Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing
PROJECT MANAGER: Tianhong Cui
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07c as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

APPROPRIATION AMOUNT: $300,000
AMOUNT SPENT: $300,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
Perovskite solar cells and modules were fabricated via two-step deposition method, hybrid chemical vapor deposition and air blade deposition, to produce electricity from free clean solar energy which reduced dependency on non-renewable energy usage and provides healthy environment and habitats for both residents and wildlife of Minnesota.

Overall Project Outcome and Results
Perovskite material is a promising candidate for the next generation of solar cells with high efficiency and significantly lower cost than silicon solar cells. The final objective of this project is low-cost roll-to-roll manufacturing for perovskite solar cells. Roll-to-roll manufacturing compatible fabrication methods, including hybrid chemical vapor deposition and air blade deposition, were developed. More specifically, chemical vapor deposition processes are optimized, and air blade coating system were developed based on a 3D printer. Perovskite solar cell compositions, structures, and additives were also investigated and optimized to enhance the performance. We developed flexible perovskite solar cells on PEN substrates, which is compatible with roll-to-roll process, and shows an efficiency of 13.3% via chemical vapor deposition method. Device with power conversion efficiency of 13.82% via air blade and chemical vapor deposition methods is also achieved. 5 cm x 5 cm perovskite solar modules with an active area of 18 cm^2 were fabricated and field test was performed. This project shows proof of the concept of CVD grown perovskite solar cells with air blade deposition. The approach shows promising results with high efficiency. Moreover, air blade and CVD deposition techniques can be integrated with roll-to-roll manufacturing systems for large volume production to reduce the overall cost. Even though these techniques are still not ready for deployment, CVD and air blade deposition methods are still recommended for further investigation due to their ease of use, low cost, and large volume production capabilities. Cheap and clean electricity produced from perovskite solar cells via the developed roll-to-roll compatible methods during this project may further benefit the residents of Minnesota. Harvesting green solar energy more efficiently and economically via the development of perovskite techniques can provide and maintain a better living and natural environment for the people of Minnesota.

Project Results Use and Dissemination
The field test was performed on University of Minnesota campus and the findings were disseminated through the following publications in archived journals.

1. Rui Zhu, Xiangyang Wei, Gongnan Xie, Terrence Simon, and Tianhong Cui. "Numerical simulation of vapor deposition process of perovskite solar cells: The influence of methylammonium iodide vapor flow to perovskite growth." *Journal of Solar Energy Engineering* 143, no. 1 (2021).

2. Xiangyang Wei, Yangke Peng, Gaoshan Jing, Terrence Simon, and Tianhong Cui, "High Performance Perovskite Solar Cells Fabricated by a Hybrid Physical-Chemical Vapor Deposition", ASME Journal of Solar Energy Engineering, Vol. 143, No. 4, 2021: 041006
3. Wei, Xiangyang, Yanke Peng, Gaoshan Jing, and Tianhong Cui. "Planar structured perovskite solar cells by hybrid physical chemical vapor deposition with optimized perovskite film thickness." *Japanese Journal of Applied Physics* 57, no. 5 (2018): 052301.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2018 Work Plan Final Report

Date of Submission: August 15, 2022

Final Report

Date of Work Plan Approval: 06/05/2018

Project Completion Date: June 30, 2022

PROJECT TITLE: Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing

Project Manager: Tianhong Cui

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Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$300,000**
	Amount Spent:	**$300,000**
	Balance:	**$0**

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07c as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

Appropriation Language: $300,000 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 with simple roll-to-roll advanced manufacturing technology, using new materials such as perovskite to make solar cells. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.

M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2022]

I. PROJECT TITLE: Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing

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.

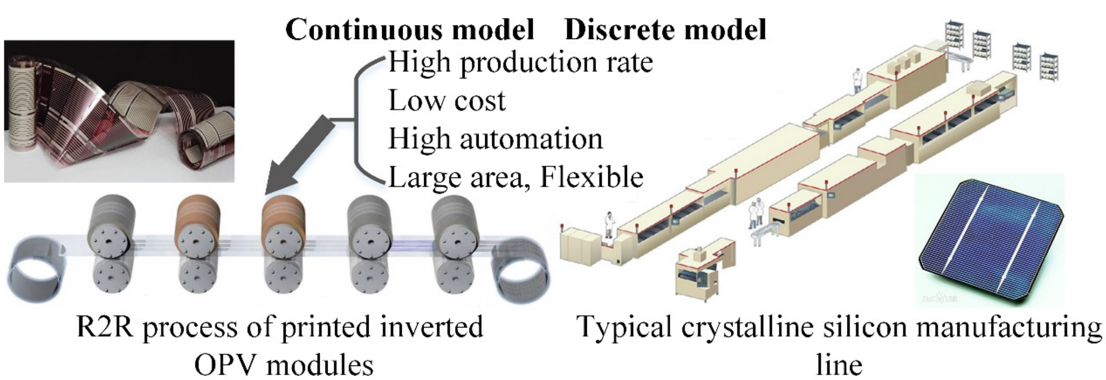


Figure 1. A comparison between roll-to-roll (R2R) manufacturing processes (left) and typical silicon solar cells manufacturing processes (right).

III. OVERALL PROJECT STATUS UPDATES:

Project Update December 31, 2018:

The University of Minnesota team started this project on July 1, 2018. Professors Cui recruited two visiting research assistants conducting the work, while collaborating with Professor Terrence Simon on the modeling of perovskite solar cells. Significant progress has been made. In this report are summaries of progress including a numerical model to analyze the fluid flow and mass transfer in the CVD deposition process of perovskite $MAPbI_3$, set-up of fabrication systems, built-up of a solar cell test system, and initial fabrication of perovskite solar cells. In summary, the initial 6-month work was successful.

