g., solar and wind), flexible loads (e.g., electric vehicles), and energy-storage devices. Renewable resources accounted for 24.9% of Minnesota's electricity generation portfolio in 2017, implying that the 25%-by-2025 target set by the state's Renewable Electricity Standard will be assuredly surpassed.[1] Energy conversion for electricity generation in the power system today is undertaken through synchronous generators: large electrical machines that convert thermal energy stored in fossil fuels to electrical energy that is ultimately delivered to our homes and businesses. The next-generation power system will be dominated by power-electronics circuits: semiconductor-device based technologies that can convert, e.g., electromagnetic energy in incident solar irradiation to electrical energy (with no moving parts!). According to some estimates, up to 80% of electricity will be processed by power-electronics circuits by 2030. Ensuring the reliability and efficiency of power-electronics circuits is therefore critical to realizing a sustainable and environmentally benign electricity infrastructure across the state and around the world.

Efficiency advancements in power-electronics circuits can be achieved by reducing conduction and switching losses in constituent semiconductor devices. In recent years, ultra-wide-bandgap (UWBG) semiconductor devices have been recognized to provide size, efficiency, and cost advantages compared to conventional Silicon-based devices. UWBG devices are innately better suited to power conversion because they can sustain higher voltages in a smaller spatial footprint. This increases current density and switching frequencies, and further minimizes the size and weight of packaged circuits. Taken together, these attributes contribute to improved efficiency and reliability of power-electronics circuits realized with UWBG devices. However, to unlock the full potential of these devices, significant R&D is required to address engineering challenges spanning thermal management, device fabrication, circuit topologies, and design optimization. The nascency of UWBG technology also implies that economic and policy-related drivers—that are critical to ensure widespread adoption—are far from understood.

Our project involves engineering techno-economic solutions that will propel pertinent stakeholders in Minnesota to the forefront of advances in next-generation UWBG power-electronics circuits for renewable energy applications. ***The primary project deliverable will be a residential-scale photovoltaic (PV) inverter with industry-leading efficiency (>95%), reliability (surface temperature <60^o), and power-density (50W/in^3) specifications built with Minnesota-made UWBG devices.*** Successful project completion will promote and demonstrate Minnesota capabilities across critical manufacturing and technology value chains ranging from advanced materials to consumer-grade electronics. The project team includes broad-based expertise across materials engineering (**Wang**), semiconductor device fabrication (**Koester**), circuit design (**Choi**), systems optimization (**Dhople**), and law/policy (**Anderson**). Specific project tasks will include:

i) Engineering UWBG thin films for industry-leading electrical and thermal properties;
ii) Fabricating semiconductor devices using UWBG materials with tailored functionalities;
iii) Prototyping and demonstration of a photovoltaic (PV) inverter built with UWBG devices;
iv) Evaluating techno-economic barriers and opportunities for MN-based industry in this technology space.

Project tasks are centered around beta-gallium oxide (β-Ga_2O_3, the most stable form of gallium oxide) serving as the UWBG material of choice given its unique electro-thermal properties. However, program activities are architected from the bottom-up and without loss of generality so that project completion will ultimately bring UWBG-based power-electronics circuits closer to widespread adoption. The proposed effort is thematically, philosophically, scientifically, and programmatically aligned with Minnesota's 2025 Energy Action Plan authored by the Department of Commerce.[2]

1. MN Department of Commerce, "Minnesota Renewable Energy Update: November 2018," *http://mn.gov/commerce-stat/pdfs/2017-renewable-energy-update.pdf*
2. MN Department of Commerce, "Minnesota's 2025 Energy Action Plan," *https://mn.gov/commerce/policy-data-reports/energy-data-reports/mn-action-plan.jsp*

II. PROJECT ACTIVITIES AND OUTCOMES:

Through the 3-year duration, our project promises innovations in three interrelated domains: i) materials & devices, ii) circuits & systems, and iii) economic analysis & policy assessment.

