Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2016 Work Plan

Date of Report: January 15, 2016

Date of Next Status Update Report: December 31, 2016

Date of Work Plan Approval:

Project Completion Date: June 30, 2019

Does this submission include an amendment request? No.

PROJECT TITLE: Solar Cells Manufacturing Research

Project Manager: Tianhong Cui

Organization: University of Minnesota

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Web Address:

Location: Minneapolis, Minnesota

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$388,000**
	Amount Spent:	**$0**
	Balance:	**$388,000**

Legal Citation: M.L. 2016, Chp. xx, Sec. 116P.10., Subd. 07a

Appropriation Language:

(a) Solar Cells Manufacturing Research

$388,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop inexpensive, high-efficiency solar energy by simple roll-to-roll advanced manufacturing technology, using perovskite a new photovoltaic material. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Solar Cells Manufacturing Research

II. PROJECT STATEMENT:

The objective of this proposal is to develop cheap clean solar energy based on roll-to-roll manufacturing approach (Figure 1). Perovskite is a brand new materials for the next generation of solar cells under development with very high efficiency and super low cost. The proposed advanced manufacturing is a simple roll-to-roll process using low-temperature physical-chemical deposition of perovskite, which is highly energy-efficient and very inexpensive. Potentially perovskite solar cells are one of the most disruptive renewable energy sources, and the proposed new manufacturing is the key to make it happen eventually. The proposed roll-to-roll manufacturing approach will enable the development of high-performance solar cells with extremely lower cost, compared to silicon solar cells. The success of this proposal will provide renewable green energy as centralized power plants to reduce the imports of energy from foreign countries. In addition, as low-cost distributed energy sources, the perovskite solar cells can be easily adopted by families or individual electronics customers, which will significantly improve the energy efficiency of all economic sectors. Through the proposed roll-to-roll manufacturing, perovskite solar cells can become a truly clean, low-cost, renewable energy source as an effective energy sources in Minnesota State. This project is intended to provide foundational knowledge of the technique and prove its feasibility of cheap perovskite solar cells. In the next phase of the research, we will closely collaborate with state manufacturers and energy providers in Minnesota to further develop an implementation and commercialization plan.

Upon completion of the project, cheap and high-efficiency perovskite solar cells for outdoor solar to electricity conversion will be developed. The knowledge learned throughout the project will provide a solid foundation for further research and development efforts that would lead to implementation of the new solar cells for residential, power plants, or consumer electronics. Eventually, cheap, clean, renewable, and high-efficiency solar energy sources will be installed in Minnesota. In addition to the low-cost of roll-to-roll manufactured solar cells, the cost of transportation, installation and support system will also decrease drastically due to their lighter weight and flexibility. This will potentially provide a supplementary energy solution to current energy sources in Minnesota, ultimately help implement the renewable energy policy, and thus enhance the economic and ecological benefits of Minnesota.

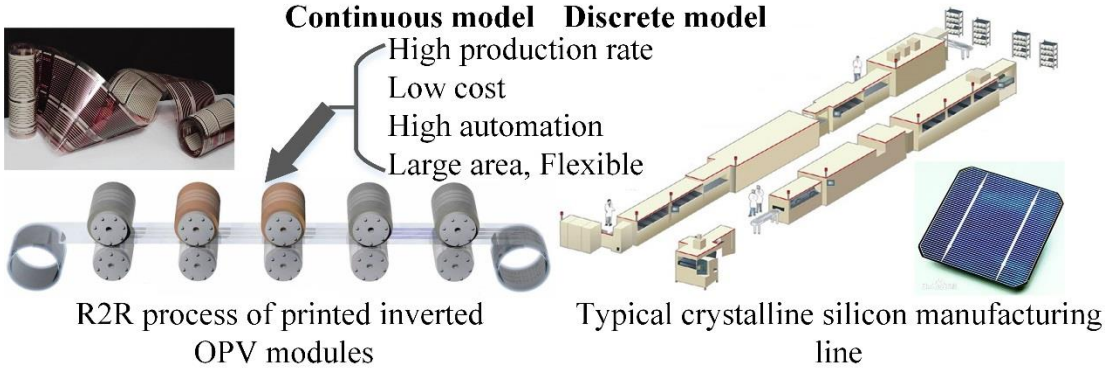

Figure 1. A comparison between roll-to-roll (R2R) manufacturing processes (left) and typical silicon solar cells manufacturing processes (right).