Project Update June 30, 2019:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with two visiting students, Xiangyang Wei and Rui Zhu, conducting the work, while collaborating with Professor Terrence Simon on the modeling of perovskite solar cells. With the fabrication system including a glove box, a CVD system and some other systems built up already, we fabricated a series of perovskite solar cells based on the mixed perovskite films by a hybrid physical chemical vapor deposition method (HPCVD), which is compatible with the roll-to-roll manufacturing processes. With the optimization of mass ratio of FAI and MABr and the growth temperature in the CVD process, a high efficiency of 15.48% is achieved. The fabrication process is being optimized further to achieve a higher efficiency for now. In addition, the growth process of the surface of perovskite film in the CVD process is also characterized by using AFM, which can help us to improve our designed the roll-to-roll system to fabricate perovskite films. At last, based on the finished results achieved, we demonstrate a designed roll-to-roll manufacturing processes coupled with low temperature chemical-physical vapor deposition for fabrication of perovskite films. In summary, the second 6-month work was productive and successful.

Project Update December 31, 2019:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with two Ph.D. students, Jungyoon Kim and Jitong Duan, conducting the work, while collaborating with Professor Terrence Simon and visiting student Rui Zhu on the modeling of perovskite solar cells.
This report includes the preparation of the materials and fabrication of flexible perovskite solar cells. We characterize the surface morphology of the perovskite to check the grain size by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The efficiency of solar cells is measured by the solar simulator. The relationship between efficiency and grain size is also included in the report. In summary, the third 6-month work was productive and successful.

Project Update June 30, 2020:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with two Ph.D. students, Jungyoon Kim and Jitong Duan, conducting the work, while collaborating with Professor Terrence Simon on the modeling of perovskite solar cells. This report includes the preparation of the materials and fabrication of perovskite solar cells. We studied the materials to introduce better hole transport layers (HTL) for roll-to-roll perovskite solar cells. PTAA is used as HTL, and the results are compared with the solar cells using PEDOT:PSS as HTL. The surface morphologies of the perovskite were characterized by atomic force microscopy (AFM). The efficiency of flexible solar cells is measured by the solar simulator. Due to lab closure from March to June 2020, we will conduct more assessment of flexible solar cells compared to silicon solar cells in the next stage. In summary, the third 6-month work was productive and successful.

Project Update December 31, 2020:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with one post-doc, Jungyoon Kim, and one Ph.D. student, Jitong Duan, conducting the work, while collaborating with Professor Terrence Simon on the modeling of perovskite solar cells. This report includes the fabrication of flexible perovskite solar cells using SnO_2 as an electron transport layer (ETL) and the comparison of the device performance between ETLs of TiO_2 and SnO_2. The devices was fabricated on different substrates, FTO/glass for TiO_2 and ITO/glass for SnO_2. After we confirm the feasibility of SnO_2 based device on glass, we changed the substrate to ITO/PEN for flexible perovskite solar cells. In the experiment, the perovskite film is synthesized by a low temperature CVD process. The surface morphology of films is characterized by atomic force microscopy (AFM). The efficiency of solar cells is measured by a solar simulator. In summary, although there is some delay on the research progress due to pandemic, we still made some progress in this project.

Project extended to June 30, 2022 by LCCMR 7/1/21 as a result of M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18, legislative extension criteria being met.

Project Update June 30, 2021:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with one post-doc, Jungyoon Kim, and one master student, Yingming Xu, conducting the work. This research includes the optimized fabrication process of perovskite solar cells on a flexible substrate and the coating equipment for roll-to-roll manufacturing. The first objective of this research is optimizing the process for high-efficiency flexible perovskite solar cells. SnO_2 was used for electron transport layers (ETL). The devices were fabricated on ITO/PEN substrate. In the experiment, the perovskite film is synthesized by a low-temperature CVD process. The surface morphology of the films is characterized by atomic force microscopy (AFM). The efficiency of solar cells is measured by the solar simulator. A 3D printer was modified to be a part of the roll-to-roll manufacturing. The printer head and air nozzle were fabricated and attached to the printer. In summary, although there is some delay on the research progress due to pandemic, we still made some progress in this project.

Project Update December 31, 2021:

The University of Minnesota team started this project on July 1, 2018. Professors Cui worked with one post-doc, Jungyoon Kim, and one master student, Yingming Xu, conducting the work. This technical report includes a scalable fabrication process on the flexible substrate and coating techniques for the fabrication of the perovskite solar cells (PSCs) and modules (PSMs). Tetramethylammonium tetrafluoroborate ($[M_4N]BF_4$) is investigated as the post treatment to assist the crystallization of the perovskite film. The perovskite film is synthesized via low temperature CVD process and uniform power conversion efficiencies across different devices are obtained. A 3D printer based slot die coater is built as the coating module of the roll-to-roll manufacturing system and highly uniform SnO_2 and PbI_2 films are obtained with controllable thicknesses. The 3D slot die coater is further developed into a low-pressure air knife coater to reduce the manufacturing costs and simplify the coating processes. The fabricated films are characterized by atomic force microscopy (AFM) and surface profiler. In summary, although there is some delay on the research progress due to pandemic, we still made some progress in this project.

