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Energy Production and Infrastructure Center
LEHIGH UNIVERSITY
Customized Energy Solutions
AIR PRODUCTS

Techno-Economic and Deployment Analysis of Fossil Fuel-Based Power Generation with Integrated Energy Storage

DE-FE0031903

October 29, 2020

Project Personnel

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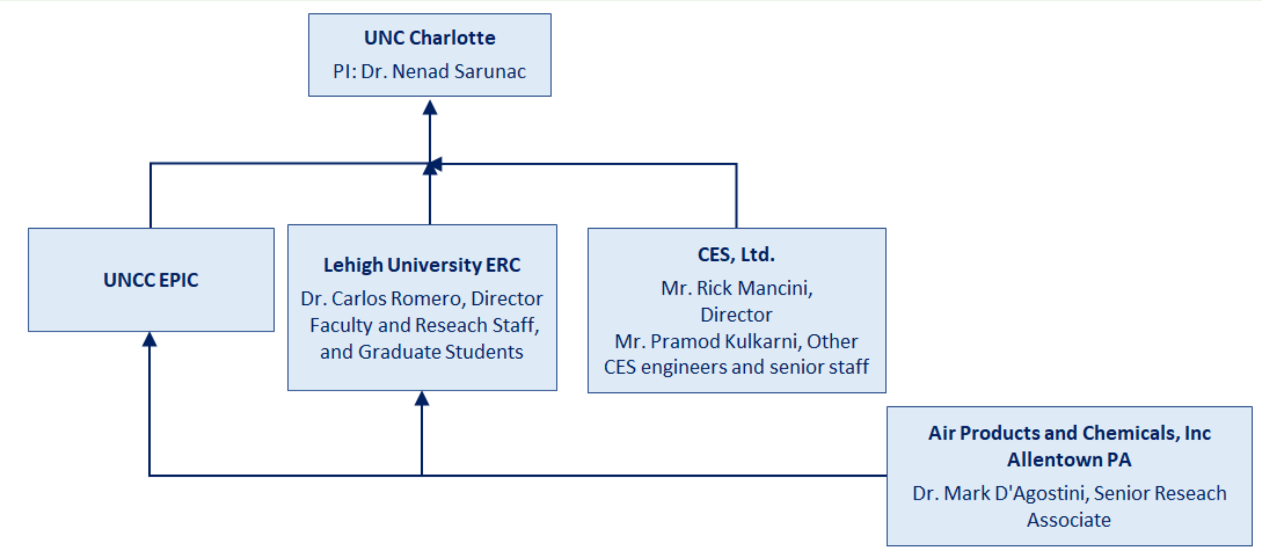
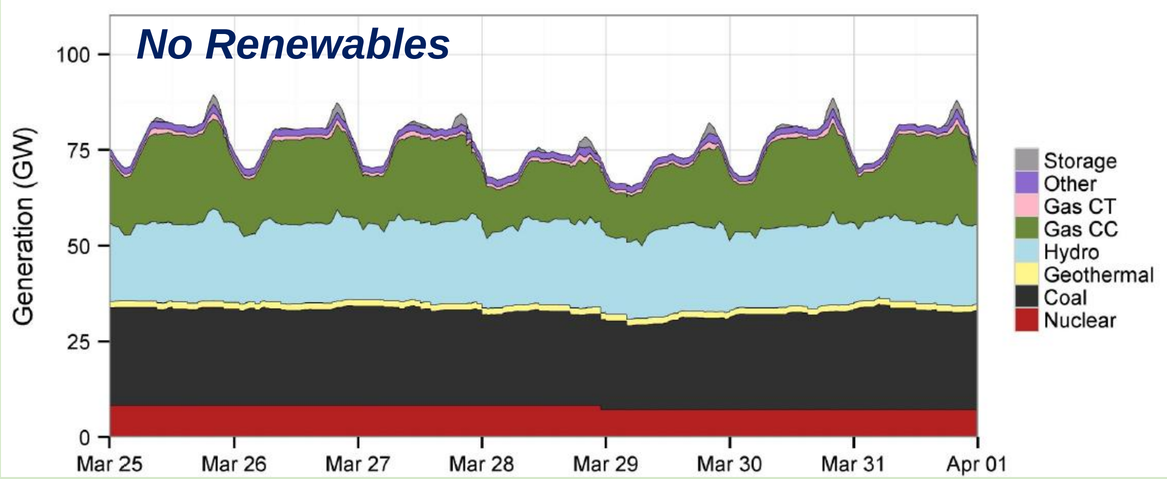
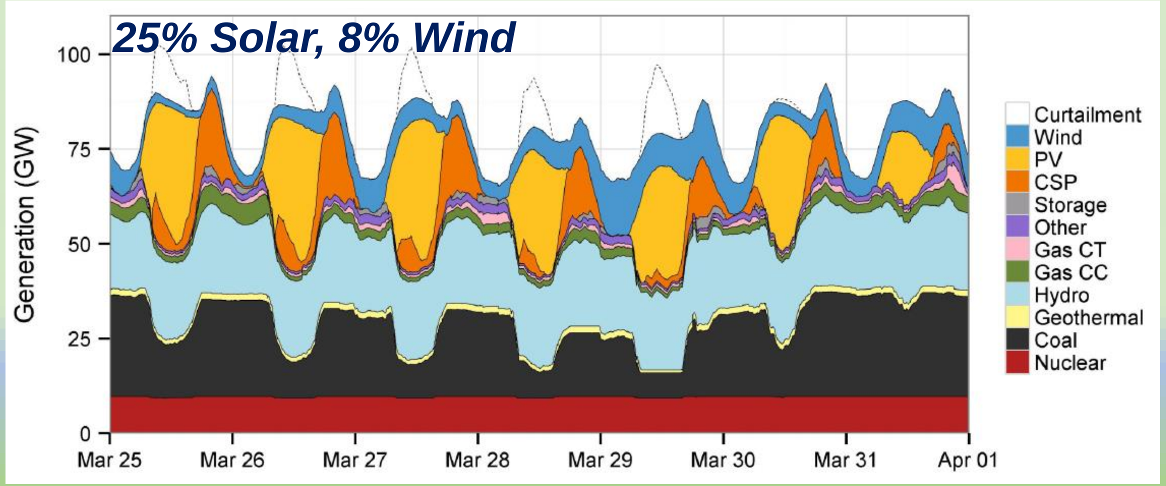


UNCC – University of North Carolina at Charlotte
LU ERC – Lehigh University Energy Research Center
CES – Customized Energy Solutions, Ltd.

The Need for Energy Storage



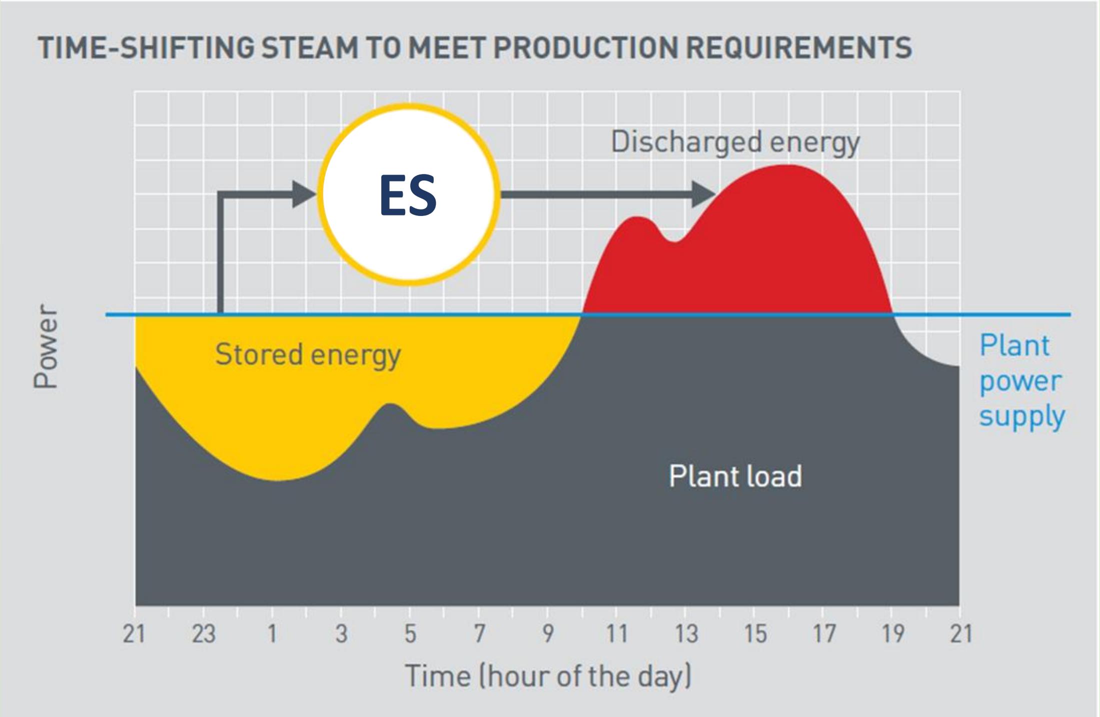


Source: "Western Wind and Solar Integration Study Phase 2", NREL

- *The increased share of feed-in from variable and non-dispatchable renewable energies results in complex challenges for the energy system.*
- *In addition to other options such as grid and demand-side management, flexible conventional power generation plays a key role for ensuring adequate system stability.*
- ***Energy storage integrated with the plant (IES) is an option that will play an important role in improving the flexibility of fossil power plants.***
- ***IES partially decouples** the plant power output from the boiler firing rate, thus:*
  - *improving flexibility of the plant (plant dynamic response)*
  - *allowing load changes at constant or nearly constant firing rate, reducing cycling and cycling damage*
  - *allowing plant operation closer to the design*
  - *time-shifting peak power generation*
  - *improving plant performance and economics*
  - *reducing emissions*

