Techno-Economic and Deployment Analysis of Fossil Fuel-Based Power Generation with Integrated Energy Storage - DE-FE0031903

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Project Objectives

The main project objective

- *Analyze selected energy storage options integrated with a Reference coal-fired power plant to determine their impact on the plant operation, performance and economics.*

The specific objectives

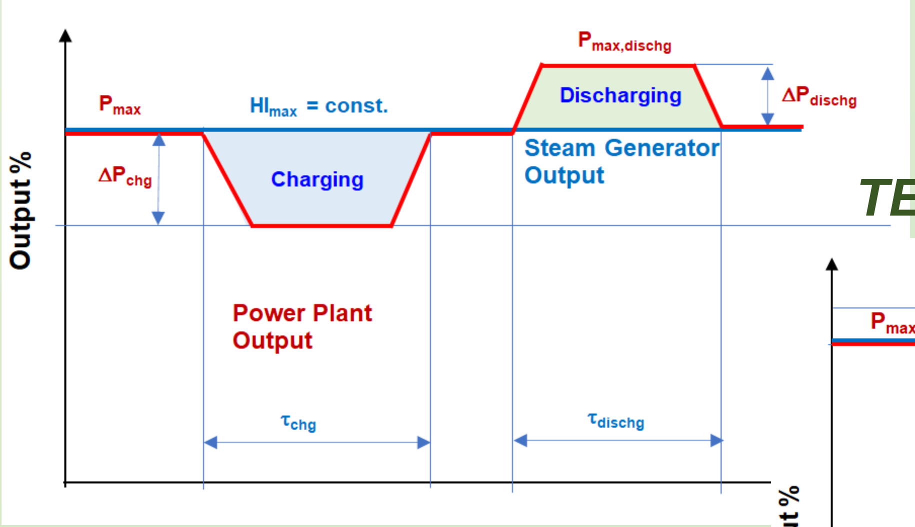
- *Establish baseline technical and economic performance of a 645 MW_{gross} reference coal-fired plant.*
  - *Model a **refence plant** and determine its technical performance.*
  - *Determine economic performance of the reference plant operating in the **PJM** and **MISO** energy markets.*
- *Integrate selected **ES** technologies into the reference plant design.*
- *Determine **technical** and **economic benefits** associated with the Integrated Energy Storage (**IES**) for constant heat input.*
  - *Improved plant flexibility and performance*
  - *Increased plant participation in the Ancillary Services market*
  - *Reduced emissions*

Technical Approach

- *Model of a subcritical 645 MW_{gross} Reference coal-fired power plant fueled by Eastern Bituminous coal was developed using Ebsilon Professional and ASPEN Plus modeling platforms.*
  - *Reference plant model was validated by using design data for the Reference plant.*
  - ***Ebsilon Professional** and **ASPEN Plus** were used to thermally integrate plant model with TES systems.*
- *Performance of the Reference plant with and without integrated TES system (IES) was simulated over the range of unit loads, concentrating on the full and minimum loads to determine plant and TES performance and the effect of IES on plant performance and flexibility.*
  - *The analysis was performed by assuming constant heat input to the plant.*
  - *TES system performance parameters included flow rate, temperature, and pressure of the charging and discharging fluids (steam, condensate, or air), thermal storage media (condensate, molten salt, crushed rock, and air), and roundtrip efficiency.*
  - *Plant performance parameters included net power output, net heat rate and net efficiency, and steam extraction flows. The analysis was performed by assuming constant heat input to the plant and steam turbine cycle.*

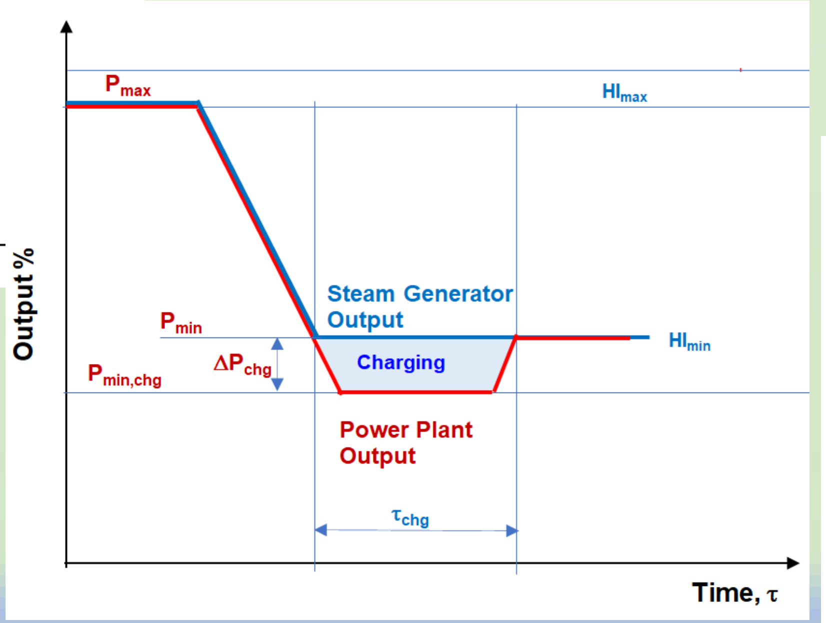
Technical Approach: Investigated Scenarios