Final Update June 30, 2022

Perovskite material is a promising candidate for the next generation of solar cells with high efficiency and significantly lower cost than silicon solar cells. The final objective of this project is low-cost roll-to-roll manufacturing for perovskite solar cells. Roll-to-roll manufacturing compatible fabrication methods, including hybrid chemical vapor deposition and air blade deposition, were developed. More specifically, chemical vapor deposition processes are optimized, and air blade coating system were developed based on a 3D printer. Perovskite solar cell compositions, structures, and additives were also investigated and optimized to enhance the performance. We developed flexible perovskite solar cells on PEN substrates, which is compatible with roll-to-roll process, and shows an efficiency of 13.3% via chemical vapor deposition method. Device with power conversion efficiency of 13.82% via air blade and chemical vapor deposition methods is also achieved. 5 cm x 5 cm perovskite solar modules with an active area of 18 cm^2 were fabricated and field test was performed. This project shows proof of the concept of CVD grown perovskite solar cells with air blade deposition. The approach shows promising results with high efficiency. Moreover, air blade and CVD deposition techniques can be integrated with roll-to-roll manufacturing systems for large volume production to reduce the overall cost. Even though these techniques are still not ready for deployment, CVD and air blade deposition methods are still recommended for further investigation due to their ease of use, low cost, and large volume production capabilities. Cheap and clean electricity produced from perovskite solar cells via the developed roll-to-roll compatible methods during this project may further benefit the residents of Minnesota. Harvesting green solar energy more efficiently and economically via the development of perovskite techniques can provide and maintain a better living and natural environment for the people of Minnesota.

Amendment request:
We request changes to the budget in the following amounts: A total of
$257,155 for Personnel, $18,494 in Professional/Technical Contracts,
$24,351 in Equipment/Tools/Supplies, and $0 in Travel. The changes are needed because the COVID extension resulted in more staff time spent on the project, supplies were cheaper than anticipated, and no travels done during pandemic.

Amendment approved by LCCMR 12/20/22

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: $ 201,002**
Amount Spent: $ 201,002
Balance: $ 0

Outcome	**Completion Date**
1. Roll-to-roll manufacturing processes set-up, coupled with low-temperature chemical-physical vapor deposition	*6/30/2019*
2. Design and experiments of roll-to-roll manufacturing processes for perovskite solar cells	*6/30/2019*
3. Design, fabrication, and characterization of perovskite solar cells in lab using the developed roll-to-roll manufacturing processes	*6/30/2020*
4. Comprehensive assessment of the new perovskite techniques and silicon solar cells	*6/30/2020*

Project Update December 31, 2018:

Activity 1 update as of December 31, 2018

Outcome 1: Roll-to-roll manufacturing processes set-up, coupled with low-temperature chemical-physical vapor deposition.

We set up the roll-to-roll manufacturing facility. We fabricated perovskite solar cells using the chemical-physical vapor deposition method. First, we installed a glove box to control humidity because some films are very sensitive to humidity including PbI2, perovskite and Spiro. The air inside the glovebox was exchanged to nitride to meet the low humidity condition. Next, we prepared the solar cell measurement system, which can measure the efficiency of the solar cells.

We also started to establish theoretical modeling of perovskite solar cells to analyze the gas flow during the chemical-physical vapor deposition process because the gas flow is a very important factor for the fabrication. The commercial software ANSYS Fluent is used to do the simulation. We believe that the simulation study helps us to find the optimized condition for the fabrication.

Outcome 2: We have not yet begun work on this because it is dependent on completion of outcome 1.

Outcome 3: We have not yet begun work on this because it is dependent on completion of outcome 2.

Outcome 4: We have not yet begun work on this because it is dependent on completion of outcome 3.

Project Update June 30, 2019:

Activity 1 update as of June 30, 2019

Outcome 2: Design and experiments of roll-to-roll manufacturing processes for perovskite solar cells

Our perovskite solar cells have the structure of FTO/ Electron transport layer (ETL)/ Perovskite film/ hole transport layer (HTL)/ gold electrode. We studied to get better quality perovskite film with mixed precursor materials. In the improved process, a PbI_2 solution was coated on the TiO_2/FTO substrate, and the coated PbI_2 film is baked on a hot plate. Next, the prepared PbI_2/TiO_2/FTO/glass samples are reacted with mixed FAI and MABr during the HPCVD process. We fabricated many samples with different ratios of the two materials to find the optimized ratio for the high-quality film. When we used the mass ratio of FAI and MABr at 95:5, we got very stable and high-quality perovskite film. We did experiments on a flexible polymer using roll-to-roll processes.

In this work, we also tried to find the optimized fabrication temperature and time. The optimal growth temperature and time were 115^{o}C and 7 h, respectively. The fabricated perovskite films were characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM), which can check the surface shape and roughness. We finally got very low RMS value (19.70 nm) that shows how rough the surface is. The fabricated perovskite solar cell shows a high efficiency of 15.48% (J_{sc} = 22.23 mA/cm^2, V_{oc} = 1.02 V, FF = 0.68).

Outcome 3: We have not yet begun work on this because it is dependent on completion of outcome 2.

Outcome 4: We have not yet begun work on this because it is dependent on completion of outcome 3.

Project Update December 31, 2019:

Activity 1 update as of December 31, 2019

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

We investigated structures and materials for the flexible perovskite solar cells, as it is necessary to use flexible substrate for the roll-to-roll fabrication. First, we changed the traditional planar structure to an inverted structure because the planar structure needs high-temperature process where the flexible substrate cannot survive. Next, we substituted the materials for the inverted structure because we need use proper materials based on the device structure. The inverted structure consists of PEN/ITO/PEDOT:PSS/Perovskite/PCBM/BCP/Ag layers. In this work, we used PEDOT doped with PSS, PCBM, and BCP for the new structure, and tried to find the optimal condition for the fabrication. PEDOT doped with PSS was spin-coated on the patterned ITO/PEN substrate (8000 rpm for 40 s). The substrate was annealed at 120 ℃ for 20 min. PCBM was coated on the perovskite film (2500 rpm for 40 s). Finally, BCP was coated on the PCBM (4000 rpm for 20 s) to help current flow in the device.

