SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Power Electronics Program Kickoff

Modular HF Isolated Medium-Voltage String Inverters Enable a New Paradigm for Large PV Farms

Georgia Tech, First Solar, Southern Company, EPRI, ORNL, Paul Centolella LLC

Deepak Divan, Professor, Georgia Tech

Team

Georgia Tech Center for Distributed Energy

Southern Company

First Solar

EPRI Electric Power Research Institute

Oak Ridge National Laboratory

Consultant for Regulatory studies: Paul Centolella & Associates LLC

Introduction: Utility Scale PV Farms

- With price of PV panels reducing exponentially, a major focus has also been on driving the cost of 'balance of systems' (BOS) down.
- One major component of BOS cost is the electrical system, including current collection, power conversion, transformer isolation, and breakers.
- Both basic approaches – central inverters and string inverters have significant loss.
- Another major source of loss is the 480 V/33 kV Step-up transformer that is used to interconnect inverters with grid.

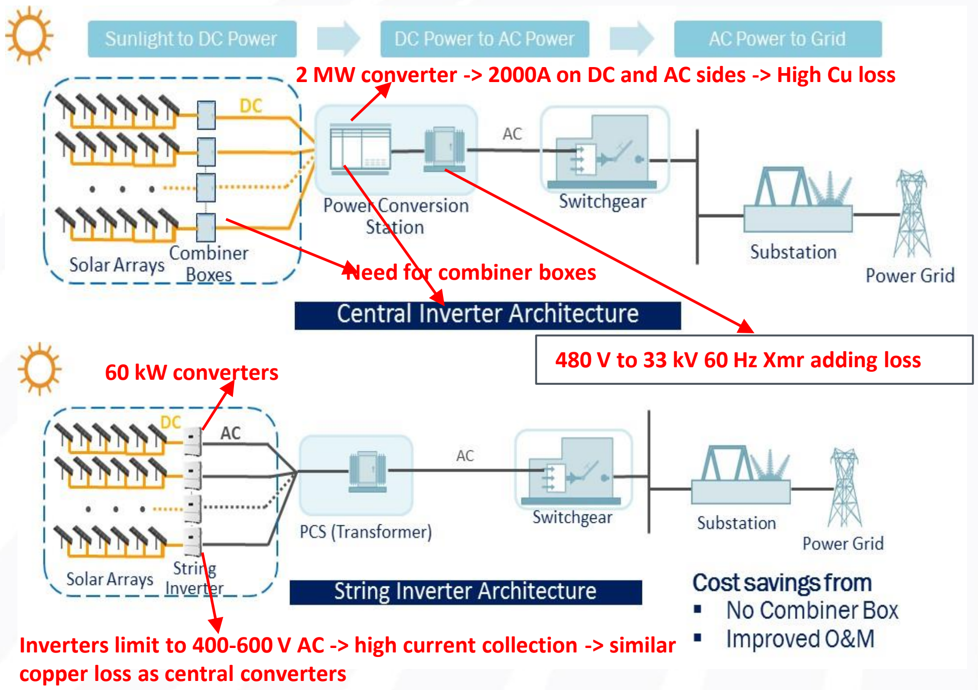


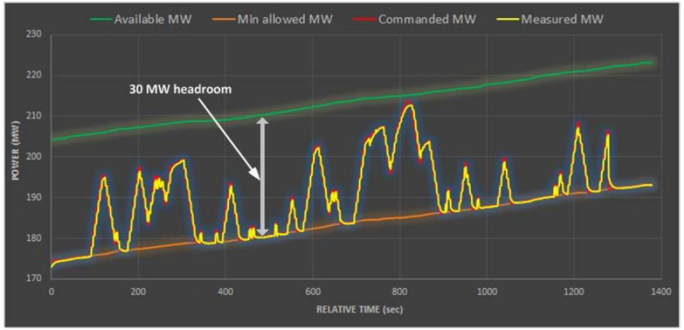
Image Courtesy: Mahesh Morjaria, FirstSolar

Introduction: Utility Scale PV Farms…contd

Georgia Tech | Center for Distributed Energy

- As PV becomes a higher percentage of the overall generation, it is important to integrate it directly into the grid.
- For example, First Solar and CAISO have demonstrated the use of a 300 MW PV plant to provide frequency regulation, ACE error and other ancillary services.
- In the years ahead, it will be increasingly important to include
  - energy storage for dispatchability,
  - ramp-rate control, grid forming capability that allows black start following a blackout,
  - grid support functions including voltage, VARs and power flow control.