Activity 1: Initial device characterization, circuit design, and PV inverter modeling **[ENRTF BUDGET: $139,378]**
Description: *In Activity 1, the team will focus on engineering the electro-thermal properties of bulk & thin-film UWBG β-Ga_2O_3 material and on initial circuit design and modeling for the PV inverter.*

Outcome	Comp. Date
1. Establishment of structure-thermal property relationships of bulk & thin-film β-Ga_2O_3	*Dec. 31, 2020*
2. Fabrication and test of field-effect transistor devices built with β-Ga_2O_3	*Jun. 30, 2021*
3. Investigation of optimal PV inverter circuit topology	*Jun. 30, 2021*
4. Formulation of physics-based models for system (devices + PV inverter)	*Jun. 30, 2021*

Activity 2: Design optimization of PV inverter built with proposed devices **[ENRTF BUDGET: $142,008]**
Description: *In Activity 2, the team will focus on prototyping the PV inverter topology and design optimization of the UWBG devices. Feedback from circuit design will be leveraged to improve device performance.*

Outcome	Comp. Date
1. Optimization of electro-thermal material properties of bulk & thin-film β-Ga_2O_3	*Dec. 31, 2021*
2. Enhancement of efficiency & reliability of field-effect transistor devices built with β-Ga_2O_3	*Dec. 31, 2021*
3. Laboratory prototyping of PV inverter topology	*Jun. 30, 2022*
4. Development of control algorithms for grid-compliant operation of PV inverter	*Jun. 30, 2022*

Activity 3: Demonstration of PV inverter and techno-economic assessment **[ENRTF BUDGET: $191,261]**
Description: *In Activity 3, the team will demonstrate the optimized PV inverter prototype with industry-leading efficiency and reliability specifications. Broader economic and policy impacts will be investigated.*

Outcome	Comp. Date
1. Broader exploration of material & device alternatives based on stakeholder feedback	*Jun. 30, 2023*
2. Testing and demonstration of the PV inverter prototype to stakeholders	*Jun. 30, 2023*
3. Economic analysis, impact & feasibility assessment	*Jun. 30, 2023*

III. PROJECT PARTNERS AND COLLABORATORS:

The diversity in professional qualifications and technical backgrounds of team members is uniquely pronounced and undeniably necessary to accomplish project activities. Minnesota is home to several companies (Honeywell, 3M), electric utilities (Xcel Energy, Great River Energy), and a power-system operator responsible for guaranteeing supply reliability for 15 US and 1 Canadian province (Midcontinent System Operator), with interests directly tied to the project objectives and broadly aligned with the electricity infrastructure. Our team will also collaborate with Agnitron: a Minnesota-based company at the forefront of advances in technologies discussed in this proposal. Contextual relevance and alignment of proposed activities with the aspirations of Minnesota industries will be ensured via engagement of the University of Minnesota's Energy Transition Lab (led by **Anderson**).