We investigated the duration time effect during the fabrication of perovskite film. The perovskite films grew by the HPCVD process for 8 h and 10 h, and we compared the fabricated films to show the duration time effect. We analyzed the surface quality of the perovskite films using AFM and SEM. 10 h process showed a much larger grain size of the perovskite than that in 8 h process. This result shows that we can get a better quality of perovskite film with a 10 h process because larger grain size means fewer defects in the film. Finally, we successfully found a proper structure and materials, and the fabricated solar cells have an efficiency of 7.6%. The structure and materials can be applied to the roll-to-roll manufacturing process.

Outcome 4: We have not yet begun work on this because it is dependent on completion of outcome 3.

Project Update June 30, 2020:

Outcome 4: Comprehensive assessment of the new perovskite techniques and silicon solar cells

We fabricated perovskite solar cells using different hole transport layer (HTL) materials such as AI4083 and PTAA. We grew the perovskite films using CVD process for 10 hours on different HTL films, and we characterized the grown perovskite film using atomic force microscope (AFM). We confirmed that the hydrophobic surface of PTAA makes larger grain size of perovskite by isolating PbI_2 nuclei from each other, and expected better device performance with larger grain size. The power conversion efficiency (PCE) is 7.6 % with AI4083. The PCE of the device with PTAA is 6.4 %. Although the device did not show the enhanced PCE with PTAA, the open-circuit voltage is increased because of the large grains. As decreasing the recombination with the large grains, we can expect the larger V_{oc}. In the research, we confirm that the grain of perovskite can be increased by the PTAA layer and PTAA can be a great candidate for HTL in perovskite solar cells. We will continue this promising work using roll-to-roll process in the next stage. Due to lab closure from March to June 2020, more assessment of flexible solar cells compared to silicon solar cells will be conducted in the next stage.

Project Update December 31, 2020:

We further improved the fabrication of perovskite solar cells on flexible substrates. For the substrates, we prepare FTO/Glass, ITO/Glass and ITO/PEN. First of all, the substrates were cleaned with acetone, isopropyl alcohol, and DI water. Before coating ETL on FTO and ITO, the surface needs to be treated by oxygen plasma for 15 min to enhance the surface energy. TiO_2 solution is prepared by diluting titanium diisopropoxide bis(acetylacetonate) into butanol. After coating the TiO_2 solution on FTO, the next step is sintering process. The substrate is annealed under 550 ℃ for 5 hours. Because of the high temperature process, we use FTO/Glass instead of ITO/Glass In terms of SnO_2 solution, the solution is prepared by diluting SnO_2 solution into DI water. SnO_2 film only needs 150 ℃ for the annealing process. The SnO_2 solution is coated on ITO/Glass and ITO/PEN substrates. The following fabrication processes are exactly same for all devices. The PbI_2 film convert to perovskite through CVD process with MABr and FAI mixed powder. The ratio is 95:5 or 95 % FAI by weight and 5% MABr by weight. The temperature is increased from room temperature to 140 ℃ for 30 min and maintained at 140 ℃ for 1 h. The spiro solution is prepared by mixing the spiro powder (0.06 mg), chlorobenzene (0.9 ml) and Li-salt ion solution and 4-tert-Butylpyridine. The coating condition is 4000 rpm for 30 s. As the last layer, Ag (120 nm) is deposited for the top electrode by the thermal evaporator. The grain size of ITO is much smaller in the flexible substrate compared to the glass and the following SnO_2 layer also shows much smaller roughness than one on glass. The roughness of SnO_2 on glass is about 1.5 nm but it is about 0.7 nm on PEN substrate. Since the roughness of TiO_2 film is about 5.3 nm, the roughness can be decreased up to 0.7 nm by using SnO_2 instead of TiO_2.

Project Update June 30, 2021:

Perovskite solar cells can be fabricated via many scalable solution coating processes and one of the most promising methods is slot die coating due to its ability to precisely controlling of the film uniformity and thickness, high ink usage efficiency, high coating speed, and compatibility with scalable processes such as roll-to-roll processing. However, commercialized slot-die coaters often only offer one coating direction and require tens of millimeters to liters of precursor ink to fill the hose and the reservoir prior to coating. To address these issues, a 3D printer was modified into a slot die coater due to its minimal precursor ink wastage, the ability to coat complex geometries, and compatibility with the roll-to-roll processing. Moreover, with additional synergistic crystallization methods, such as dry air quenching and substrate heating, uniform dry films can be achieved. This work is to improve the efficiency of roll-to-roll manufacturing process for perovskite solar cells.

Project Update December 31, 2021:

Perovskite solar cells can be fabricated via several scalable methods. Slot die coating technique is shown to be one of the most promising methods that achieve high quality PSCs. Due to its compatibility with the roll-to-roll system, a 3D printer is modified into a 3D slot die coater that achieves precise control of the film thickness and uniformity. Moreover, in order to control the crystallization of the films, dry air quenching is applied during the coating process.

During the testing of the slot die coating, the air quenching is found to mobilize the precursor ink and coating bead formed by the slot die head. According to this phenomenon, a new coating method that utilizes air knife is proposed and tested. Basing on the slot die coating method and dry air quenching, an air knife nozzle is designed and fabricated to replace the slot die head as the main coating element. The dry air is directly used to coat the precursor and assist the crystallization. Unlike the slot die coating technique, the air knife coating module can achieve high-quality and low-cost films that does not require ultraprecise control of the precursor ink distribution via the slot die head.