Aerial photo of First Solar's 300-MW PV power plant



Frequency regulation illustration from NREL, First Solar

Source: NREL, "Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant"

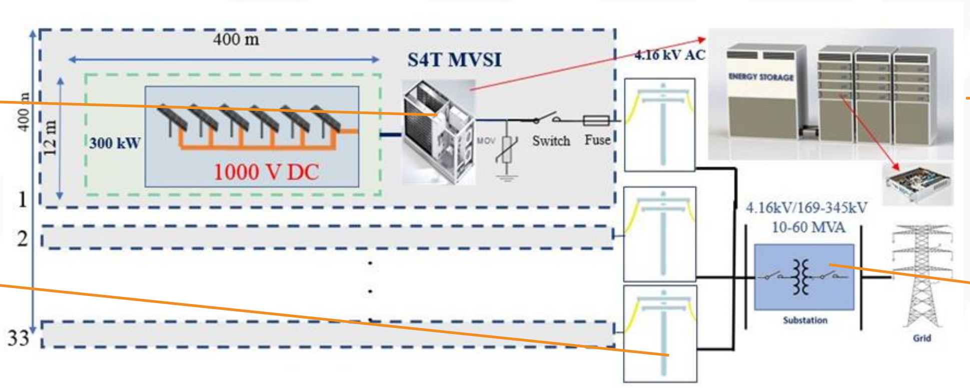
Project Objective

Georgia Tech Center for Distributed Energy

- Develop and demonstrate a new approach for larger commercial and utility scale PV farms which reduces the ‘balance of systems’ (BOS) cost by
  - Employing a novel Medium Voltage String Inverter (MVSI) topology (soft switching solid state transformer – S4T) to convert 1000 Vdc to 4.16 kVac.
  - Plant collection using standard, low-cost overhead MV distribution network.
  - Enabling energy storage integration without additional converter cost to achieve dispatchability of the PV resource.
  - Providing advanced functionality: autonomous operation, track ISO signals for dynamic balancing and ancillary services, and PV farm operation as a virtual grid resource.

Add 1-1.5 MWHr storage as needed w/o additional converter

Standard & low cost 4.16 kV AC (13 kV) overhead distribution

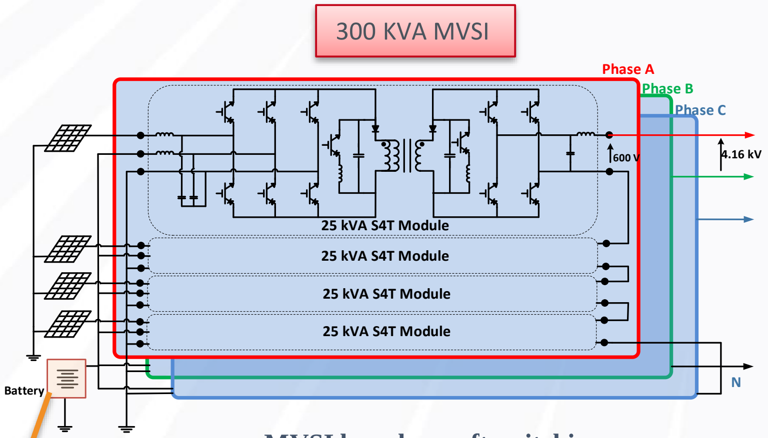


300 kVA 1 kV DC to 4.16 KV 3-ph AC (eventually 13 KV) MVSI converter - with isolation

Eliminate one 60 Hz transformer

Soft Switching Solid State Transformer (S4T) Based MVSI

- S4T is a modular bidirectional solid state transformer using 1.7 kV Si IGBTs and SiC diodes with ZVS for the main power devices over the entire load range, with full-load efficiency of ~98%.
- Four of these S4T modules are series-connected to realize 2.4 kV line-neutral voltage per phase, realizing a standard 4 kV distribution system (increase eventually to 13 kV).
- The overall MVSI would have a rating of 300 kVA, much more than would be feasible with traditional 480 V string inverters.
- Provides the mechanism to connect a (1-1.5 MWHr) battery in the 600-1000 VDC range without any additional power converters.