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Overall Project Outcomes and Results as of June 30, 2019:

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Development of low-cost roll-to-roll manufacturing for perovskite solar cells
Description: The objective of this activity is to develop cheap advanced manufacturing technique based on roll-to-roll low-temperature processes and to build economical perovskite solar cells accordingly. New perovskite solar cells will be designed and fabricated for high-efficiency solar energy to electricity conversion. Through this new advanced manufacturing, the target is to develop perovskite solar cells with a power conversion efficiency of 15% ~ 25% comparable to silicon solar cells and the fabrication cost at 1/10 ~ 1/100 of silicon-based solar cells, resulting in an overall installation cost at least 5 times lower than the existing silicon photovoltaics.

We propose to address the following issues of the roll-to-roll manufacturing processes for solar cells: (1) Choosing appropriate flexible substrate materials. (2) Fabricating high-performance functional materials. (3) Integrating a series heterogeneous manufacturing processes. We will come up with solutions for the manufacturing of perovskite solar cells.

Specific tasks will be:
1. Roll-to-roll manufacturing processes set-up, coupled with low-temperature chemical-physical vapor deposition
    a. Design hardware set-up for roll-to-roll manufacturing process based on the chemical-physical vapor deposition facility available at Dr. Cui's Lab
    b. Fabricate and assemble roll-to-roll manufacturing process set-up
    c. Test roll-to-roll manufacturing process set-up

2. Design and experiments of roll-to-roll manufacturing processes for perovskite solar cells
    a. Design roll-to-roll manufacturing processes for perovskite solar cells
    b. Test, characterize and optimize roll-to-roll manufacturing processes for perovskite solar cells

3. Design, fabrication, and characterization of perovskite solar cells in lab using the developed roll-to-roll manufacturing processes

a. Design and simulate perovskite solar cells using the developed roll-to-roll manufacturing processes
b. Fabricate solar cells using the developed roll-to-roll manufacturing processes
c. Characterize solar cells using the developed roll-to-roll manufacturing processes

4. Comprehensive assessment of the new perovskite techniques and silicon solar cells
a. Assess the design of roll-to-roll processes set-up, and compare to silicon solar cells
b. Assess the roll-to-roll fabrication techniques of perovskite solar cells, and compare to silicon solar cells
c. Assess the performance of perovskite solar cells including power conversion efficiency, cost, and stability in lab, and compare to solar cells

Summary Budget Information for Activity 1:

ENRTF Budget: $ 258,828
Amount Spent: $ 0
Balance: $ 258,828

Outcome	Completion Date	Budget
1. Roll-to-roll manufacturing processes set-up, coupled with low-temperature chemical-physical vapor deposition	*6/30/2017*	*$55,000*
2. Design and experiments of roll-to-roll manufacturing processes for perovskite solar cells	*6/30/2017*	*$75,000*
3. Design, fabrication, and characterization of perovskite solar cells in lab using the developed roll-to-roll manufacturing processes	*6/30/2018*	*$98,000*
4. Comprehensive assessment of the new perovskite techniques and silicon solar cells	*6/30/2018*	*$30,828*

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status (Integration Work with Activity 2) as of December 31, 2018:

Final Report Summary (Integration Work with Activity 2) as of June 30, 2019:

ACTIVITY 2: Development of perovskite solar cells and field test
Description: A prototype panel of perovskite solar cells will be designed and constructed to demonstrate the feasibility. Field testing protocol and hardware will be developed and tested. Field testing will include setting up a test site in Minnesota. Upon completion of the project, we will demonstrate the perovskite solar cells panel to the stakeholders and LCCMR committee members and officials.

Based on the roll-to-roll manufacturing processes, we will focus on fabricating a prototype panel of perovskite solar cells and field testing of the solar panel. The specific objectives of the development of perovskite solar cells and field testing are (1) to develop a prototype panel of perovskite solar cells based on the fabricated solar cells using roll-to-roll manufacturing, (2) to develop field testing protocol and hardware, and (3) to test real-time solar irradiation of perovskite solar cells by setting up the prototype unit on an outdoor site.