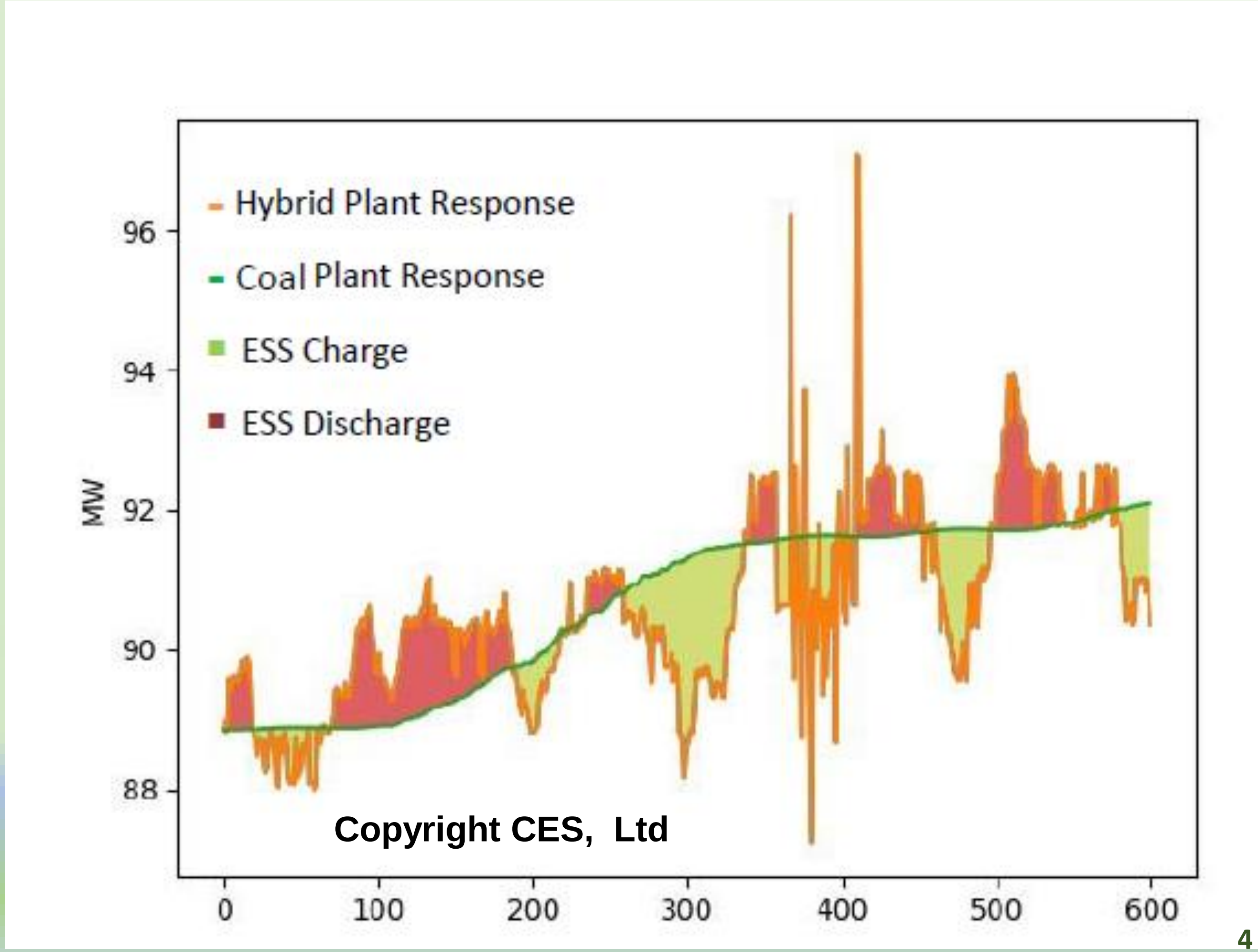
Benefits of Integrated Energy Storage

Time-shifting peak power generation



*From the **power plant** perspective, enhancing the plant flexibility would result in a higher profitability due to reduced losses at minimum load operation, additional revenues on intraday and control power markets, avoidance of shutdowns, and faster start-ups.*

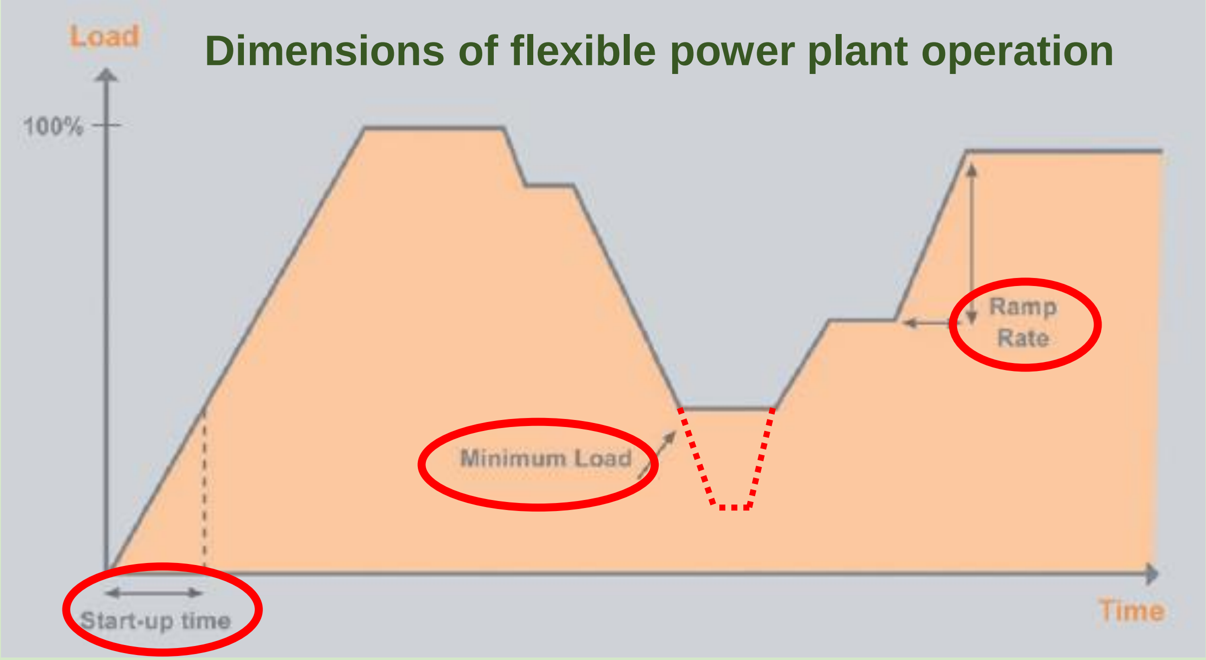
Minimize (Eliminate) Load Cycling

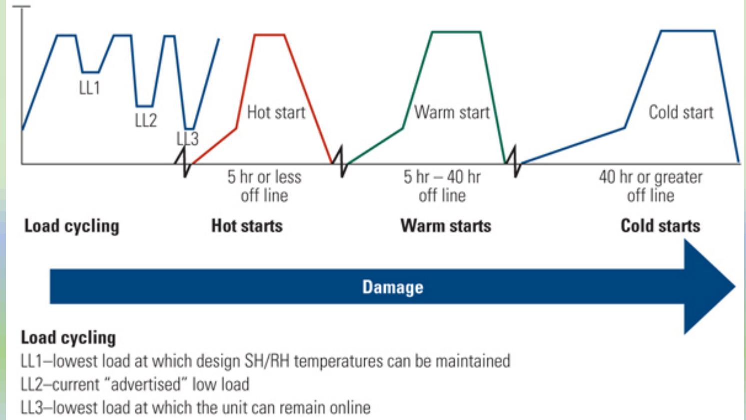


Flexible Power Plant Operation

- *Off-design (flexible) operation of coal-fired units contributes to **lower plant efficiency, lower availability,** and **higher O&M costs**.*
- *Flexible power plant operation comprises **three dimensions**:*
  - *Low minimum load*
  - *Short and frequent shut-downs and start-ups*
  - *Frequent unit **ramping** and **cycling***