MVSI based on soft switching solid state transformer (S4T)

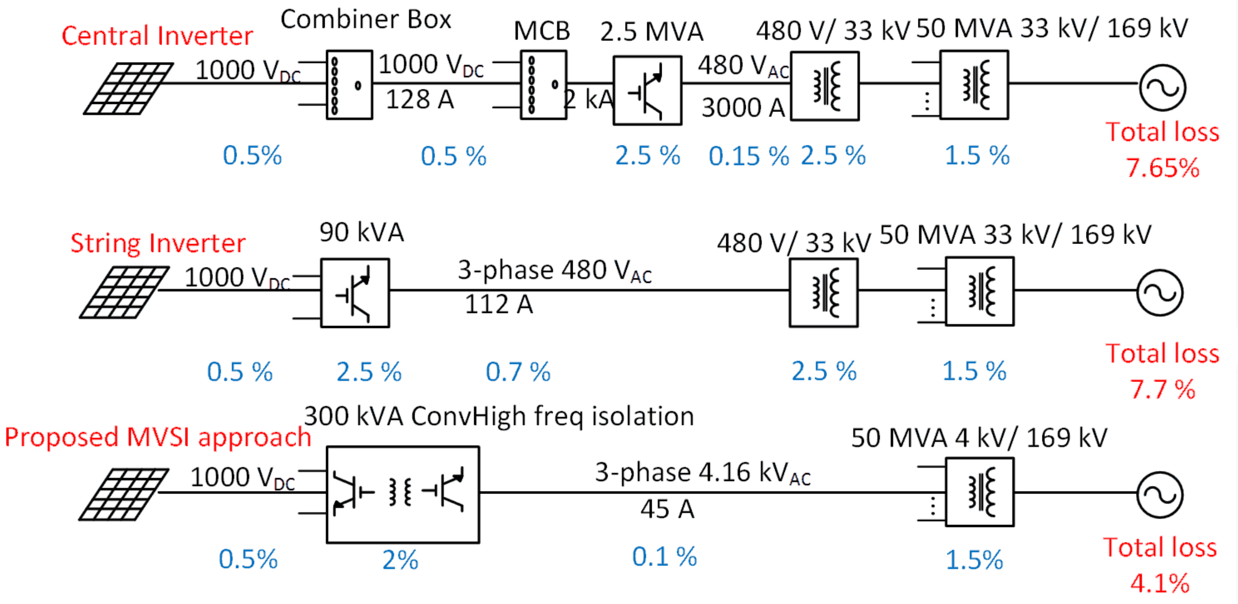
Benefits with S4T MVSI

- **Partial shading:**
  - The common capacitor/battery allows exchange of power between modules as needed to allow for occasional cloud shading on individual solar panel strings.
  - This can reduce curtailment and improve energy capture for the PV farm.
  - Individual S4T modules can interface with individual PV strings, allowing optimization and maximum power tracking at the string level.
- **Wide panel voltage range:** S4T's buck-boost operation can accommodate a wide range of PV panel, battery, and grid voltages without needing additional DC/DC converters.
- **Galvanic isolation:** Eliminates additional stages of 60 Hz transformers and simplifies PV panel and battery connection.
- **Safety and cost:** The current source nature of the S4T, and the galvanic isolation, result in a greatly simplified approach to managing both AC and DC side grounding and faults.
- **Higher reliability and life**: The S4T does not use any DC bus capacitors, and is expected, based on similar designs, to have a 25 year life.
- **Easy maintenance**: Modular nature of the S4T MVSI allows for a 'rip and replace' strategy for field maintenance, reducing O&M expenses.