Specific tasks will be:

1. A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing
    a. Design prototype perovskite solar panel, based on the fabricated solar cells using roll-to-roll manufacturing techniques
    b. Assemble a prototype perovskite solar panel

2. Field testing protocol and hardware will be developed
    a. Design field testing protocol and hardware for a prototype panel of perovskite solar energy
    b. Characterize the protocol and hardware for a prototype panel of perovskite solar energy on power conversion efficiency and stability

3. The prototype unit will be set up on an outdoor site and real-time solar irradiation of perovskite solar cells will be tested.
    a. Design a field site used to long-term test the prototype unit outdoors. Environmental condition, transmission method and the surroundings will be arranged appropriately for a long-term and precise test.
    b. Develop a system which can test and record the illumination intensity of sunshine and the current-voltage data of the prototype unit running in sunshine outdoors.

Summary Budget Information for Activity 2:

ENRTF Budget: $ 129,172
Amount Spent: $ 0
Balance: $ 129,172

Outcome	Completion Date	Budget
1. A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing	*6/30/2019*	*$60,000*
2. Field testing protocol and hardware will be developed	*6/30/2019*	*$50,000*
3. The prototype unit will be set up on an outdoor site and real-time solar irradiation of perovskite solar cells will be tested.	*6/30/2019*	*$19,172*

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Final Report Summary as of June 30, 2019:

V. DISSEMINATION:

Description:

The findings will be disseminated through:
(1) On site demonstration as described in the activities
(2) Public seminars
(3) Progress update on www.me.umn.edu/labs/tianlab
(4) Presentations at national and international technical conferences
(5) Communications with interested entrepreneurs
(6) Peer reviewed papers
(7) Collaboration with Solar Cell Manufacturers

The technologies, if demonstrated successfully, may be implemented to many fields and residentials in the State of Minnesota and beyond. Any intellectual properties and related revenues as a result of the program will be shared between UMN and LCCMR.

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Final Report Summary as of June 30, 2019:

VI. PROJECT BUDGET SUMMARY:
A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 292,665	• Dr. Tianhong Cui, PI, 1 month summer salary (11% FTE) & 33.7% fringe for 3 years • Post-Doc, 6 months (50% FTE) plus 22.4% fringe for 3 years • Graduate Research Assistant, 50% FTE (fall & spring semesters include 17.6% fringe plus $18.29/hour tuition, summer 17.6% fringe only) for 3 years
Professional/Technical/Service Contracts:	$37,500	Scientific Services: User fees at Minnesota Nano Center and Characterization Facility at the University of Minnesota. The cost is about $541 per month for the Post-Doc, and $500 per month for the research assistant for 3 years.

Equipment/Tools/Supplies:	$53,835	Lab Materials & Supplies: fabrication materials & supplies including silicon wafers ($6,000), polymer substrates ($5,000), chemicals ($20,835), roll-to-roll manufacturing set-up items ($16,000), bottles, gloves, other electronics for testing, etc. ($6,000)
Travel Expenses in MN:	$4,000	Travel- Cui Domestic travel year 2 & 3: Mileage, lodging, and meals for travel to and between the solar testing sites and the university based on the university compensation policy
TOTAL ENRTF BUDGET:	**$388,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 3.33 FTE

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
Mocon Inc.	$173,199	$50,000	Development of graphene gas sensors
State			
The university overhead unpaid	$175,039	$0	Development of R2R process for solar cells
TOTAL OTHER FUNDS:	**$348,238**	**$50,000**	

VII. PROJECT STRATEGY:

A. Project Partners:

Tianhong Cui, professor in Department of Mechanical Engineering and affiliated graduate faculty in Department Electrical and Computer Engineering, will serve as PI and project manager. He will be responsible for overseeing the project, all reports, and deliverables. He will also design the roll-to-roll manufacturing processes and perovskite solar cells based on the advanced manufacturing technique. Under Professor Cui's supervision, the Post-Doc will be responsible for the manufacturing facility and the outdoor experimental test set-up, and the Ph.D. student will be in charge of design, fabrication, and characterization of perovskite solar cells.

B. Project Impact and Long-term Strategy:

Given the state's latitude, many people are surprised to learn that Minnesota has annual solar radiation similar to portions of Florida and Texas, with sunshine for about 5 hours per day in average in Minneapolis. Solar energy production is a small but exponentially growing resource in Minnesota, where we now have more than 15 Megawatts (MW) of solar electric capacity. In May 2013, the Minnesota legislature adopted a mandate on investor-owned utilities in the state that requires them to produce 1.5% of their electricity from solar power by 2020. The Minnesota Legislature established a

solar photovoltaic and solar thermal incentive program for consumers who install photovoltaic and solar thermal systems using solar modules and collectors certified as manufactured in Minnesota.

