Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2017 LCCMR Work Plan

Date of Submission: October 11, 2016

Date of Next Status Update Report: January 1, 2018

Date of Work Plan Approval: 06/07/2017

Project Completion Date: June 30, 2020

Does this submission include an amendment request? _No_

PROJECT TITLE: Extraction of Solar Thermal Energy in Minnesota

Project Manager: Filippo Coletti

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Location: Statewide

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$250,000**
	Amount Spent:	**$0**
	Balance:	**$250,000**

Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 07a

Appropriation Language:
$250,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to develop new solar particle receivers as a low-cost, high-efficiency, and clean technology to absorb, store, and utilize solar thermal energy. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2020, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Enabling Extraction of Solar Thermal Energy in Minnesota

II. PROJECT STATEMENT:

The objective of this project is to develop a novel Solar Particle Receiver (SPR), a low-cost, high-efficiency technology to absorb, store, and utilize solar thermal energy.

The most prevalent concentrated solar thermal systems use mirrors to concentrate solar radiation on the surface of a pipe, which then transfers heat to a fluid running in it. For the hot fluid to produce electricity (for example to power a turbine generator), its temperature needs to be at least 500°C (almost 1000°F). At Minnesota's latitudes the sun radiation is not sufficiently strong to achieve this goal with the standard type of solar thermal systems. In fact, almost all solar energy installations in the state are photovoltaic (PV), which convert radiation directly into electricity. However PV systems require sophisticated materials for energy conversion. Also, because electricity is difficult to store, PV solar systems are only usable when the sun is shining.

The SPR technology represents a step change in solar thermal energy. In these systems particles suspended within the fluid (typically a gas) directly absorb the sunlight and transfer the heat evenly throughout the fluid. This means higher energy absorption and heat transfer rates, higher efficiency of the system, and much less solar radiation needed to reach the required fluid temperatures. Importantly, the hot particles also serve as a chemically benign, low-cost heat storage medium, which is crucial to utilize the solar energy around the clock: energy can be stored during daytime and used to extend power generation during cloudy days or at night. Heat storage is much cheaper than storing electric energy in large batteries: even for a relatively small 10 MW power plant, to store the daily absorbed energy one would need a 400 ton battery, which at the present market price would cost about 30 million dollars.

The concept of SPR has been demonstrated in pilot sites, using curtains of free falling particles and slow gas-particle streams. Most of these installations use large particles, essentially pebbles, in the centimeter range. These pebbles are not very good at releasing heat to the air through which they fall. This problem is due to the fact that large particles have a limited surface area per unit volume, and they fall too fast to have sufficient time to release the heat to the fluid. In these conditions the process is not very efficient: at most 20% of the incoming solar energy is available to generate electricity, and energy extraction becomes advantageous only with a level of solar radiation typical of Southwest US. On the other hand, the new concept of solar receiver we propose uses fine particles, which greatly alleviates the limitations mentioned above. Specifically, we will use silica particles of just 20 microns in size. These particles are extremely cheap and have been shown to be excellent absorbers of sunlight. Some exploratory study of this approach has been carried out, but only at small scales. For this technology to move from laboratory experimentation to the energy market, the SPR performance needs to be tested in realistic situations, including high gas flow rates and exposed to radiation like that in a solar field.

We therefore propose to design, build, test, and optimize an SPR prototype, to demonstrate its viability for the Minnesota energy needs. Our target is to reach temperatures of 1000°F in the dusty air, and with a heat transfer efficiency of 35%. In order to achieve this, we will determine the optimal set of design parameters that maximizes thermal efficiency in realistic operating conditions. For this purpose we will leverage existing facilities and resources available to our team, including: (i) a flow facility in which air flow laden with microscopic particles is metered and analyzed; (ii) a solar simulator facility that reproduces concentrated solar radiation in the laboratory; (iii) a performance prediction tool that uses the power of super-computing. Finally we will use our results to assess the economical and environmental benefits of implementing this novel and optimized SPR design in large-scale solar thermal fields.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 1, 2018:

Project Status as of July 1, 2018:

Project Status as of January 1, 2019:

Project Status as of July 1, 2019:

Project Status as of January 1, 2020:

Overall Project Outcomes and Results:

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Build, design, and test a prototype of Solar Particle Receiver

Description: In this activity we will leverage an existing laboratory apparatus that our team built to investigate the flow of gas-particle mixtures. This consists of a 2.5 meter tall duct in which air flows at up to 300 liters/min, carrying microscopic solid particles injected at precise concentrations. We will use silica carbide particles, a low-cost material that absorbs 80% of the incoming thermal radiation, and will irradiate them using our solar simulator: an array of seven 6.5 kW xenon lamps that produces a radiation flux up to 8.5 MW/m^2. This facility is the most powerful of its kind in the country, and produces concentrated radiation equivalent to that given by parabolic mirrors over 500 acres of land and focused over a 3 square inch spot. The radiation will be transmitted through a transparent quartz window on the channel, so that the dusty air can be heated. We will vary the design parameters (air flow rate, particle size and concentration) and monitor the device performance in terms of thermal efficiency. To this end we will use a calorimeter, a device that measures the amount of radiation transmitted through the air-particle mixture, and so indirectly measures the radiation absorbed by the particles. We will also measure the air flow temperature using thermocouples.

Summary Budget Information for Activity 1:

ENRTF Budget:	**$ 92,357**
Amount Spent:	**$ 0**
Balance:	**$ 92,357**

Outcome	Completion Date
1. Design and build a prototype of Solar Particle Receiver	June 2018
2. Measure thermal efficiency of the receiver in different air-particle mixture regimes.	January 2019

Activity 1 Status as of January 1, 2018:

Activity 1 Status as of July 1, 2018:

Activity 1 Status as of January 1, 2019:

Activity 1 Status as of July 1, 2019:

Activity 1 Status as of January 1, 2020:

Final Report Summary:

ACTIVITY 2: Optimize the performance of the Solar Particle Receiver

Description: In this activity we will incorporate the findings of Activity #1 into an advanced predictive tool to calculate the SPR thermal efficiency. We will leverage a state-of-the-art framework that our team has developed and used extensively to simulate flows of fluid and particles in environmental and renewable energy settings. Our model incorporates the laws of physics involved in the energy transfer processes, which are expressed as mathematical equations and solved by a cluster of 17,000 computers working in parallel. To this end, the existing framework will be extended to include thermal radiation. The results will be validated against the laboratory experiments. We will then exploit the super-computer capabilities available at St. Anthony Falls Laboratory to evaluate the performance of numerous sets of design parameters, which would take an excessive amount of time to be tested experimentally. This will greatly speed up the design cycle, allowing us to virtually test and compare tens of combinations of parameters. Specifically, in the simulations we will vary: flow rate, particle concentration, particle size, radiation intensity, and cross-sectional channel dimension. An especially important aspect on which the simulations will shed light is the phenomenon of particle accumulation near the walls. This phenomenon, which is especially strong when the flow rate becomes turbulent, is expected to strongly influence the performance of the solar particle receiver.

Summary Budget Information for Activity 2:	**ENRTF Budget:**	**$ 69,413**
	Amount Spent:	**$ 0**
	Balance:	**$ 69,413**

Outcome	**Completion Date**
1. Extend the existing predictive tool to include thermal radiation	January 2018
2. Validate the model against laboratory results	January 2019
3. Vary systematically the simulation parameters until the optimal efficiency is obtained	December 2019

Activity 2 Status as of January 1, 2018:

Activity 2 Status as of July 1, 2018:

Activity 2 Status as of January 1, 2019:

Activity 2 Status as of July 1, 2019:

Activity 2 Status as of January 1, 2020:

Final Report Summary:

ACTIVITY 3: Demonstrate the optimized design of Solar Particle Receiver and evaluate benefits

Description: In this activity we will perform new tests on the SPR prototype under conditions that replicate the high temperatures, gas atmosphere, and heating rates involved in a concentrated solar facility using the University of Minnesota's 45 kW indoor high-flux solar simulator. This activity will achieve a meaningful transition from laboratory experiments to operation under concentrated solar radiation. We will compare the data with the predicted performance, using the optimal set of parameters (flow rate, particle concentration, etc.) indicated by the simulations carried out in Activity #2. Modifications to the prototype may be applied to improve performance. We will then verify the predicted improvement in thermal efficiency in the solar simulator. The experimental validation of the computer model will be crucial, as it will demonstrate that the model can be used as an accurate prediction tool for future designs of devices at larger scale. Using information on solar irradiation, cost of fossil fuel, and efficiencies of existing power plants (which is available from sources such as the National Renewable

Energy Laboratory), we will implement a software to quantify the positive impact of the new SPR design in terms of energy saving and reduction of pollution.

Summary Budget Information for Activity 3: **ENRTF Budget: $ 88,230**
Amount Spent: $ 0
Balance: $ 88,230

Outcome	**Completion Date**
1. Carry out performance measurements at predicted optimal regimes	January 2020
2. Demonstrate competitive thermal performance at radiation levels typical of Minnesota	June 2020
3. Quantitatively assess environmental benefit of optimized solar receiver design	June 2020

Activity 3 Status as of January 1, 2018:

Activity 3 Status as of July 1, 2018:

Activity 3 Status as of January 1, 2019:

Activity 3 Status as of July 1, 2019:

Activity 3 Status as of January 1, 2020:

Final Report Summary:

V. DISSEMINATION:

Description: The design and test results will be made available to the public via a web portal powered by the University of Minnesota, where the public can contribute ideas for further improvements. In particular, using the portal every step in our design process will be made publicly available in real time, inviting private and public entities to contribute ideas for further improvements, and at the same time extending the knowledge base. In the long term we aim at creating an open-source solar thermal project that can leverage the creativity of the people in Minnesota and beyond, and inspire future renewable energy start-ups. The results and findings of this project will be presented at national and international conferences on renewable energy attended by our research team and the involved personnel, as well as in scientific journal articles.

Status as of January 1, 2018:

Status as of July 1, 2018:

Status as of January 1, 2019:

Status as of July 1, 2019:

Status as of January 1, 2020:

Final Report Summary:

VI. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview:

***This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report.**

Budget Category	$ Amount	Overview Explanation
Personnel:	$230,127	1 graduate student at 25% FTE for each year for 3 years; 1 graduate student at 50% FTE for each 2 years and at 12.5% FTE for the last year; 1 research associate at 25% FTE for 2 years
Equipment/Tools/Supplies:	$9,873	Fused quartz window for radiation experiment in the receiver prototype; particulate material for radiation absorption; materials for constructing the receiver prototype
Capital Expenditures over $5,000:	$0	See explanation below
Others:	$10,000	Machining of components for receiver prototype
TOTAL ENRTF BUDGET:	**$250,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: The prototype of solar particle receiver will have a manufacturing cost (including materials and machining time) of about $20,000, but none of its components will have a cost greater than $5,000. After the end of the three-year project, the prototype might be further modified to pursue further funding at governmental level.

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.375

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

B. Other Funds: N/A

VII. PROJECT STRATEGY:

A. Project Partners:

Partners receiving ENRTF funding:

- Filippo Coletti, Assistant Professor, University of Minnesota, Project manager: $123,310 for salary of graduate student, equipment, and supplies
- Jane Davidson, Professor, University of Minnesota, co-Investigator: $57,276 for salary of research associate
- Lian Shen, Associate Professor, University of Minnesota, co-Investigator: $69,413 for salary of graduate student

Partners NOT receiving ENRTF funding : N/A

B. Project Impact and Long-term Strategy:

Although solar energy production in Minnesota has been growing, a substantial leap forward is urgently needed to comply with the 2013 Solar Energy Jobs Act, which requires investor-owned utilities in the state to produce

1.5% of their electricity from solar power by 2020. Current solar energy systems produce electricity at a cost 3 to 6 times higher than fossil fuels. This project will help impose a clean and low-cost renewable energy technology, demonstrating that solar thermal energy extraction is economically viable at our latitudes.