System Loss Comparison

Georgia Tech Center for Distributed Energy

Preliminary Loss Comparison of traditional central and string inverter approaches



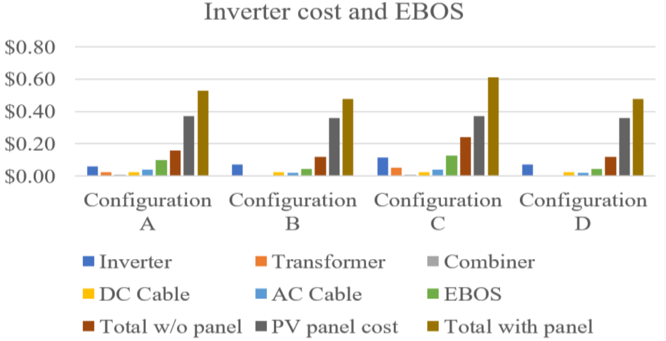
SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Preliminary BOS Analysis

- EBOS cost reduced from $0.158/watt for standard string inverter to $0.118/watt for the proposed converter– a 55% reduction.
  - Elimination of the 60 Hz transformer, the combiner box, reduction in the cost of AC conductors translates into a reduction of

  Assumptions:
  - Standard String inverter ~$17,500 : ($0.058/watt) and EBOS (transformer (33 kV/ 480 V 60 Hz), combiner, DC cable and AC cable) of $0.10 per watt. (Total: $0.158/W)
  - S4T MVSI is estimated to be somewhat higher (more devices plus high frequency transformer).
- If energy storage is integrated, the cost differential becomes significant- $0.241/watt to $0.118/watt

BOS cost comparison of state-of-art string inverter approach vs proposed MVSI approach based on S4T

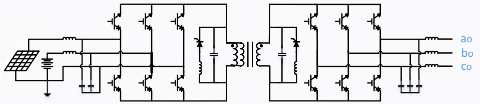


Configuration A	**Standard String Inverter at 300 kW/ 1000 VDC**
Configuration B	**S4T MVSI at 300 kW/ 1000 VDC**
Configuration C	**Standard String Inverter + ESS Inverter**
Configuration D	**S4T MVSI with ESS Integration**

Feasibility

- Previous work on the S4T topology has demonstrated the technical feasibility of the triport operation.
- The proposed MVSI based on the S4T will have single phase bridges cascaded on the MV side.
- The key challenge in the proposed work lies in maintaining the total voltage as well as equal voltage sharing on the cascaded side during various events like transients or PV power variations, and still having the triport capability.

Triport Schematic



Experiment Setup

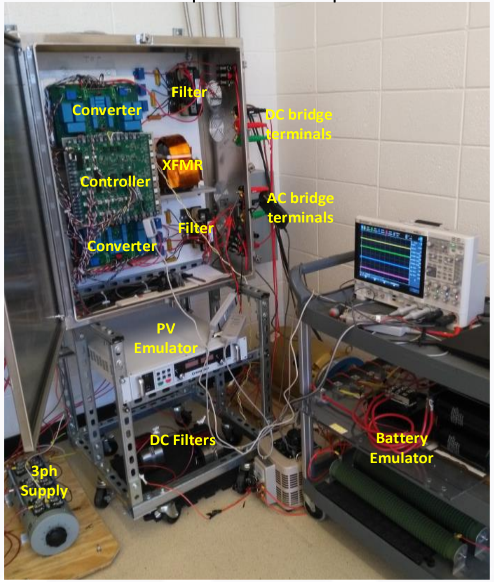
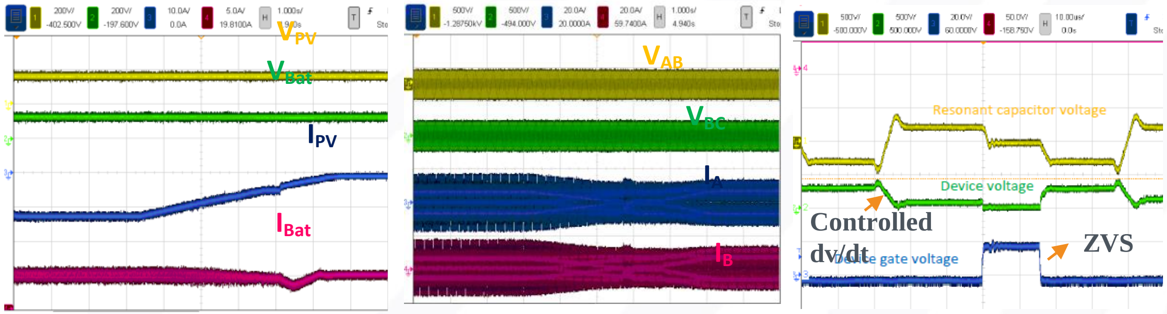