TES Charged and Discharged at Full Load



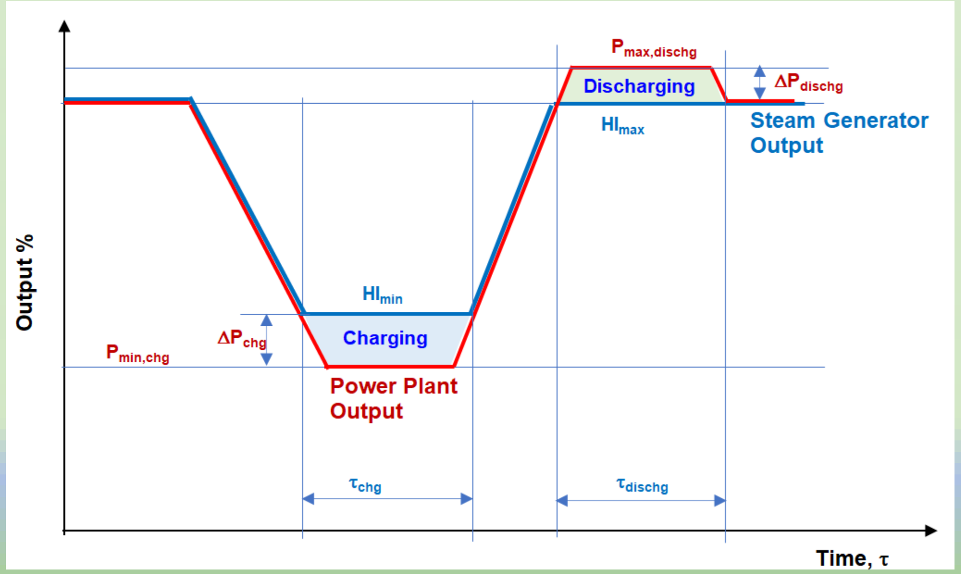
Increases max plant power output and improves load following (frequency regulation)

TES Charged at Min Load



Lowers min plant power output

TES Charged at Minimum Load and Discharged at Full Load



Load Shift

Technical Approach: TES Roundtrip Efficiency

- *The roundtrip **power-to-power** efficiency η_{PP} can be determined as*

$$\eta_{PP} = \frac{\int \Delta P_{net,dchg}}{\int \Delta P_{net,chg}}$$

- *The roundtrip **energy-to-energy** efficiency η_{RTE} can be determined as*

$$\eta_{RTE} = \frac{\int_0^{\tau_{dchg}} \Delta P_{net,dchg}(t)\,dt}{\int_0^{\tau_{chg}} \Delta P_{net,chg}(t)\,dt}$$

  - *Where $\Delta P_{net,chg}$ and $\Delta P_{net,dchg}$ are net power decrease during charging and net power increase during discharging, respectively, while τ_{chg} and τ_{dchg} are charging and discharging times.*
    - *For the steady net power increase and decrease, where values $\Delta P_{net,chg}$ and $\Delta P_{net,dschg}$ are constant during charging and discharging, η_{RTE} can be calculated from η_{PP} using*

$$\eta_{RTE} = \frac{\eta_{PP}}{f_z}$$

    - ***f_z** is the charging to discharging time ratio, which, for a constant volume/mass storage, can be expressed as a ratio of charging and discharging times, or discharging and charging flows.*