According to the National Renewable Energy Laboratory, Minnesota's annual potential of concentrated solar thermal energy in Minnesota exceeds 16 megawatt hours per acre of land, so that indeed each medium-size power plant using this technology would avoid the emission of 35,000 tons of CO2. Our project will be critical to exploit this largely untapped potential, helping to reduce carbon emissions to prevent further climate change, facilitating local power generation critical in rural areas, and improving energy affordability for everyone. Additionally, by making solar thermal energy possible in Minnesota, this technology will generate numerous green job opportunities.

If we can demonstrate, as our preliminary results indicate, that the target temperature and thermal efficiency can be achieved, it will mean that the solar particle receiver technology is technically feasible and economically viable. This would represent a breakthrough that will improve the renewable energy market in Minnesota, and in the whole Midwest. To be quantitative, for each square mile of solar thermal field we project that this technology can translate into 10 million kWh of produced energy. And since it is estimated that 10 cents are saved for each kWh of solar energy, this would result in one million dollar of cost saving per square mile of installed solar field.

Given such potential, this project will lay the groundwork for collaborations with companies members of the Minnesota Solar Energy Industries Association (MnSEIA), several of which have already partnered with St. Anthony Falls Lab, for the technology commercialization and the installation of the first solar thermal field in the state. Additional potential partners include 3M, which has recently expressed interest in the research conducted by our team in this area.

C. Funding History:

We have carried out preliminary research that indicates the feasibility of the proposed project (e.g. the evaluation of the high absorption efficiency of the silica carbide particles, as well as the theoretical calculations on the achievable thermal efficiency in the solar particle receiver). This work was performed by the investigators and through the engagement of undergraduate research assistants, without external funding.

VIII. REPORTING REQUIREMENTS:

- **The project is for 3 years, will begin on 07/01/17, and end on 06/30/20.**
- **Periodic project status update reports will be submitted January 1 and July 1 of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2020**.

IX. VISUAL COMPONENT or MAP(S): See attached graphic.

Environment and Natural Resources Trust Fund
M.L. 2017 Project Budget

Project Title: Extraction of Solar Thermal Energy in Minnesota
Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 07a
Project Manager: Filippo Coletti
Organization: Regents of the University of Minnesota
M.L. 2017 ENRTF Appropriation: $250,000
Project Length and Completion Date: 3 Years, June 30, 2020
Date of Report: 10/11/2016

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	***Build, design, and test a prototype of Solar Particle Receiver***			***Optimize the performance of the Solar Particle Receiver***			***Demonstrate the optimized design of Solar Particle Receiver and evaluate benefits***				
Personnel (Wages and Benefits)	$80,357			$69,413			$80,357			$230,127	
50% Graduate Student, $59,676 salary + $43,761 fringe											
25% Graduate Student, $40,182 salary + $29,232 fringe											
25% Research Associate, $42,839 salary + $14,437 fringe											
Lab Supplies	$6,000			$0			$3,873			$9,873	
Fused quartz window with 99.5% transparency in infrared radiation (estimated $4,000); materials for constructing solar receiver prototype ($3,000); gas supplies to run solar simulator and relative instrumentation ($2000); silica carbide particulates with high absorption properties ($873)											
Other	$6,000			$0			$4,000			$10,000	
Machining of prototype components, to be performed in the College of Science and Engneering Workshop ($10,000)											
COLUMN TOTAL	**$92,357**			**$69,413**			**$88,230**			**$250,000**	