    Load cycling also refers to providing primary and secondary frequency control.
  - *Extended operating load range*
- *Improving flexibility of coal-fired power plants is a great challenge.*





Relative damage caused by cycling steam plants.
Courtesy: Intertek-Aptech

Source: "TOOLBOX: Compilation of Measures for the Flexible Operation of Coal-Fired Power Plants", VGB Power Tech, VGB-B-033, March 2018

Project Objectives

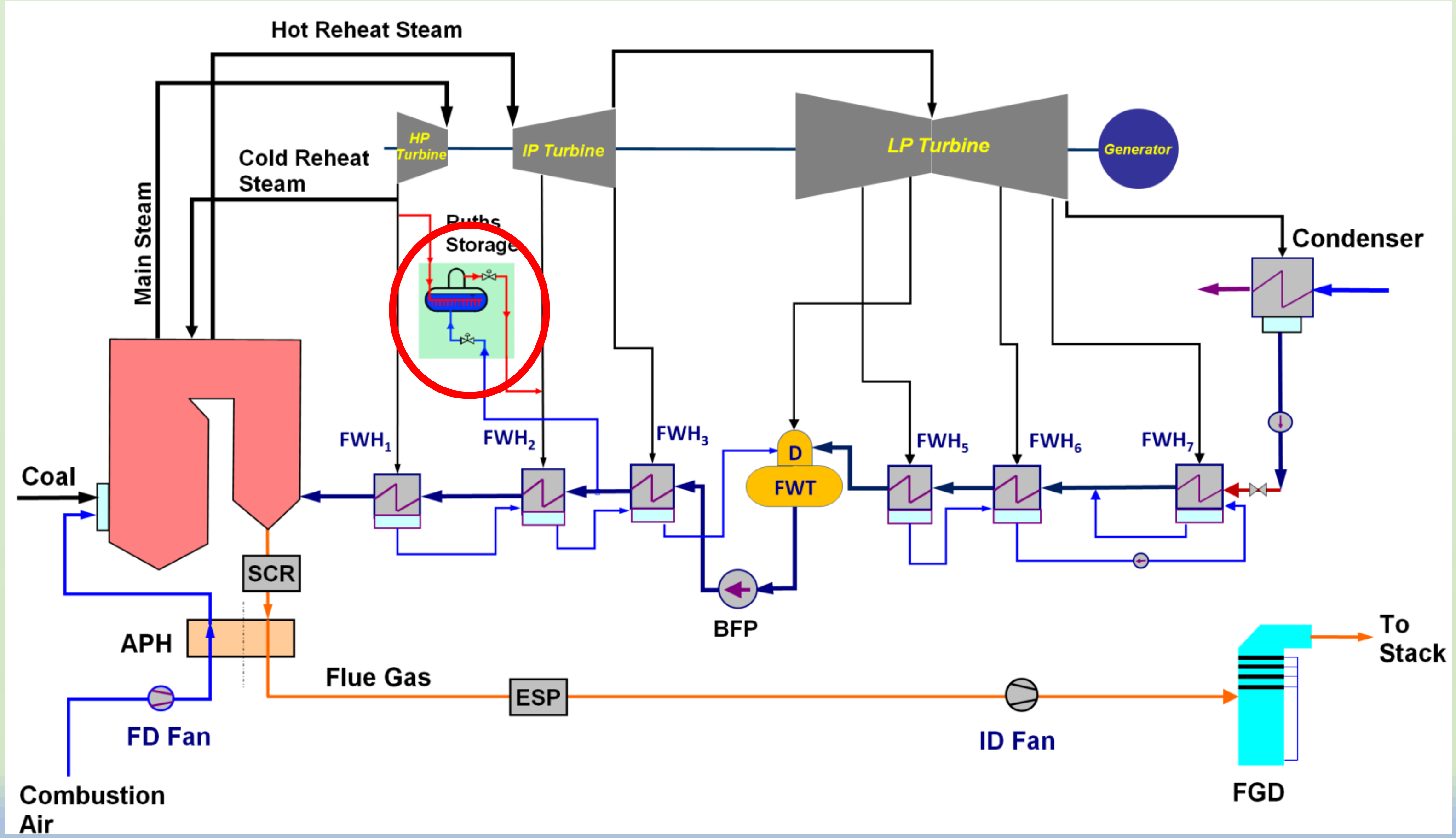
The objective of this project is to analyze a set of energy storage (ES) options *(technologies)* ***and determine their impact on the operation and economics of a representative coal-fired power plant. The specific objectives include:***

- *Establish a Refence plant design and apply it to the PJM and MISO energy markets to determine the dispatch and production costs associated with reference design.*
  - *The reference plant will establish a benchmark for the technical and economic analysis which can be used for other fossil fuel facilities.*
  - *The coal-fired steam facility represents the greatest potential benefits for an integration of ES and can be a basis for other fossil plant designs.*
- *Integrate the various **ES** technologies into the reference plant design and determine the dispatch and production costs and economic benefits associated with **IES**.*
  - *The economic benefits due to integrated energy storage and increased plant flexibility include:*
    - *Improved operating efficiency and system reliability*
    - *Lower operating costs*
    - *Efficient plant participation in frequency control and other ancillary services*
    - *Reduced emissions (CO_2 and non-GHG)*

Energy Storage Options Selected for Analysis

- ***Thermal Energy Storage (TES)***
  - *Ruths steam accumulator (RSA)*
  - *Sensible heat storage:*
    - *LP Condensate Storage*
    - *Molten Salt*
    - *Solid Media*
- ***Liquid Air (Cryogenic) Energy Storage (LAES*** *or* ***CES)***
  - *Integrated with a power plant*
  - *Stand alone version will not be analyzed*
- ***Battery Energy Storage in combination with Super-capacitors***
  - *Batteries provide capacity, capacitors provide fast response*
- ***Hydrogen Energy Storage (H_2ES)***

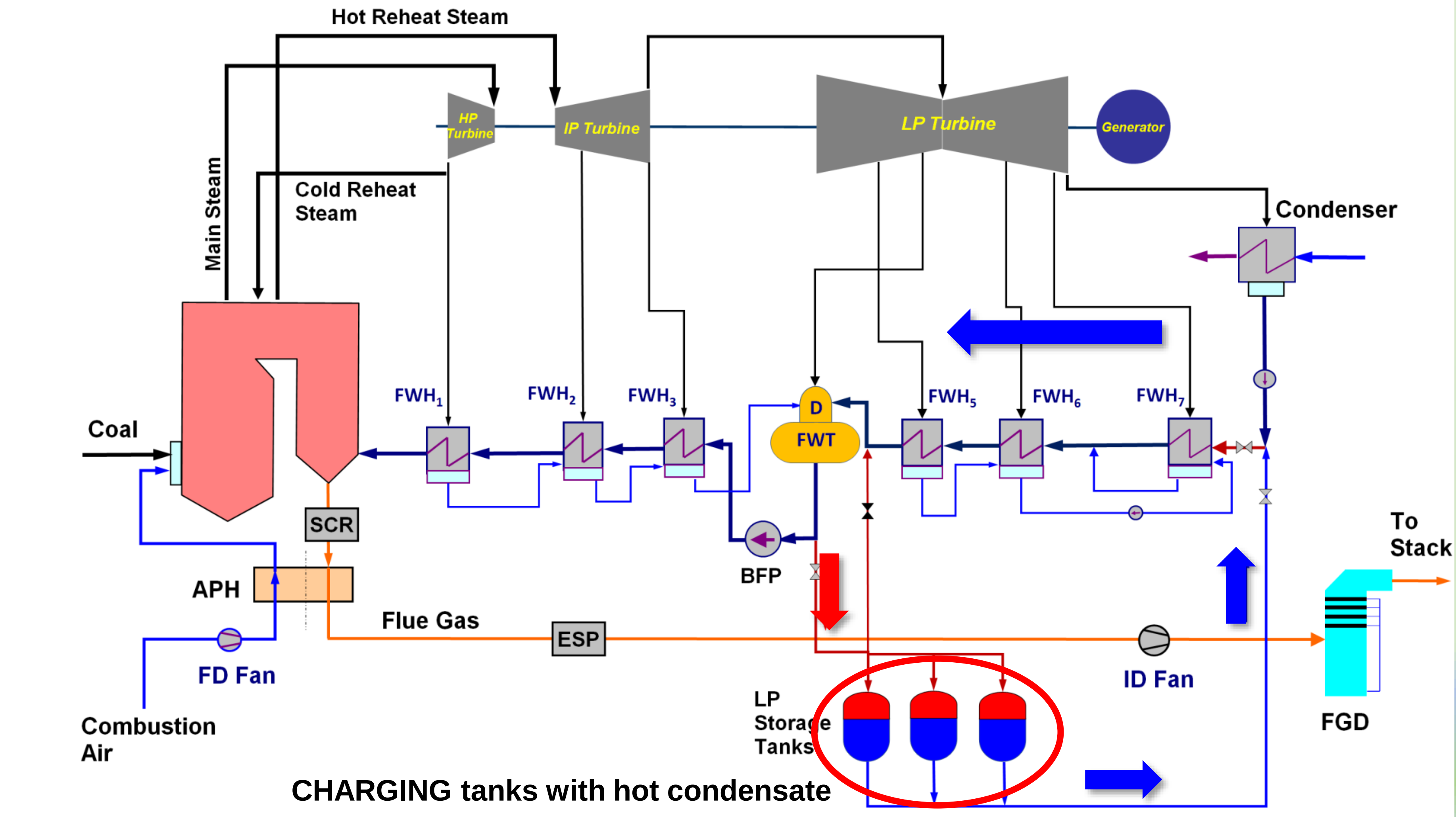
Ruths Steam Accumulator (RSA)



RSA is **charged by the cold reheat (CRHT) steam** and discharged to the steam extraction line for HP FWH 2.