IV. LONG-TERM IMPLEMENTATION AND FUNDING:

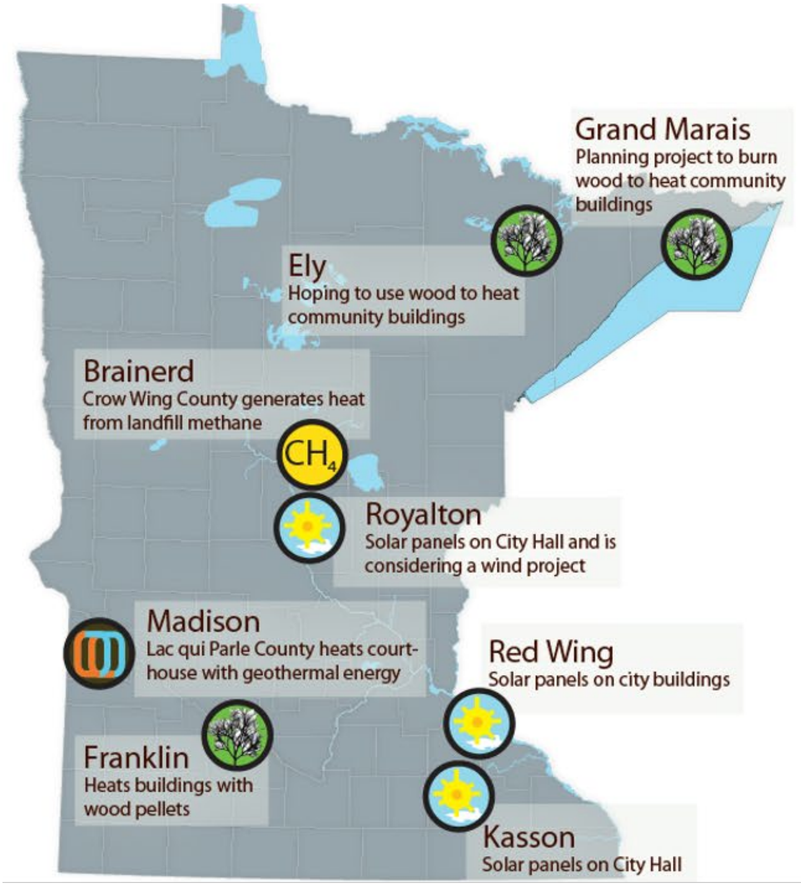
The completion of this project requires 36 months from July 01, 2020 to June 30, 2030. We anticipate that successful project completion will not only outline optimal topologies, companion control methods, and engineering rules of thumb for UWBG power-electronics circuits, but also establish the foundational science that governs relationships between material engineering and device performance. The preliminary results generated through this effort will be leveraged for composing multiple federal grant proposals. Our plan is to target agencies such as the National Science Foundation and the U. S. Department of Energy which have mature research funding portfolios focused on advanced materials, novel devices, circuits design, and systems engineering for renewable and sustainable energy applications.

Attachment A: Project Budget Spreadsheet
Environment and Natural Resources Trust Fund
M.L. 2020 Budget Spreadsheet
Legal Citation:
Project Manager: Steven Koester
Project Title: Power Electronics Circuits for Minnesota's Renewable Energy Future
Organization: University of Minnesota
Project Budget: 472,647
Project Length and Completion Date: 3 years, July 1, 2020, through June 30, 2023
Today's Date: April 10, 2019