To further reduce the cost of fabrication,3D slot die coater is redesigned where the mini slot die head is removed, and the dry air nozzle is directly used as the coating element. A stainless-steel blade is attached to the nozzle and the height is set to 100 μm. During the coating process, the blade initially distributes the precursor solution, and the air knife serves as the primary thickness control element. The film thickness can be directly controlled by the coating speed and the air flowrate. The highest power conversion efficiency exceeds 10% with an average PCE of 8.6%. With the [M4N]BF4 passivation layer, the device-to-device uniformity in improved as shown in Table 1. However, the majority PCEs of the PSCs fall below 10%. In the next stage, more ILs will be tested to improve the power conversion efficiency and stability simultaneously.

Final Update June 30, 2022

The air blade coating system was further studied. A 3D printer is modified as the base platform of the air blade coating system that offers precise control of coating speed and air nozzle height. A stainless-steel blade is attached in the front of the air nozzle to disperse the PbI_2 solution to form an initial wet film of 100 µm. The dry air blade is then scanned over the initially dispersed wet film for drying and reducing the film thickness to 200 to 300 nm. The height of the dry air nozzle is set to 10 mm, and the air flow rate is controlled at 900 SCCM.

To improve the PSC efficiency, additives are further investigated. The first additive is KOH during the formation of SnO_2 film. It was found that the SnO_2 solution consists of KOH that is desirable for highly efficient PSCs. The SnO_2 colloidal solution was diluted from 15 wt% concentration to 2.67 wt% by deionized water. The solution should contain KOH with a desired concentration of 10 mM. The second additive is KI that is added during the PbI_2 film deposition. 10 µM of KI was added to the PbI_2 precursor solution for dry air blade thin film deposition. The final additive is Ionic liquid $[M_4N]BF_4$ that was dissolved in IPA and deposited on CVD perovskite film. However, it was not suitable for CVD developed perovskite layer as the $[M_4N]BF_4$ in IPA would wash out the perovskite film. $[M_4N]BF_4$ was then used as the additive that is introduced to the PbI_2 solution before CVD growing perovskite.

By utilizing the mentioned additives and optimizing the air blade coating parameters, the power conversion efficiency of 13.82% was achieved. The same fabrication procedure was used to fabricate 5 cm x 5 cm perovskite solar modules (PSMs) with an active area of 18 cm^2. The PSMs utilized a parallel structure and silver grids with busbars were deposited to reduce the resistance losses from FTO. Finally, encapsulation modules were designed for the PSMs, and field test was performed.

In summary, even though the airblade deposition and CVD showed poorer performance compared to other coating techniques, such as spin coating and slot die coating in the literature. It is still a very promising approach due to its easiness of use, low cost, and large-scale production capability. The potassium salts, KOH and KI, additives are successful demonstrated to improve the power conversion efficiency, except the ionic liquid $[M_4N]BF_4$. Moreover, perovskite solar modules with active areas of 18 cm^2 was demonstrated and further investigation is recommended.

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: $ 98,998
Amount Spent: $ 98,998
Balance: $ 0

Outcome	Completion Date
1. A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing	*6/30/2022*
2. Field testing protocol and hardware will be developed	*6/30/2022*
3. The prototype unit will be set up on an outdoor site and real-time solar irradiation of perovskite solar cells will be tested.	*6/30/2022*

Project Update December 31, 2018:

N/A

Project Update June 30, 2019:

N/A

Project Update December 31, 2019:

N/A

Project Update June 30, 2020:

N/A

Project Update December 31, 2020:

Outcome 1: A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing

We fabricated flexible perovskite solar cells using SnO_2 as an electron transport layer (ETL) and compared the device performance of solar cells using TiO_2 and SnO_2 as ETLs. We fabricated the devices on different substrates, FTO/glass for TiO_2 and ITO/glass for SnO_2. After we confirmed the feasibility of SnO2 based device on glass, we changed the substrate to ITO/PEN for flexible perovskite solar cells. In the experiment, we synthesized the perovskite film using a low temperature CVD and roll-to-roll processes. We characterized the surface morphology of films by an atomic force microscopy (AFM). We measured the efficiency of solar cells with a solar simulator. The power conversion efficiencies of perovskite solar cells are 15.43 % and 15.64 % with TiO_2 and SnO2 on glass, respectively. The power conversion efficiency of flexible solar cells is 8.7%. Although the flexible device shows a lower efficiency than glass substrate, we believe that the performance of flexible solar cells can be enhanced by an optimization in the next phase. In summary, although there is some delay on the research progress due to pandemic, we made some progress in this project. We applied for a no-cost extension for one more year to finish the overall project.

Outcome 2: We have not yet begun work on this because it is dependent on completion of outcome 1.

Outcome 3: We have not yet begun work on this because it is dependent on completion of outcome 2.

Project Update June 30, 2021:

Outcome 1: A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing

Perovskite solar cells were developed on flexible substrate successfully. Many research groups have been focused on perovskite solar cells among several types of solar cells because of their high performance. Traditionally, TiO_2 is used for the electron transport layer (ETL) due to its proper bandgap and work function for solar cells. However, there is an issue that we must tackle. Since the TiO_2 needs a high temperature (about 550 ℃) sintering process to get the electrical properties, it is necessary to find another candidate which does not need the high-temperature process. A SnO_2 can be a great candidate for the because we can get down the annealing temperature to 150 ℃. SnO_2 also has a wider bandgap, higher conductivity and greater optical transparency than TiO_2. As a result, we can expect the high efficiency of the device with SnO_2. The morphology is characterized by atomic force microscopy and the performance of the device is measured by a solar simulator. In the research, we used SnO_2 for the ETL in perovskite solar cells instead of TiO_2. ITO/PEN substrates were used for the flexible substrate. The perovskite films grew by the CVD process on the ETL film and the surface morphology was characterized by AFM. The fabricated devices are evaluated by a solar simulator and the results show that SnO_2 is a great candidate for ETL. The champion device has 13.3 % efficiency.