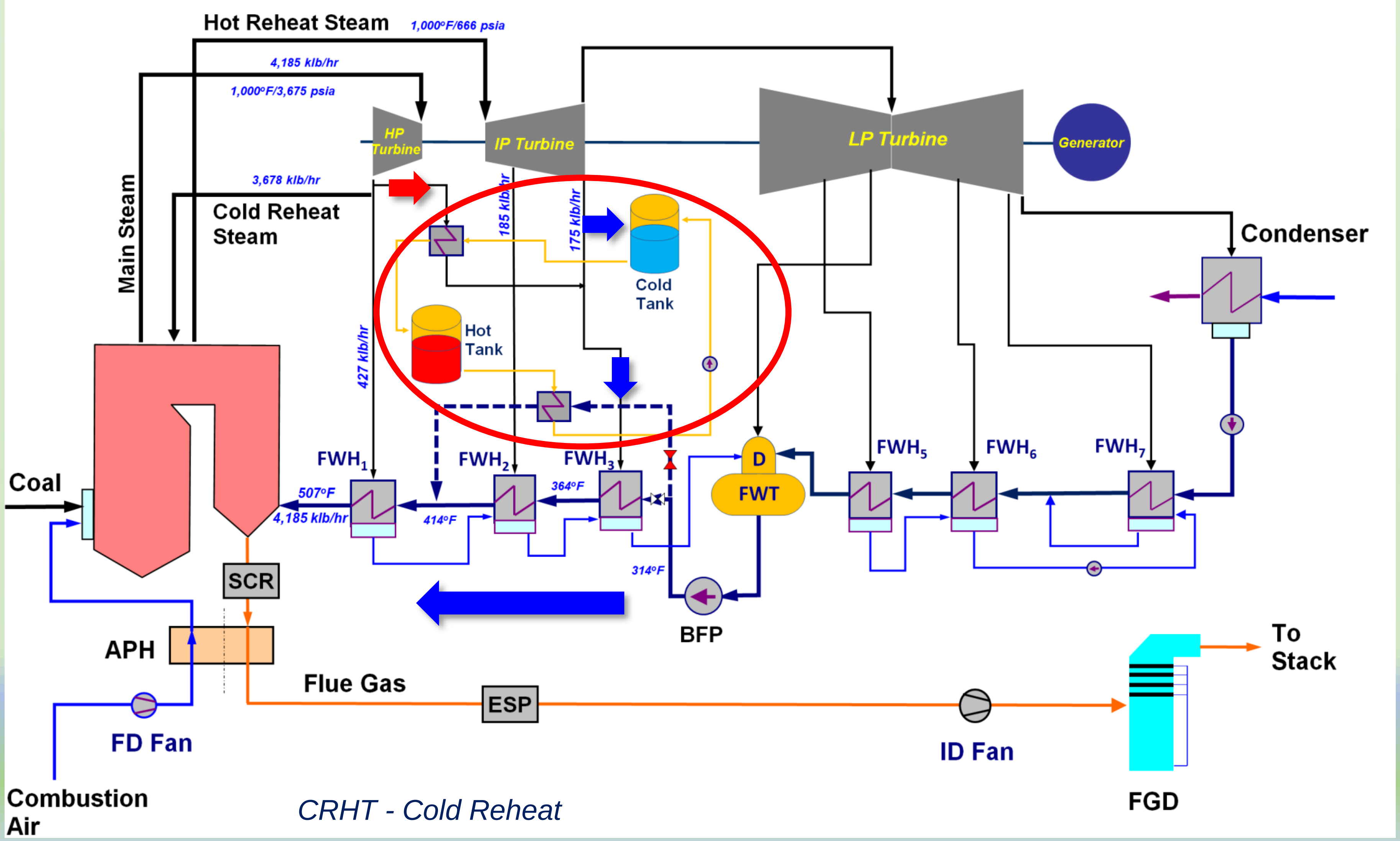
- *RSA is a* ***TES*** *technology characterized with variable pressure operation and the release of saturated steam when discharged.*
- *RSA can provide high power output and very good dynamic response with relatively limited storage capacity*.*
- ***During RSA charging, plant power output is decreased.***
- ***RSA discharging results in fast increase in power output.***
- *The magnitude of load increase-decrease depends on the RSA storage capacity.*
- *Integrating RSA with a coal-fired power plant offers improvement in the short-term dynamic behavior of the plant, enables fast load changes, and plant participation in the primary frequency control.*

Low Pressure (LP) Condensate Storage



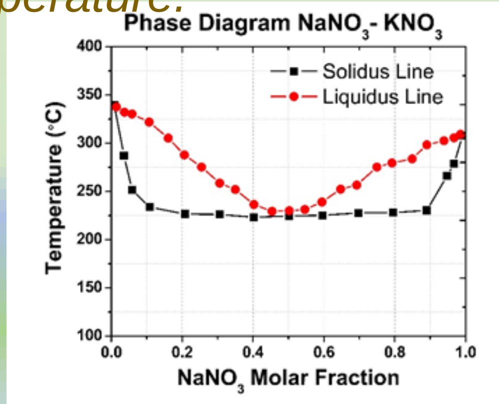
- *When plant power output needs to be reduced, the storage tanks are filled with hot condensate, taken from the outlet stream of the feedwater storage tank (**FWT**).*
- *Storage tanks operate at low pressure.*
- *The condensate mass flow through the **LP FWHs** to **FWT** is increased.*
- *Steam extractions from the **IP** and **LP turbines** are increased, reducing power output.*