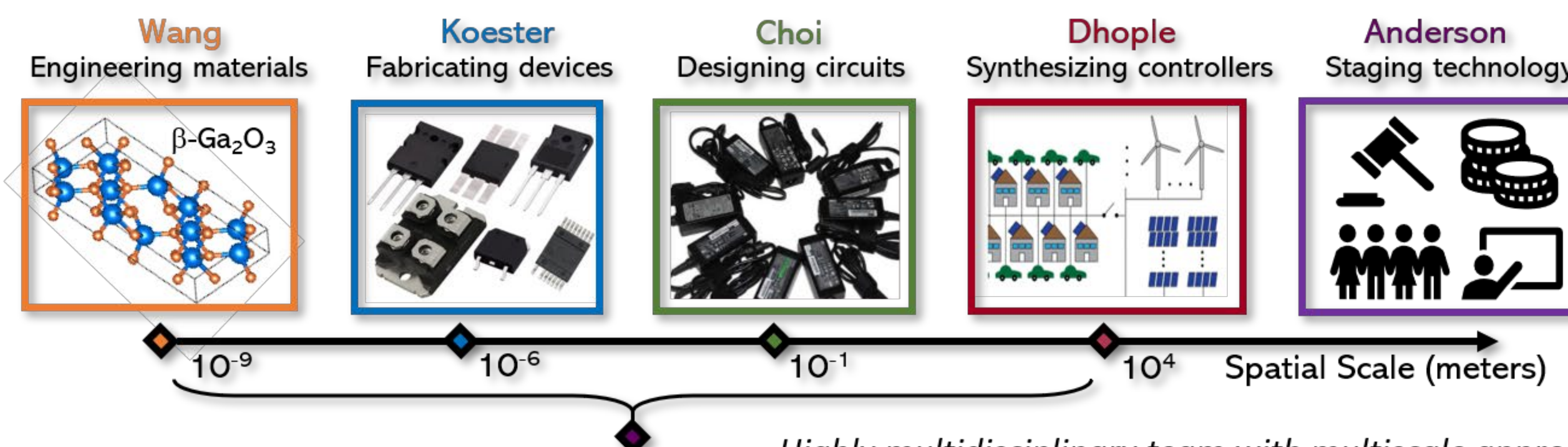
ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Budget	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits)	$ 412,647	$ -	$ 412,647
Steven Koester, Project Manager (1 week (.03FTE) + fringe 36.0% fringe) for 3 years	$ 19,003		
Xiaojia Wang (1 week (.03FTE) + fringe 36.0% fringe) for 3 years	$ 10,954		
Jungwon Choi (1 week (.03FTE) + fringe 36.0% fringe) for 3 years	$ 10,779		
Sairaj Dhople (1 week (.03FTE) + fringe 36.0% fringe) for 3 years	$ 12,503		
Ellen Anderson (1 week (.03FTE) + fringe 36.0% fringe) for 3 years	$ 8,705		
One-Graduate Research Assistant in ME (co-advised by Wang and Koester), 50% FTE (fall & spring include 16.1% fringe plus $20.50/hour tuition, summer 16.1% fringe only) for 3 years	$ 153,334		
One-Graduate Research Assistant in ECE (co-advised by Choi and Dhople), 50% FTE (fall & spring include 16.1% fringe plus $20.50/hour tuition, summer 16.1% fringe only) for 3 years	$ 150,825		
One-Graduate Research Assistant in ETLE (advised by Anderson), 50% FTE (fall & spring include 16.1% fringe plus $20.50/hour tuition, summer 16.1% fringe only) for the last year only (year 3)	$ 46,544		
Professional/Technical/Service Contracts	$ -	$ -	$ -
Equipment/Tools/Supplies	$ 51,000	$ -	$ 51,000
Purchasing reference materials, including bare silicon ($2000), silicon dioxide ($1000), sapphire ($2000) wafers for thermal characterization. Purchasing wide-bandgap materials with different doping ($8000), substrates for interface study, diamonds ($5000). Purchasing of characterization accessories, including AFM tips, TEM grids, electrical current sources, probes, objective lenses, among others ($9000). All #s are given in	$ 27,000		
User fees for rental and usage of facilities at the campus CharFac center for sample thermal property characterization (electrical conductivity, ellipsometry, and atomic force microscopy, $3000*3=$9000 for three years); User fees for rental and usage of facilities at the campus CharFac center for materials structural/property characterization (X-ray diffraction, secondary electron microscopy, Raman spectroscopy, tunneling electron microscopy, $4000*3=$12000)	$ 21,000		
User fees at MNC for thin-film deposition of metal transducers and electrods for electrical measurements (sputtering and thermal evaporation, $1000*3=$3000);	$ 3,000		
Capital Expenditures Over $5,000			
	$ -	$ -	$ -
Fee Title Acquisition			
	$ -	$ -	$ -
Easement Acquisition			
	$ -	$ -	$ -
Professional Services for Acquisition			
	$ -	$ -	$ -
Printing			
	$ -	$ -	$ -
Travel expenses in Minnesota			
	$ 9,000	$ -	$ 9,000
Other			
	$ -	$ -	$ -
COLUMN TOTAL	$ 472,647	$ -	$ 472,647

SOURCE AND USE OF OTHER FUNDS CONTRIBUTED TO THE PROJECT	Status (secured or pending)	Budget	Spent	Balance
Non-State:		$ -	$ -	$ -
State:		$ -	$ -	$ -
In kind:		$ -	$ -	$ -

Other ENRTF APPROPRIATIONS AWARDED IN THE LAST SIX YEARS	Amount legally obligated but not yet spent	Budget	Spent	Balance
		$ -	$ -	$ -



Highlighting renewable-energy projects in MN (left). We will engineer techno-economic solutions for efficient and reliable solar energy conversion (center). The primary project deliverable will be a residential-scale inverter that converts solar energy to electricity (right) with industry-leading efficiency & reliability specifications built with MN-made UWBG devices.



Highly multidisciplinary team with multiscale approaches.