Outcome 2: We have not yet begun work on this because it is dependent on completion of outcome 1.

Outcome 3: We have not yet begun work on this because it is dependent on completion of outcome 2.

Project Update December 31, 2021:

Outcome 1: A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing

The 3D slot die coater is redesigned, where the mini slot die head is removed, and the dry air nozzle is directly used as the coating element. This process is also applied to fabricate large area (10 x 10 cm) perovskite solar modules (PSMs). Au grids are designed on top of the PSMs to collect the electrons efficiently. Since the area of the perovskite film is significantly larger, the CVD fabrication process need to be further optimized to improve the quality.

To achieve high quality perovskite films with large surface areas, slot die coating technique is investigated. The 3D printer modified slot die coater is used to deposit SnO_2 and PbI_2 films. The slot die head to substrate height, coating speed, and precursor feed rate are first optimized. For the head to substrate height of 100 µm and constant ink feed rate of 130 µL/min, the coating speed can be increased up to 1200 mm/min. To reduce the fabrication time, a higher coating speed is desired. However, as the coating speed increases, the viscous force caused by the ink becomes more significant, thus higher thickness film can be fabricated. The optimized coating speed to fabricate SnO_2 film is found to be 800 mm/min. The 3D slot die coated SnO_2 film shows desired surface coverage and low RMS surface roughness of 15.53 nm that is comparable to the spin coated SnO_2 film. Similar procedures are carried out to optimize the PbI_2 film. Since the coating module needs to be compatible with the roll-to-roll systems, constant coating speed is desired throughout the whole fabrication process. Therefore, the same coating speed of 800 mm/min is used to fabricate the PbI_2 film and the thickness is easily controlled by adjusting the PbI_2 concentration. To assist the PbI_2 crystallization, a dry air quenching module is implemented to extract the PbI_2 from the solvent. Small-scale (2 x 2 cm) film and continuous large-scale film (2 x 10 cm) are fabricated with the dry air quenching assistance.

Outcome 2: We have not yet begun work on this because it is dependent on completion of outcome 1.

Outcome 3: We have not yet begun work on this because it is dependent on completion of outcome 2.

Final Update June 30, 2022

Outcome 1: A prototype panel of perovskite solar energy will be developed, based on the fabricated solar cells using roll-to-roll manufacturing

Outcome 2: Field testing protocol and hardware will be developed.

Outcome 3: The prototype unit will be set up on an outdoor site and real-time solar irradiation of perovskite solar cells will be tested.

The highest power conversion efficiency (PCE) via spin coating and chemical vapor deposition methods was enhanced from 8.59% to 9.45%. However, no significant enhancements were made with the ionic liquid $[M_4N]BF_4$ due to its low solubility in the solvent, DMF and DMSO, during PbI_2 deposition.

To achieve roll-to-roll manufacturing of the PSCs, dry air blade coating technique was further investigated. PbI_2 film was first deposited via dry air blade coating method and uniform film with low roughness of 3.4 nm was obtained. The air blade deposited PbI_2 film showed desired surface characteristics that was comparable to the spin coating method. The dry air quickly extracted the solvent and distributed thick wet film, thus forming uniform PbI_2 films to serve as the growing seeds for the perovskite film during CVD process.

Air blade deposited PbI_2 film was moved to undergo seven hours of perovskite growth process under 115 ℃ in vacuum and was cooled to room temperature with a rate of 0.7 ℃/minute. PbI_2 film reacted with FAI and MABr during CVD process and was fully converted into black perovskite. The developed perovskite film exhibited promising film qualities with high smoothness and uniformity. The average size of perovskite grains is more than 500 nm with some grain sizes near 1 µm. After incorporating KI, KOH, and $[M_4N]BF_4$ additives, defects in the perovskite film were reduced. The power conversion efficiency of air blade fabricated champion devices was enhanced to 13.82 %, whereas the spin coated PSC from the same batch of fabrication achieved a lower PSC of 8.3%. However, the air blade fabricated PSCs can still be improved by improving the interface between perovskite and SnO_2 films.

Perovskite solar modules were also fabricated. PSMs showed a size of 5 cm x 5 cm with four light absorbing subcells with a total active area of 18 cm^2. The four subcells are laid in parallel to each other to simplify the fabrication process. However, the conventional parallel structure exhibits low power conversion efficiency due to the high resistance of the base transparent conductive oxide layer, such as FTO. Therefore, silver grids were deposited to minimize the distance that the generated electrons must travel in FTO to reduce the resistance losses. The PSMs were encapsulated by PMMA board, and sealed by epoxy to eliminate any undesired effects of moistures and gases in the atmosphere. Measurement system consists of an electrochemical station and a computer. The PSMs were setup for field test. They consist of two copper strips directly connected the exposed silver coated FTO and silver coated Spiro-OMeTAD respectively to form a closed loop.

The approach shows promising results with high efficiency. Moreover, air blade and CVD deposition techniques can be integrated with roll-to-roll manufacturing systems for high volume production to reduce the overall cost. Even though these techniques are still not ready for deployment. CVD and air blade deposition methods are still recommended for further investigation due to their ease of use, low cost, and large volume production capabilities.