Molten Solar Salt TES

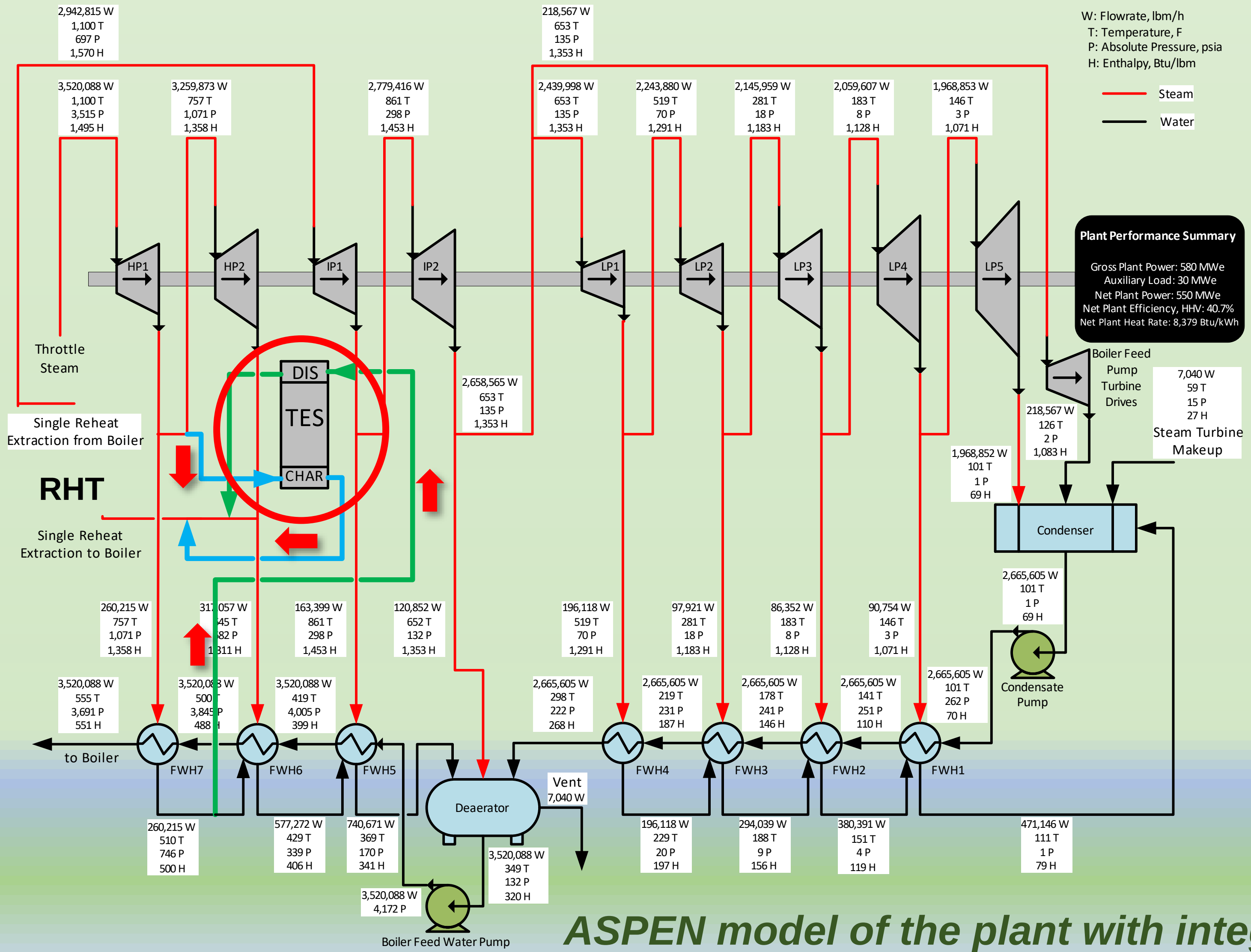


CRHT - Cold Reheat

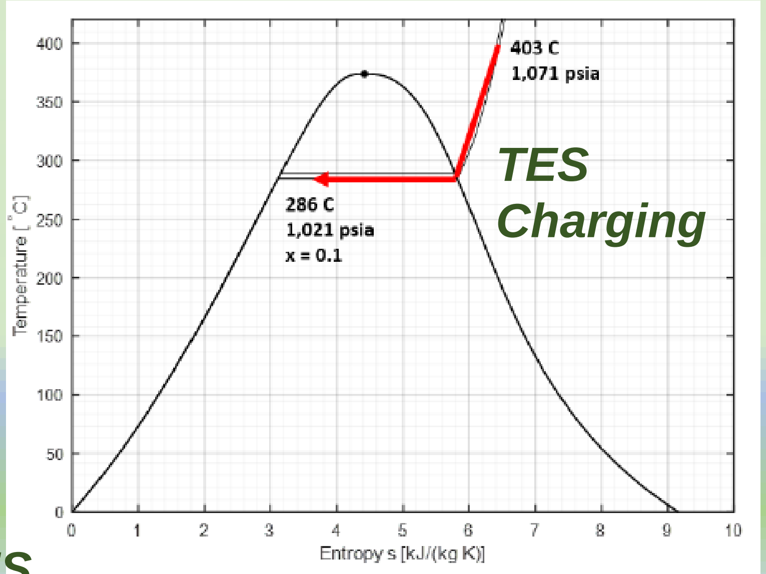
- *During **TES** charging with **CRHT steam**, plant power output is reduced because of the reduced steam flow through the **IP and LP turbines**.*
- *Steam extractions for **HP FWHs 1, 2, and 3** increase due to higher feedwater flow.*
- *Temperature of the steam leaving TES must be higher than the salt freezing temperature.*



Solid State (SS) TES

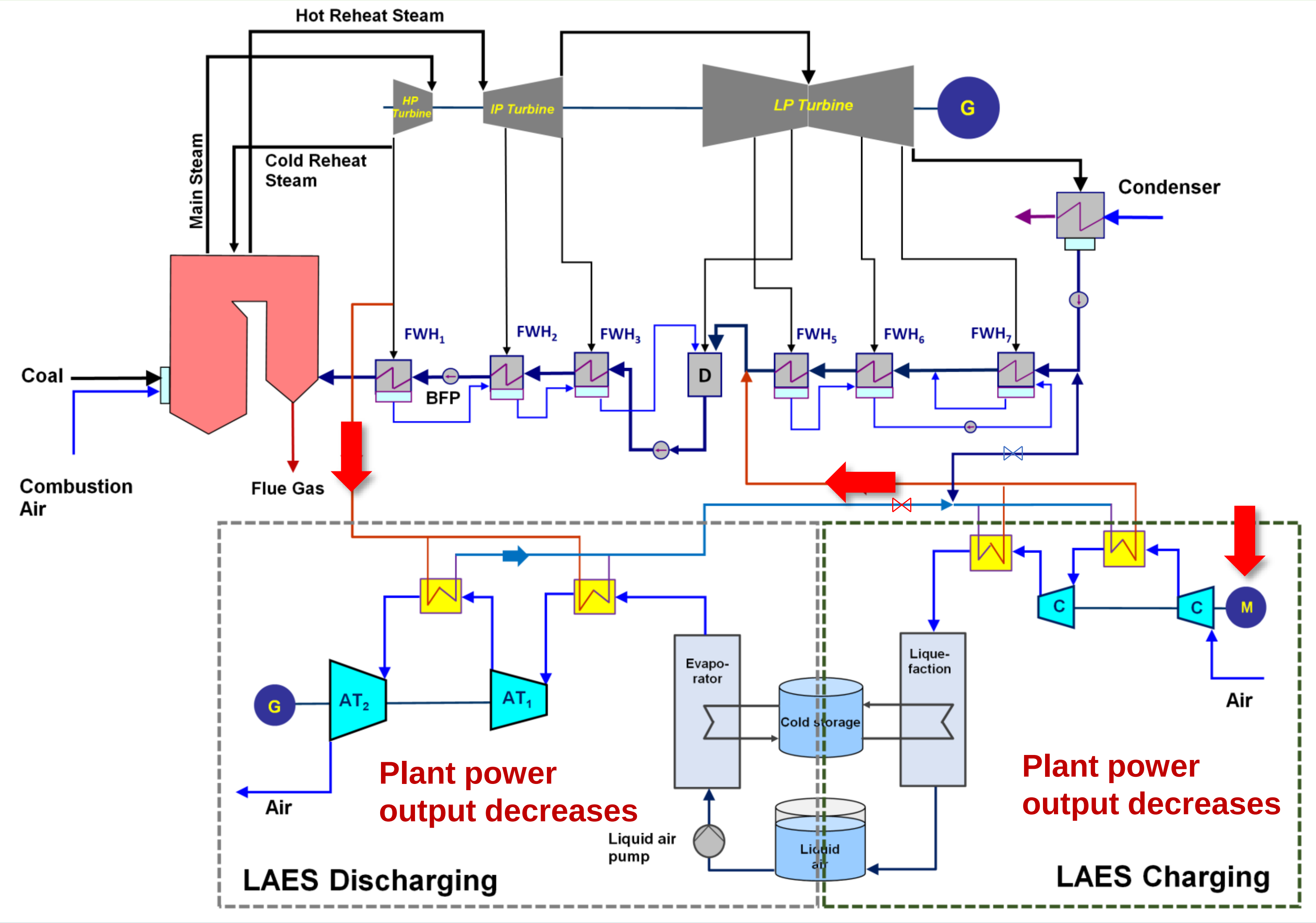


- *When a reduction in plant power output is needed, **TES** is charged by the steam extracted from the steam turbine cycle reducing steam flow through the **IP** and **LP** turbines and decreasing power output.*
- *When the plant power output needs to be increased, a portion of the **HP FWH7** drain is diverted through the **TES** where is heated and evaporated by the stored heat.*



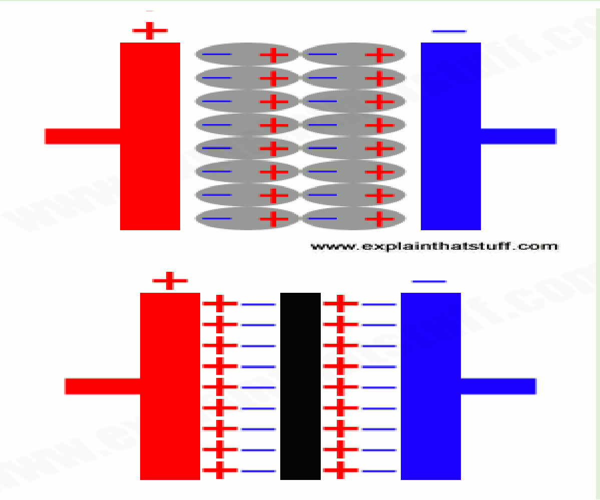
ASPEN model of the plant with integrated TES.

Liquid Air Energy Storage (LAES)



- *When plant power output needs to be decreased, **LAES** is operated in the charging mode where part of the plant power output is used for air compression.*
- *The compression heat is used for feedwater heating to improve system efficiency and simplify the **LAES** system because hot storage is not needed.*
- *When higher plant power output is needed, **LAES** is discharged by pumping liquid air from the storage tank, evaporating it, and superheating it by using steam extracted from the **HP turbine**. Condensed HP steam is used to heat the feedwater.*
- *By storing energy in the liquid air tank and discharging it when power is needed, LAES acts as a buffer absorbing part of the variations load profile the plant needs to follow thus increasing plant flexibility.*

Battery- Super-capacitor Energy Storage



Capacitors store energy as an electrostatic charge between two plates separated by a dielectric. They have low voltage, low energy but high-power density. Can be charged & discharged very quickly.