Image credit: Google Images

Project Manager Qualifications & Organization Description

A. Project Manager Qualifications

Steven Koester is a professor in the Department of Electrical and Computer Engineering at the University of Minnesota (UMN). He received the Ph.D. in 1995 from the University of California, Santa Barbara, and the M.S.E.E. and B.E.E.E degrees in 1991 and 1989, respectively, from the University of Notre Dame. From 1995-1997 he was a postdoctoral research associate at the IBM T. J. Watson Research Center, and then stayed on as a research staff member from 1997 to 2010. Dr. Koester joined UMN in the spring of 2010, where his research focuses on novel electronic, photonic and sensing devices using 2D and ultra-wide-gap materials. His group specializes in device fabrication and characterization and his laboratory has a wide range of electronic characterization equipment for semiconductor devices. Dr. Koester has authored or co-authored over 250 technical publications, conference presentations, and book chapters, and holds 68 United States patents. He is a Fellow of the IEEE, and an associate editor of *IEEE Electron Device Letters*. **Steven Koester** will lead this proposed work and he will be responsible for the overall management of this project and the status reports of project update.

Xiaojia Wang is an assistant professor in the Department of Mechanical Engineering at the UMN starting in the fall of 2014. She received the Ph.D. in Mechanical Engineering from the Georgia Institute of Technology in 2011, and the M.E. and B.E. degrees in 2007 and 2004, respectively, from Xi'an Jiaotong University, China. She was a postdoctoral research associate in the Department of Materials Science & Engineering at the University of Illinois, Urbana-Champaign from 2012 to 2014. Her research focuses on the fundamental mechanisms of thermal and magnetic transport in micro/nano-engineered structures for energy conversion and harvesting, by utilizing the ultrafast pump-probe technique and other optical spectroscopic approaches. Her work has been featured on the cover images of *Advanced Functional Materials, Advanced Electronic Materials*, and *Nanoscale and Microscale Thermophysical Engineering*. She is currently a member of ASME Heat Transfer Division K9 Committee on Nanoscale Thermal Transport. She also serves as the editor of *Scientific Reports*

Jungwon Choi is an assistant professor in the Electrical and Computer Engineering at the UMN. She received the Ph.D. in the Department of Electrical Engineering at Stanford University, in 2019, the M.S. in Electrical Engineering and Computer Science from the University of Michigan, Ann Arbor, in 2013 and B.S. in Electrical Engineering from Korea University, in Seoul, Korea, in 2009. Her research interest is to design efficient RF resonant converters and matching networks in wireless power transfer (WPT) systems for consumer and industrial applications, and to evaluate wide band gap devices to operate at high switching frequency. She has been collaborating with Daihen Corporation to develop WPT systems and they have adopted her inverter design to implement their next-generation product. In 2017, she has been selected to the Rising Stars in EECS.

Sairaj Dhople is an Associate Professor in the Department of Electrical and Computer Engineering at the UMN. He received the Ph.D., M.S., and B.S. degrees in electrical engineering, in 2012, 2009 and 2007, respectively, from the University of Illinois, Urbana-Champaign. The main research interests of Prof. Dhople include modeling, analysis, and control of power electronics and power systems with a focus on renewable integration. He has received many awards, including the McKnight Land-grant Professorship (2017-2019), Associate of the Institute on the Environment (2017-2019), the Residential Fellow of Institute of Advanced Study (2017-2018) and National Science Foundation (NSF) Faculty Early CAREER Award in 2015.

Ellen Anderson received the J.D degree from the University of Minnesota Law School. She is a former Minnesota State Senator, and she currently serves as the Executive Director of the Energy Transition Laboratory (ETL) at the UMN. She is an expert in legal and policy issues related to energy, sustainability, and the environment. Through her leadership of the ETL, Dr. Anderson has successfully completed several high-impact collaborative projects on various topics engaging experts from public, private, community, and nonprofit spheres.

B. Organization Description

(1) Koester Nano-Device Laboratory (KNDL), Directed by Koester

Prof. Koester has laboratories in 6-158 and 3-154 Keller Hall, and office space in 6-149, 6-130 and 5-153 Keller Hall, all in the Department of Electrical and Computer Engineering at the UMN. The