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 Update December 31, 2018:

N/A

Project Update June 30, 2019:

N/A

Project Update December 31, 2019:

N/A

Project Update June 30, 2020:

One peer reviewed paper was accepted for a publication by an archived journal:
Rui Zhu, Xiangyang Wei, Gongnan Xie, Terrence Simon and Tianhong Cui, "Numerical simulation of vapor deposition process of perovskite solar cells: the influence of MAI vapor flow to perovskite growth", *ASME Journal of Solar Energy Engineering* (Accepted)

Project Update December 31, 2020:

One peer reviewed paper was accepted for a publication by an archived journal:
Xiangyang Wei, Yangke Peng, Gaoshan Jing, Terrence Simon and Tianhong Cui, "High Performance Perovskite Solar Cells Fabricated by a Hybrid Physical-Chemical Vapor Deposition", *ASME Journal of Solar Energy Engineering* (Accepted)

Project Update June 30, 2021:

N/A

Project Update December 31, 2021:

One peer reviewed paper was published for a publication by an archived journal:
Xiangyang Wei, Yangke Peng, Gaoshan Jing, Terrence Simon, and Tianhong Cui, "High Performance Perovskite Solar Cells Fabricated by a Hybrid Physical-Chemical Vapor Deposition", ASME Journal of Solar Energy Engineering, Vol. 143, No. 4, 2021: 041006

Final Update June 30, 2022

N/A

Final Report Summary

The field test was performed on University of Minnesota campus and the findings were disseminated through the following publications in archived journals.

1. Rui Zhu, Xiangyang Wei, Gongnan Xie, Terrence Simon, and Tianhong Cui. "Numerical simulation of vapor deposition process of perovskite solar cells: The influence of methylammonium iodide vapor flow to perovskite growth." *Journal of Solar Energy Engineering* 143, no. 1 (2021).
2. Xiangyang Wei, Yangke Peng, Gaoshan Jing, Terrence Simon, and Tianhong Cui, “High Performance Perovskite Solar Cells Fabricated by a Hybrid Physical-Chemical Vapor Deposition”, ASME Journal of Solar Energy Engineering, Vol. 143, No. 4, 2021: 041006
3. Wei, Xiangyang, Yanke Peng, Gaoshan Jing, and Tianhong Cui. "Planar structured perovskite solar cells by hybrid physical chemical vapor deposition with optimized perovskite film thickness." *Japanese Journal of Applied Physics* 57, no. 5 (2018): 052301.

VI. PROJECT BUDGET SUMMARY:
A. ENRTF Budget Overview: See attached budget spreadsheet

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: 0.61 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
The university overhead unpaid	$137,587	$0	Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing
TOTAL OTHER FUNDS:	**$137,587**	**$0**	

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 Ph.D. student will be responsible for the manufacturing facility and the outdoor experimental test set-up, and he will also 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. REPORTING REQUIREMENTS:

- The project is for 4 years, will begin on 07/01/18, and end on 06/30/22.
- Periodic project status update reports will be submitted *[06/30]* and *[12/31]* of each year.
- A final report and associated products will be submitted between June 30 and August 15, 2022.