- *Super-capacitors get their bigger capacitance from plates with a bigger, effective surface area (advances in material science) and smaller distance between plates (because of the very effective double layer).*
- *Can be charged and discharged any number of times (close to a million), have little or no internal resistance, store and release energy without using much energy, and work at very close to 100% efficiency (97–98% is typical) and have capacitance running in several thousand Faradays.*
- *Super-capacitors have very high power but limited energy. In combination with a battery, super-capacitors provide very high power, and the battery provides longer duration energy.*
- *Commercial products are available for use with solar and wind generators that need instantaneous power to compensate for sudden variations in these power output; and meet need for longer duration energy when solar and wind are not present.*

Technical Approach

- ***To achieve the project objectives, project tasks are divided into two groups.***

Technical Analysis

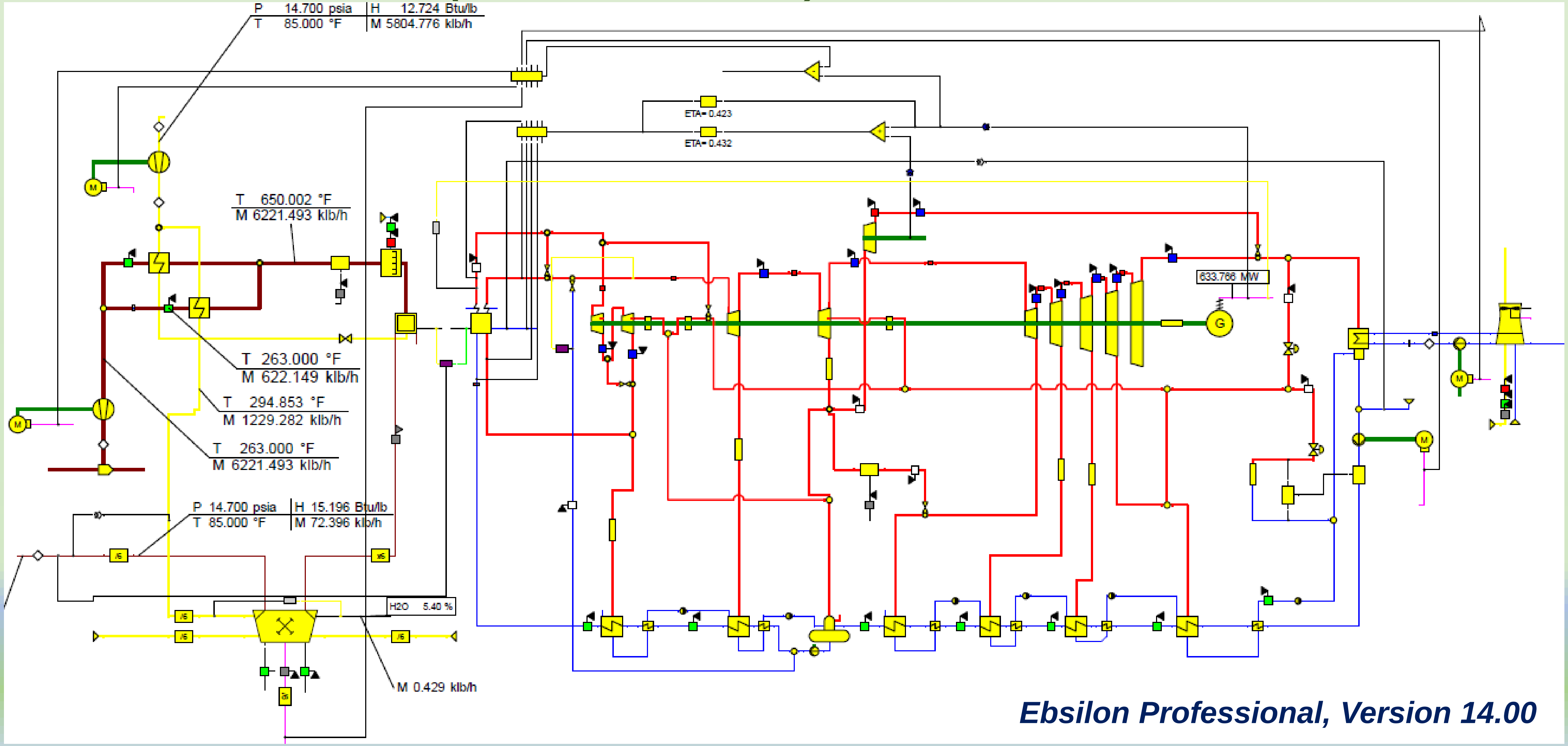
- *Build a first principles model of a reference plant to determine baseline performance (plant performance w/o IES) over the load range.*
  - *Use model results to develop **baseline** performance curves: Input-Output (**I-O**) and Incremental Cost (**IC**) curves.*
- *Integrate ES into the reference plant model and determine plant performance.*
  - *Develop **modified I-O** and **IC** curves for a plant with **IES** (Integrated Energy Storage).*

Economic Analysis

- *Use **IC** curves in combination with actual grid and market price data to simulate operation of the reference plant in the PJM and MISO energy markets and determine plant economics without and with **IES** under realistic market conditions.*
  - *Economic benefits will include cost savings due to the efficiency improvements, emission reduction, and additional revenues due to increased plant flexibility from the integration of ES.*
  - *The ancillary services revenues will largely result from the improved plant IC curves as applied to system dispatch.*

Technical Approach - Plant Model

Model of the Reference Plant (650 MW subcritical)