Solar energy out-powers anything that human technology could ever produce. However, today's commercial solar cells, most often made from silicon, typically convert sunlight into electricity with an efficiency of about 10 percent to 20 percent, although some test cells do a little better. Given their manufacturing costs, modules of today's cells incorporated in the power grid would produce electricity at a cost roughly 3 to 6 times higher than current prices. To make solar economically competitive, engineers must find ways to lower their manufacturing costs and to improve the efficiency of the cells. This project will provide one solution for lowering the cost and improving solar efficiency is to use new materials perovskite together with low-cost roll-to-roll advanced manufacturing techniques.

Upon completion of the project, cheap and high-efficiency perovskite solar cells for outdoor solar to electricity conversion will be developed. The knowledge learned throughout the project will provide a solid foundation for further research and development efforts that would lead to implementation of the new solar cells for power plants or consumer electronics enabling very cheap, clean, renewable, and high-efficiency solar energy sources in Minnesota eventually. This will potentially provide a supplementary energy solution to current energy sources in Minnesota, ultimately help implement the renewable energy policy, and thus enhance the economic and ecological benefits of Minnesota.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Mocon Inc., Graphene gas sensors	Nov. 2014 - July 2016	$173,199
Alexandria Extrusion Inc., Microstructures for Heat Transfer	Nov. 2011 - Dec. 2015	$165,516
DARPA, MEMS-Based Active Heat Sink Technology	Jan. 2009 - Sept. 2013	$2,579,025
MN Partnership, Nano-Sensors	Jan. 2010 – Dec. 2012	$637,500

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

IX. VISUAL COMPONENT or MAP(S):

X. RESEARCH ADDENDUM:

Enclosed

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than September 2016, March 2017, September 2017, March 2018, September 2018, and March 2019. A final report and associated products will be submitted on June 30, 2019.

Environment and Natural Resources Trust Fund
M.L. 2016 Project Budget
Project Title: Solar Cells Manufacturing Research
Legal Citation: M.L.2016, Section 116P.10., Subd. 07a
Project Manager: Tianhong Cui
Organization: University of Minnesota
M.L. 2016 ENRTF Appropriation: $388,000
Project Length and Completion Date: 3 Years, June 30, 2019
Date of Report: January 15, 2016

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	***Development of low-cost roll-to-roll manufacturing for perovskite solar cells***			***Development of perovskite solar cells and field testing***							
Personnel (Wages and Benefits)	$192,678		$192,678	$99,987		$99,987				$292,665	$292,665
Tianhong Cui, PI: $21,909 (75% salary, 25% benefits) for Year 1; 11% FTE each year for 3 years, 3% increase years 2-3. $67,720 for 3 years in total.											
PostDoc: $27,500 (82% salary, 18% benefits) for Year 1: 50% FTE each year for 3 years, 3% increase years 2-3. $85,123 for 3 years in total.											
1 RA's at 50%: $45,736 (58% salary, 24% benefits) for Year 1; 50% FTE each year for 3 years, 3% increase years 2-3. $139,822 for 3 years in total.											
Equipment/Tools/Supplies	$39,650		$39,650	$14,185		$14,185				$53,835	$53,835
Lab Materials & Supplies: fabrication materials & supplies including silicon wafers ($6,000), polymer substrates ($5,000), chemicals ($20,835), roll-to-roll manufacturing set-up items ($16,000), bottles, gloves, other electronics for testing, etc. ($6,000)											
Travel expenses in Minnesota	$2,000		$2,000	$2,000		$2,000				$4,000	$4,000
Travel- Cui Domestic travel year 2 & 3: Mileage, lodging, and meals for travel to and between the solar testing sites and the university based on the university compensation policy											
Other	$24,500		$24,500	$13,000		$13,000				$37,500	$37,500
Scientific Services (Cui): User fees at Minnesota Nano Center and Characterization Facility at the University of Minnesota. The cost is about $541 per month for the Post-Doc, and $500 per month for the graduate research assistant for 3 years.											
COLUMN TOTAL	**$258,828**		**$258,828**	**$129,172**		**$129,172**				**$388,000**	**$388,000**