Image of 208V 3-ph AC, 200 V DC Battery/PV S4T triport prototype



Experiment results of S4T module in triport mode demonstrating ability to operate PV, battery and grid

Technical Risks And Challenges

- **Multi-function control of the MVSI**
  - Multiple control objectives have to simultaneously satisfied in a highly coupled non-linear system
    - Dynamic voltage sharing across series connected modules
    - Independent control of PV and battery
    - Providing grid volt/VAR support
    - Control of power flow at each PV string for optimum performance under partial shading
  - A novel model prediction based priority switching method is being developed.
- **Cost-effective disconnect of the MVSI from the grid**
- **Ability to fully control battery**
- The above stated challenges are unique to this application and are the main differentiating point compared to other DOE funded SST projects the team is working on.

Model Prediction Priority Switching Control

$$T_A = (v_{C1A}^*(t+T_A) - v_{C1A}(t)) \cdot \frac{C_{1A}+C_{2A}}{i_{Lm}(t)}$$

Adjust T_A s.t. $i_{Lm}(t+T_A)$ within (0.7,1.3)p.u.

↓

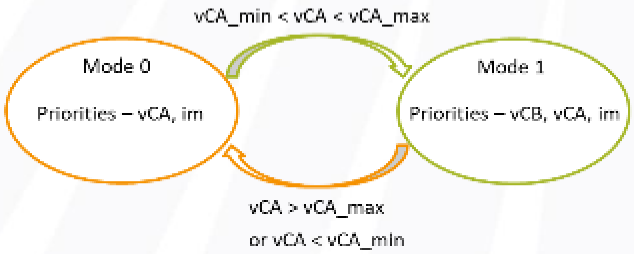
$$T_B = (i_{Lm}(t+T_A) - i_{Lm}^*(t+T_A+T_B)) / \frac{v_{CB}}{L_m}$$

Adjust T_B s.t. $i_{Lm}(t+T_A+T_B)$within (0.7,1.3)p.u.

↓

Calculate T_z s.t. $T_s = 1/20\text{kHz}$.

Model prediction.

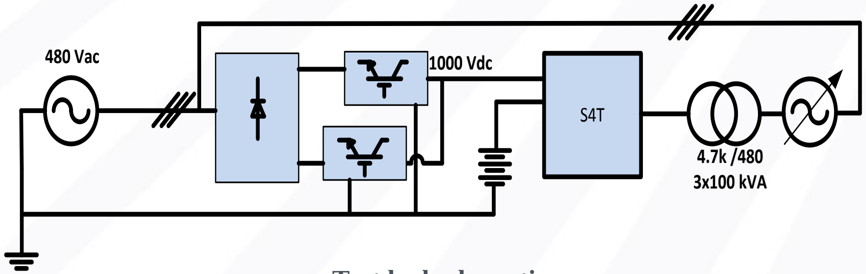


Market Transformation Plan

- The team includes market leaders First Solar and Southern Power, who are together part of over 12 GW in utility scale PV solar farm installations, both existing and planned.
- Together, they offer an opportunity to drive acceptance of new technologies, such as the MVSI based concept shown here.
- It is anticipated that successful demonstration of the MVSI technology, and articulation of the new value propositions, will lead over the next 18 months to a pilot at >20 MW scale.
- The project will also explore the regulatory and commercial implications of the proposed architecture.
  - Enhancing the performance of larger PV farms will improve solar cost-effectiveness, facilitate tracking of solar output, and enable customers who do not have access to rooftop PV to secure fractional ownership shares in clean energy resources.

Project Deliverables/Goals

- Demonstration of 300 kVA S4T MVSI integrating the 1000 Vdc (PV) and 650 Vdc (Battery) to 4.16 kVac.
- LCOE and LBOE/LCAE or any suitable metric to define the benefits of the MV distribution in PV farms compared to the state of art approaches.
- Grid/farm interaction and optimized energy storage level of the proposed approach to provide required functionalities in terms of grid ancillary services.
- New potential regulatory models that enables more Utility interaction in PV farms based on the proposed approach