IX. VISUAL COMPONENT or MAP(S):

N/A

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

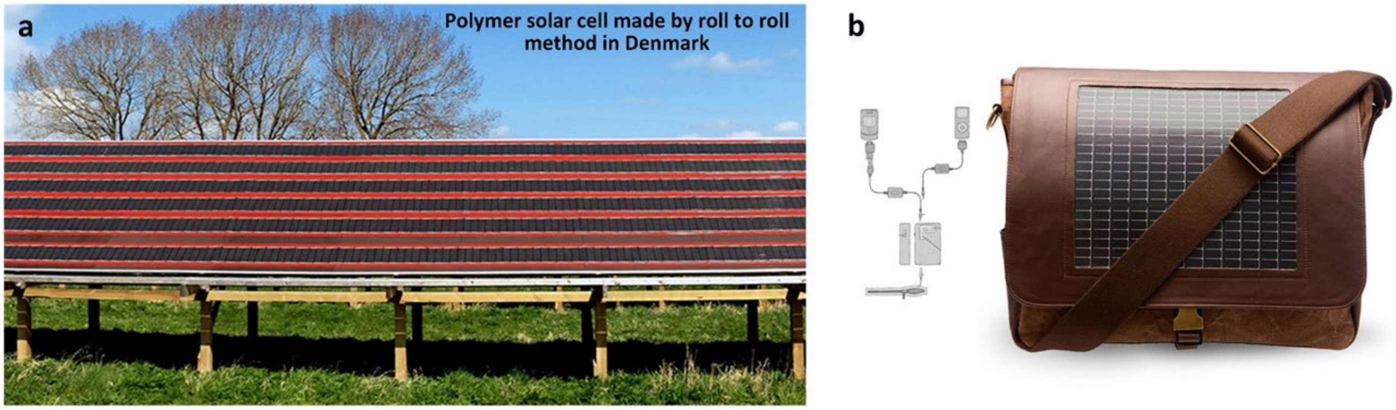
N/A

Appendix: Visual Component

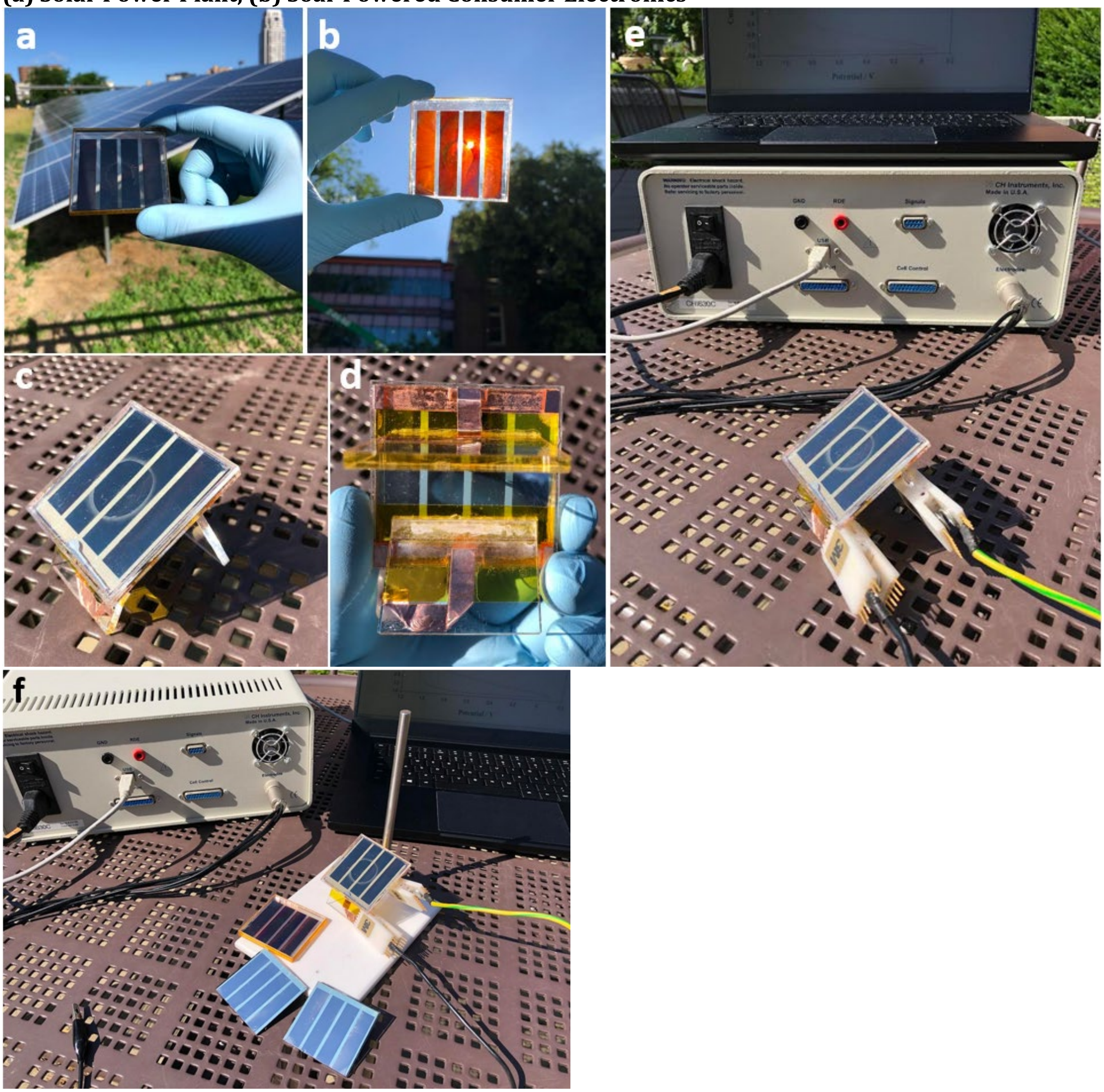
Project Title: Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing (160-E)

Current Silicon Solar Cell Production Line from CETC (Very Complex and Expensive)

Proposed Roll-to-Roll Processing of Perovskite Solar Cells (Very Simple and Cheap)



Future Applications of Proposed Cheap Solar Cells (Cheap, Clean, and Renewable)
(a) Solar Power Plant, (b) Soar Powered Consumer Electronics



In-lab fabricated 5 cm x 5 cm perovskite solar modules and field test setup

(a) & (b) perovskite solar panel vs silicon solar panel, (c) front view of perovskite solar panel encapsulation module, (d) back view of the perovskite solar panel encapsulation module, (e) & (f) perovskite solar panel field test

Environment and Natural Resources Trust Fund
M.L. 2018 Budget Spreadsheet - FINAL

Project Title: Develop Inexpensive Energy from Simple Roll-to-Roll Manufacturing
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07c
Project Manager: Tianhong Cui
Organization: University of Minnesota
College/Department/Division: College of Science and Engineering, Mechanical Engineering
M.L. 2018 ENRTF Appropriation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07c
Project Length and Completion Date: Four years - June 30, 2022
Date of Report: Actuals through 8/9/22

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	**Total Budget**	**Amount Spent**	**Balance**
BUDGET ITEM			
Personnel (Wages and Benefits) - Overall	$257,155	$257,155	$0
Dr. Tianhong Cui, PI, 1 month summer salary (11% FTE) & 33.5% fringe for 3 years (Total estimated amount $70,903)			
Graduate Research Assistant, 50% FTE (fall & spring semesters include 16.9% fringe plus $18.94/hour tuition, summer 15% fringe only) for 3 years (Total estimated amount $144,562)			
Professional/Technical/Service Contracts			
Scientific Services: User fees at Minnesota Nano Center and Characterization Facility at the University of Minnesota. The cost is about $875 per month for the research assistant for 3 years.	$18,494	*$18,494*	$0
Equipment/Tools/Supplies			
Lab Materials & Supplies: fabrication materials & supplies including silicon wafers ($8,000), polymer substrates ($9,000), chemicals ($9,035), roll-to-roll manufacturing set-up items ($16,000), bottles, gloves, other electronics for testing, etc. ($6,000)	*$24,351*	*$24,351*	$0
Travel expenses in Minnesota			
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	*$0*	*$0*	$0
COLUMN TOTAL	$300,000	$300,000	$0