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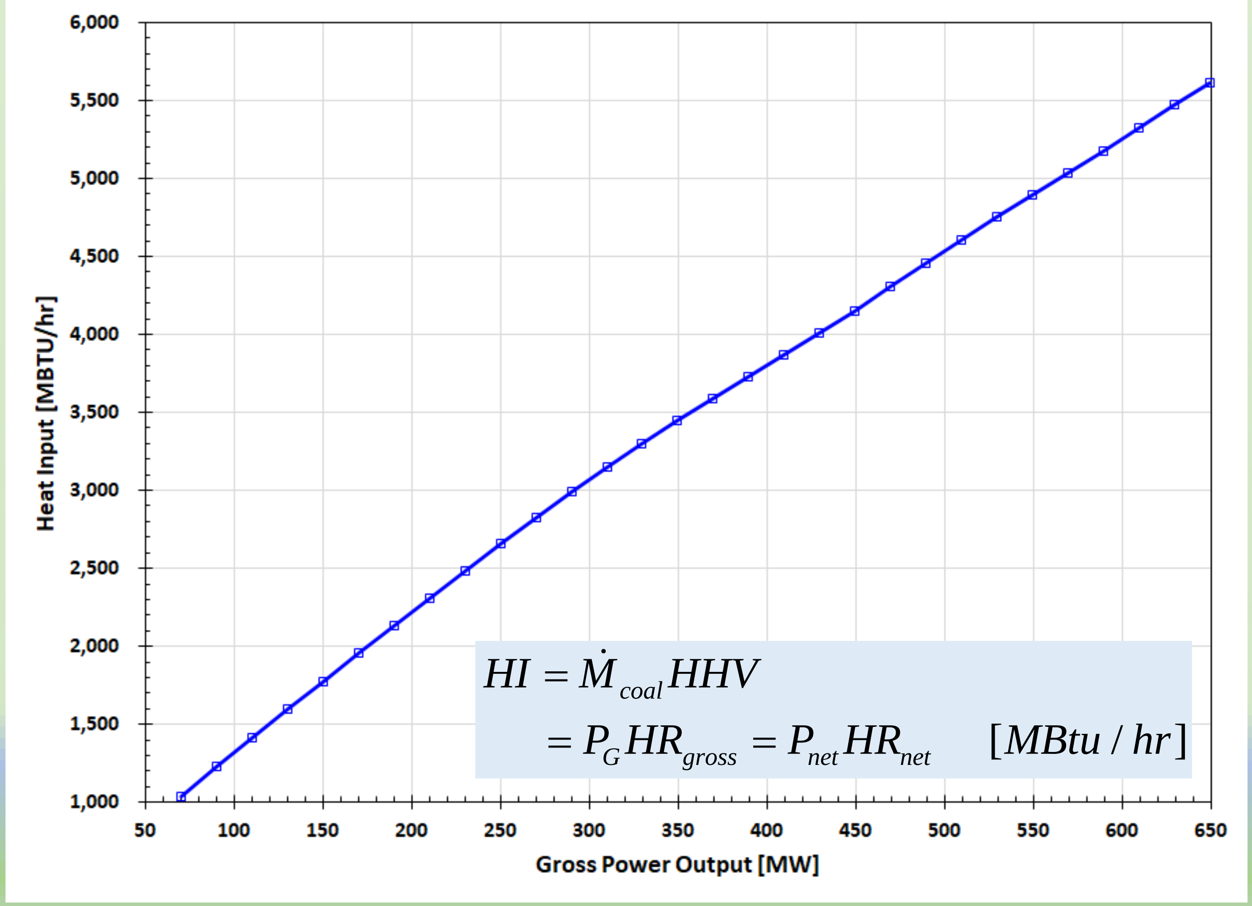
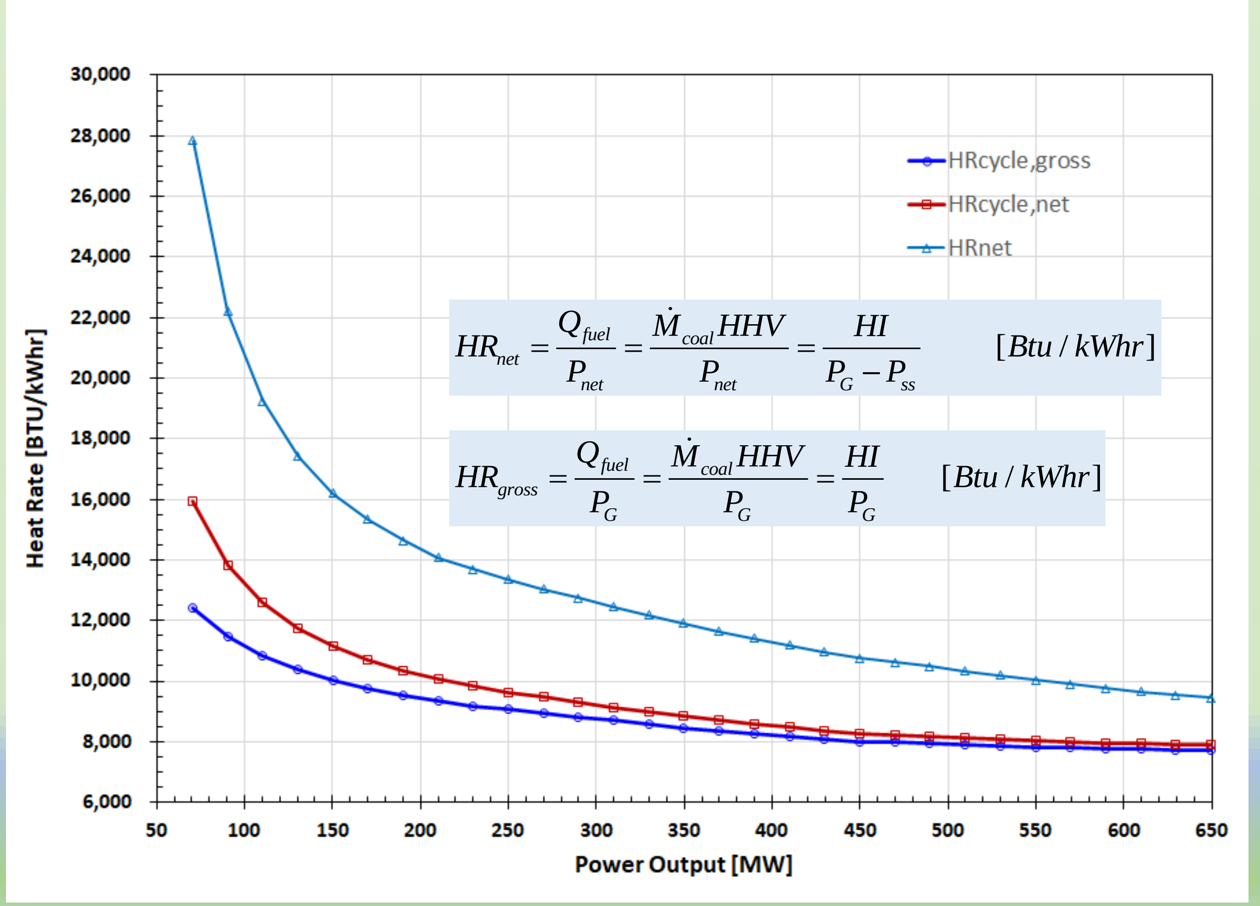
Technical Approach – Preliminary Results

Input-Output (I-O) Curve



$$HI = \dot{M}_{coal} HHV = P_G HR_{gross} = P_{net} HR_{net} \quad [MBtu / hr]$$

Heat Rate (HR) Curves



$$HR_{net} = \frac{Q_{fuel}}{P_{net}} = \frac{\dot{M}_{coal} HHV}{P_{net}} = \frac{HI}{P_G - P_{ss}} \quad [Btu / kWhr]$$

$$HR_{gross} = \frac{Q_{fuel}}{P_G} = \frac{\dot{M}_{coal} HHV}{P_G} = \frac{HI}{P_G} \quad [Btu / kWhr]$$

Project Tasks

- ***Task 1.0*** *– Project Management*
  - ***Subtask 1.1*** *– Project Management Plant (PMP)* ►*Done*
- ***Task 2.0*** *– Determination of Baseline Performance*
  - ***Subtask 2.1*** *- Development of Reference Plant Model* ► *In Progress*

    *A model of the reference coal-fired power plant without energy storage will be developed. Model results will be verified against plant design data. The model will be used to determine benchmark performance of the Reference plant and establish baseline Input/Output (**I-O**) and Incremental Cost (**IC**) curves.*

  - ***Subtask 2.2*** *- Determination of Baseline Economic Performance*

    *An economic analysis of the selected Reference plant without energy storage will be performed using the **IC** curve developed in **Subtask 2.1** in combination with the actual grid and market price data to simulate operation of the Reference plant in selected energy markets and determine baseline plant economics under realistic operating conditions. A plant-level and system-level analyses will be performed.*

Project Tasks

- ***Task 3.0*** *– Integrated Thermal Energy Storage (TES)*
  - ***Subtask 3.1*** *– Determination of Technical Performance for Thermal Energy Storage (TES) Options*

    *Integrate the selected energy storage options into the reference plant model developed in **Subtask 2.1** to determine the effect of energy storage on plant operation and performance. The selected energy storage options include:*

    - ***Subtask 3.1.1*** *– Ruths Steam Accumulator (RSA)*
    - ***Subtask 3.1.2*** *– Low Pressure Condensate Storage*
    - ***Subtask 3.1.3*** *– Molten Salt TES*
    - ***Subtask 3.1.4*** *– Solid-State TES*
  - ***Subtask 3.2*** *- Determination of Economic Performance for TES*

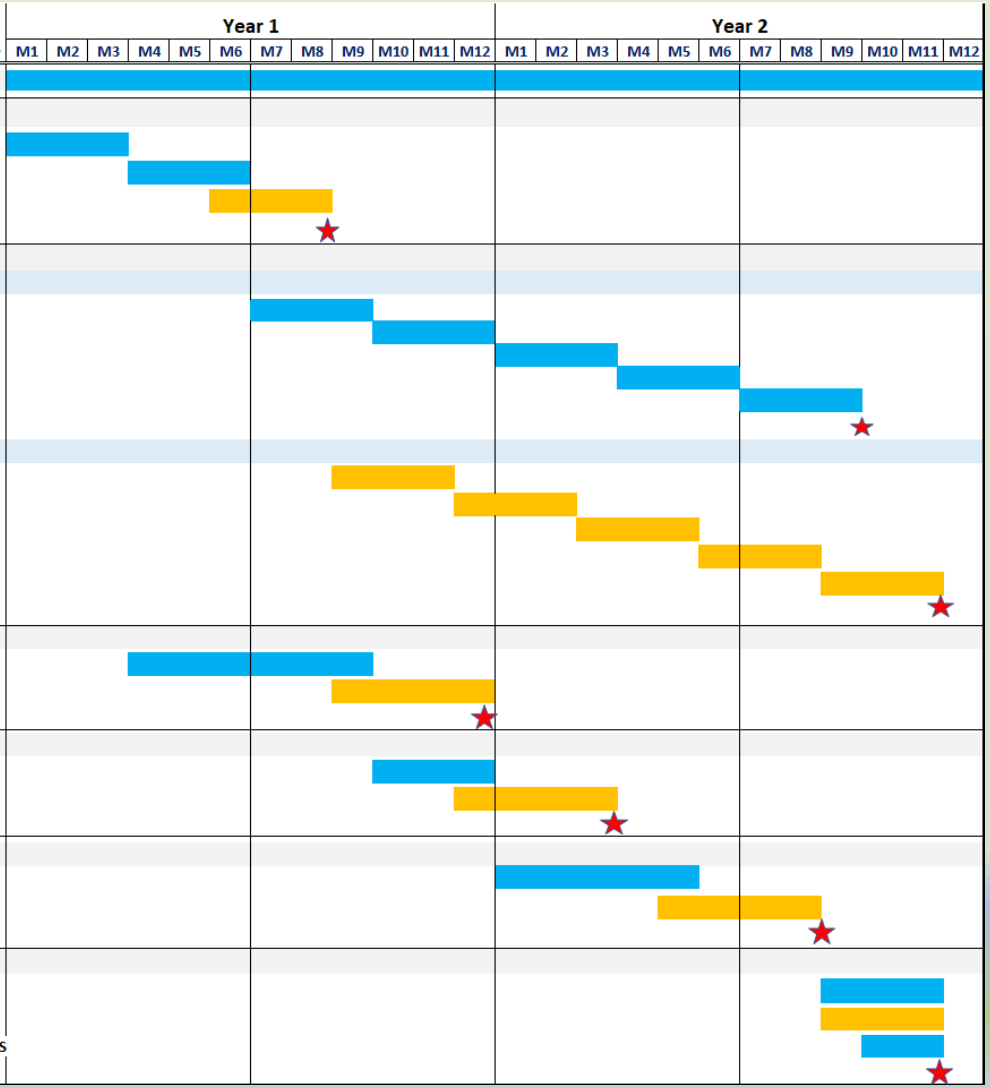
    *Economic analysis of the integrated TES options from **Subtasks 3.1.1** to **3.1.4** to determine plant economics under realistic energy market conditions. Determine the effect of TES storage capacity on economic performance. The analysis will be divided into **Subtasks 3.2.1** to **3.2.4**.*