Test bed schematic

Summary and Key Idea/Takeaway

- Introduced 300 kVA Medium voltage string Inverter (MVSI) realized using series-connected 25 kVA S4T modules to realize 2.4 kV line-neutral voltage.
- MVSI enables 4.16 kVAC (eventually 13 kV AC) distribution inside the PV farm, standard voltage levels for utilities.
- Future energy storage integration without need of additional converter and cost.
- Without considering the benefits from storage integration, 55% reduction in EBOS and 25% reduction including converter cost -> 5% (0.003c/kWh) LCOE reduction.
- Will explore potential new regulatory models that take advantage of the new paradigm for large PV farms and to increase utility participation in solar PV farms
- If successful, proposed MVSI paves the way for new utility scale PV farm build with medium voltage level distribution

Thanks

Project Overview

Georgia Tech | Center for Distributed Energy

Effort 1: S4T MVSI Simulation and Design

- Defining specifications of the MVSI, design of the MVSI and design of a 20 MW solar farm based on the proposed MVAC distribution architecture
- Complete design of the MVSI including high frequency transformer, selection of switching devices, thermal design, controller design, layout and packaging, 4.16 kV AC and 1000 V DC disconnect, and protection
- Operation of the MVSI will also be validated through hardware-in-loop (HIL) simulations.

Effort 2: System analysis and Storage Optimization

- System level benefits of the proposed MV distribution architecture based on MVSI inverters.
- Simulation of the 20 MW solar farm, modeling parameters such as cable and transformer impedances, partial shading etc., using the OpenDSS or equivalent platform.

Project Overview

Georgia Tech | Center for Distributed Energy

Effort 3: Financial analysis

- *LCOE analysis* tasks will quantify the benefits of proposed MV distribution architecture based on MVSI inverters.
- The Financial (LCOE and First Cost) analysis tasks will be performed

Effort 4: Prototype Build and Test

- 300 kVA prototype and validating the functionality

Effort 5: Regulatory and Commercial Impact Study

- Exploring different regulatory models to increase Utility participation in solar PV farms
- Commercial analysis to develop (a) Commercial and regulatory mechanisms that can lead to new business models and (b) Evaluation of new commercial, regulatory and business models enabled by the proposed MVSI approach

Tasks and Timeline

SOPO Item Identification Number	Item Description	Item Performer	Planned											
			BP1				BP2				BP3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
T-1	S4T MVSI - Converter simulation	Georgia Tech	X	X	X	X								
T-2	300 kVA S4T MVSI bronze prototype design	All				X								
T-3	Solar PV Farm design based on MVSI	SoCo/ All	X	X	X	X								
T-4	Financial analysis of State of the art	FirstSolar/ SoCo		X	X	X								
T-5	Test bed setup	Georgia Tech		X	X	X								
T-6	Explore regulatory issues	Paul		X	X	X								
T-7	300 kVA S4T MVSI HIL Simulation and Golden prototype design	Georgia Tech					X	X						
T-8	Solar PV Farm design based on MVSI	All							X	X				
T-9	Simulation for system analysis						X	X	X	X				
ST-9.1	Farm-level simulation	EPRI					X	X						
ST-9.2	Grid/Farm Interaction study	EPRI							X	X				
ST-9.3	Analysis of storage requirements for PV farm based on proposed converter	ORNL					X	X	X	X				
T-10	Financial analysis of the proposed approach								X	X				
ST-10.1	LCOE and First cost analysis based on the proposed approach	First Solar							X	X				
ST-10.2	Reliability impact on the financial analysis	Georgia Tech							X	X				
T-11	MVSI prototype build and test	Georgia Tech					X	X	X	X				
T-12	Explore regulatory issues	All					X	X	X					
ST-12.1	Regulatory issues: Explore different regulatory models to increase Utility participation in solar PV farms	Paul					X	X	X					
T-13	MVSI testing	Georgia Tech									X	X		
T-14	Commercial Impact study	All									X	X		

Preliminary LCOE Analysis

- Assumption of $1/Wdc translates roughly to a **LCOE of $0.06/kWHr**
- If the 3.5% efficiency improvement is factored in as a saving in PV panel first cost, the overall cost reduction achieved is **$0.06/watt** over the conventional design.
- Given that this proposal expects to reduce the first cost by $0.05/Wdc, it is estimated that the impact on LCOE will be **at least $0.003/kWHr, or a reduction of 5%**
- Further, for every 1% improvement in energy throughput (due to efficiency gains), one would expect a 1% gain in LCOE.
- Furthermore, the ability to offer grid support will further reduce the LCOE for the plant.