Project Tasks

- ***Task 4.0*** *– Integrated Liquid Air Energy Storage (LAES)*
  - ***Subtask 4.1*** *– Determination of Technical Performance*
  - ***Subtask 4.2*** *– Determination of Economic Performance*
- ***Task 5.0*** *– Battery/Supercapacitor Energy Storage*
  - ***Subtask 5.1*** *– Determination of Technical Performance*
  - ***Subtask 5.2*** *– Determination Economic Performance*
- ***Task 6.0*** *– Hydrogen Energy Storage (H_2ES)*
  - ***Subtask 6.1*** *– Determination of Technical Performance*
  - ***Subtask 6.2*** *– Determination Economic Performance*
- ***Task 7.0*** *– Analysis of Results*

Project Schedule

Task No. / Task Name/Activity	Assigned Resources
Task 1.0 - Project Management and Planning	UNCC and LU
Task 2.0 - Determination of Basic Performance	
Subtask 2.1 Development of the Reference Plant Model	UNCC and LU
Subtask 2.2 Determination of Baseline Technical Performance	UNCC and LU
Subtask 2.3 Determination of Baseline Economic Performance	CES
Milestone 1	
Task 3.0 - Integrated Thermal Energy Storage (TES)	
Subtask 3.1 TES – Technical Performance	UNCC
3.1.1 Reference Plant with Integrated Ruths Steam Accumulator	UNCC
3.1.2 Reference Plant with Integrated Pressurized Water TES	UNCC
3.1.3 Reference Plant with Integrated Molten Salt TES	UNCC
3.1.4 Reference Plant with Integrated Solid-State TES	UNCC
3.1.5 Reference Plant with Integrated TES Combinations	UNCC
Milestone 2	
Subtask 3.2 TES – Economic Performance	CES
3..2.1 Reference Plant with Integrated Ruths Steam Accumulator	CES
3.2.2 Reference Plant with Integrated Pressurized Water TES	CES
3.2.3 Reference Plant with Integrated Molten Salt TES	CES
3.2.4 Reference Plant with Integrated Solid-State TES	CES
3.2.5 Reference Plant with Integrated TES Combination	CES
Milestone 3	
Task 4.0 - Integrated Liquid Air Energy Storage (LAES)	
Subtask 4.1 LAES – Technical Performance	LU
Subtask 4.2 LAES – Economic Performance	CES
Milestone 4	
Task 5.0 - Battery/Supercapacitor Energy Storage	
Subtask 5.1 Battery/Supercapacitor Storage - Technical Performance	LU and CES
Subtask 5.2 Battery/Supercapacitor Storage - Economic Performance	CES
Milestone 5	
Task 6.0 - Hydrogen Energy Storage (H2ES)	
Subtask 6.1 Hydrogen – Technical Performance	LU and APCI
Subtask 6.1 Hydrogen – Economic Performance	CES, LU, APCI
Milestone 6	
Task 7.0 - Anlysis of Results	
Analysis of Technical Results and Final Report	UNCC and LU
Analysis of Economic Results	CES
Joint Techno-Economic Analysis	UNCC, LU, CES
Milestone 7	



***Subtasks 3.1** and **3.2** are inter-related and will be performed in a parallel-staggered sequence and in close cooperation between UNCC and CES.*

Stars denote milestones.

PMP: Milestones

Task	Milestone Title & Description	Planned Completion Date (relative to project start)	Verification method
2.0	**Milestone 1**: Determination of Basic Performance	8 months after project start date	Compare project results to the actual energy market indicators, results from previous work, and information from the literature.
3.0	**Milestone 2**: Integrated TES – Technical Performance (Subtasks 3.1.1 and 3.1.4)	21 months after project start date	
3.0	**Milestone 3**: Integrated TES – Economic Performance (Subtasks 3.2.1 and 3.2.4)	23 months after project start date	
4.0	**Milestone 4**: Integrated LAES	12 months after project start date	
5.0	**Milestone 5**: Integrated Battery/Super Capacitor	16 months after project start date	
6.0	**Milestone 6**: Hydrogen Energy Storage	20 months after project start date	
7.0	**Milestone 7**: Analysis of Results	23 months after project start date	

Progress reports will be delivered according to the reporting schedule.

PMP: Milestones

- ***Milestone 1*** *will be reached upon completion of **Task 2**, which consists of three subtasks: Development of the Reference Plant Model, Determination of Baseline Technical Performance, and Determination of Baseline Economic Performance.*

  Baseline plant performance will be combined with actual grid and market plant data to determine baseline plant economics. The plant baseline economic performance indicators will be compared to the actual indicators from the energy market.

- ***Milestone 2*** *will be reached upon the completion of **Subtask 3.1**, which includes determination (simulation) of performance of the reference plant with integrated thermal energy storage.*

  The results will be verified against information from the literature.

- ***Milestone 3*** *will be reached after completion of **Subtask 3.2** where economic performance of the energy storage options will be determined by combining technical performance indicators with actual grid and market price data to determine plant economics under realistic conditions in the energy market.*

  The predicted economic indicators will be compared to the actual indicators from the energy market.

PMP: Milestones

- ***Milestones 4, 5 and 6*** *are related to the technical and economic evaluation of the Battery-Supercapacitor, Integrated Liquid Air Energy Storage (**LAES**) also referred to as Cryogenic Energy Storage (CES), and Hydrogen Energy Storage (**H2ES**) options.*

  Evaluation of the battery-supercapacitor option will be led by CES, who has a significant experience in evaluation of this technology. The results will be compared to the previously completed studies.

  LAES *is relatively novel technology and analysis of its technical performance will require close collaboration between UNCC and Lehigh University. The results will be compared to the information from the literature.*

  *The analysis of the Hydrogen energy storage (**H2ES**) option will be led by Lehigh University and Air Products and Chemicals, Inc (APC). APCI is a world leader in hydrogen production and storage and the project will rely on their experience in analysis of this energy storage option.*

Deliverables

- ***Periodic and final reports*** *will be submitted in accordance with the Federal Assistance Reporting Checklist.*
- *Project Management Plan (**PMP**) will be updated 30 days after project award. Revisions to the PMP will be submitted as requested by the NETL program manager.*
- *Technology Maturation Plan (**TMP**) will be updated within 90 days of award. Revisions to the TMP will be submitted as requested by the NETL program Manager.*

Acknowledgment and Disclaimer

Acknowledgment

- *This presentation is based upon work supported by the Department of Energy under Award Number DE-FE0031903.*
- *The Project Manager is **Mr. Jason C. Hissam**.*

Conclusions and Comments

- *The increased share of feed-in from variable and non-dispatchable renewable energies results in complex challenges for the energy system.*
- *In addition to other options such as grid and demand-side management, flexible conventional power generation plays a key role for ensuring adequate system stability.*
- *Energy storage integrated with the plant (**IES**) is an option that will play an important role in improving the flexibility of fossil power plants.*
  - *Flexible power plant operation comprises minimum load operation, short and efficient start-ups and shut-downs, increased load ramp rates, and peak power when needed.*
- ***IES** partially decouples the plant power output from the boiler firing rate improving plant dynamic response.*
- *The energy storage options selected for analysis include: Thermal Energy Storage, Liquid Air Energy Storage, Battery Storage in combination with Super-capacitors, and Hydrogen Energy Storage.*

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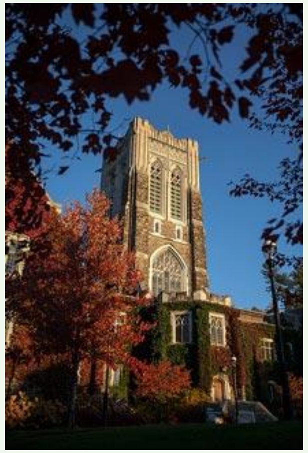

Questions?