$$f_z = \frac{\tau_{chg}}{\tau_{dchg}} = \frac{\dot{m}_{dchg}}{\dot{m}_{chg}}$$

Energy Storage Options Selected for Analysis

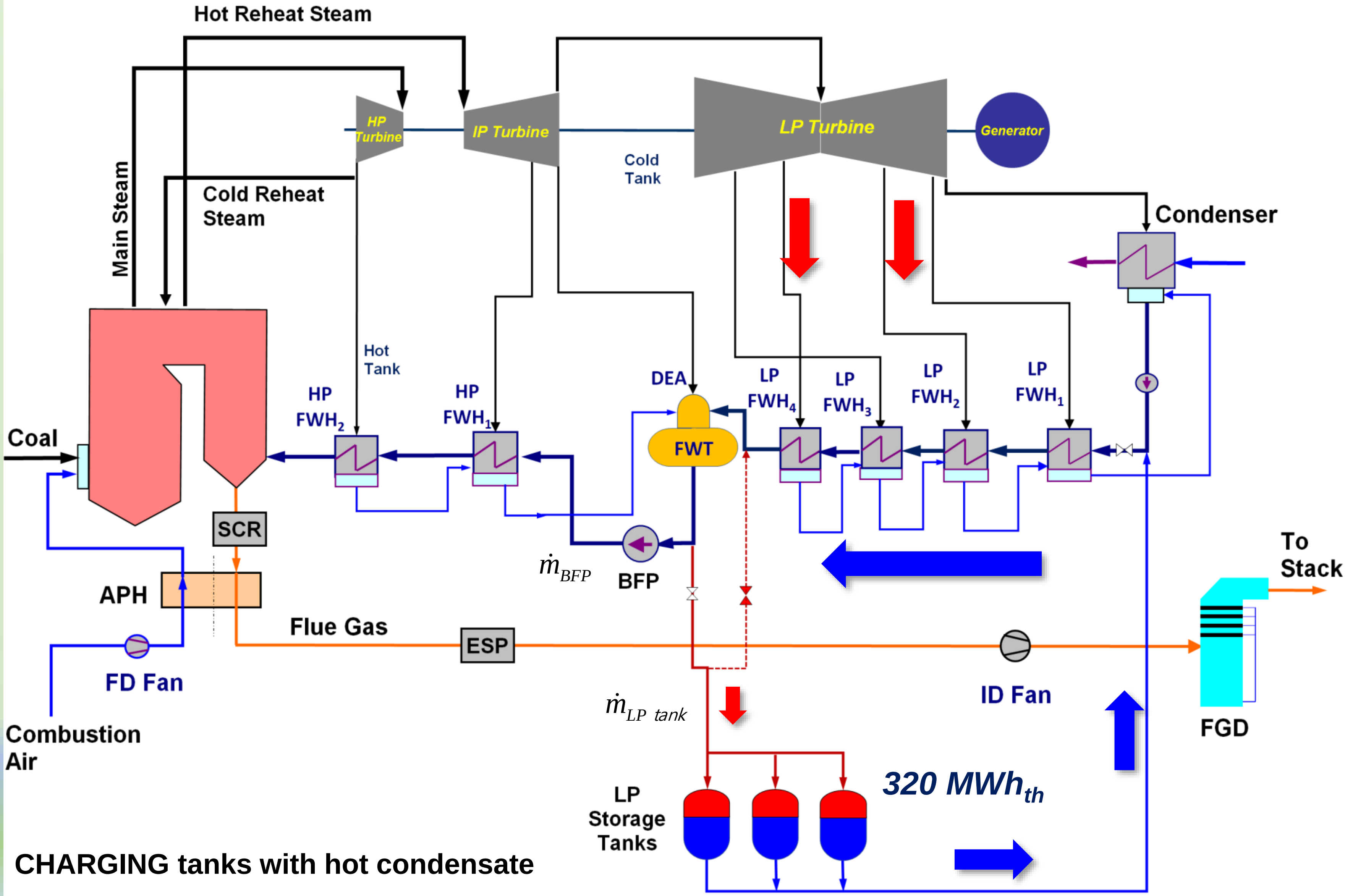
Energy storage technologies integrated with a Reference power plant selected for the analysis include:

- Thermal Energy Storage (TES)
  - Low Pressure (LP) Condensate Storage ► Technical analysis finished
  - Two-Tank Molten Solar Salt Storage ► Technical analysis finished
  - Fixed Bed ► Technical analysis finished
  - Ruths Steam Accumulator (RSA) ► Technical analysis finished
- Liquid Air Energy Storage (LAES) ► Technical analysis finished
- **Economic analysis** ► In progress
- Battery Energy Storage ► Technical and economic analysis finished
- Hydrogen Energy Storage (H_2ES) ► In progress

These energy storage systems represent a range of TES technologies and thermal energy storage media considered for integration with thermo-electric power plants.

Low Pressure (LP) Condensate Storage

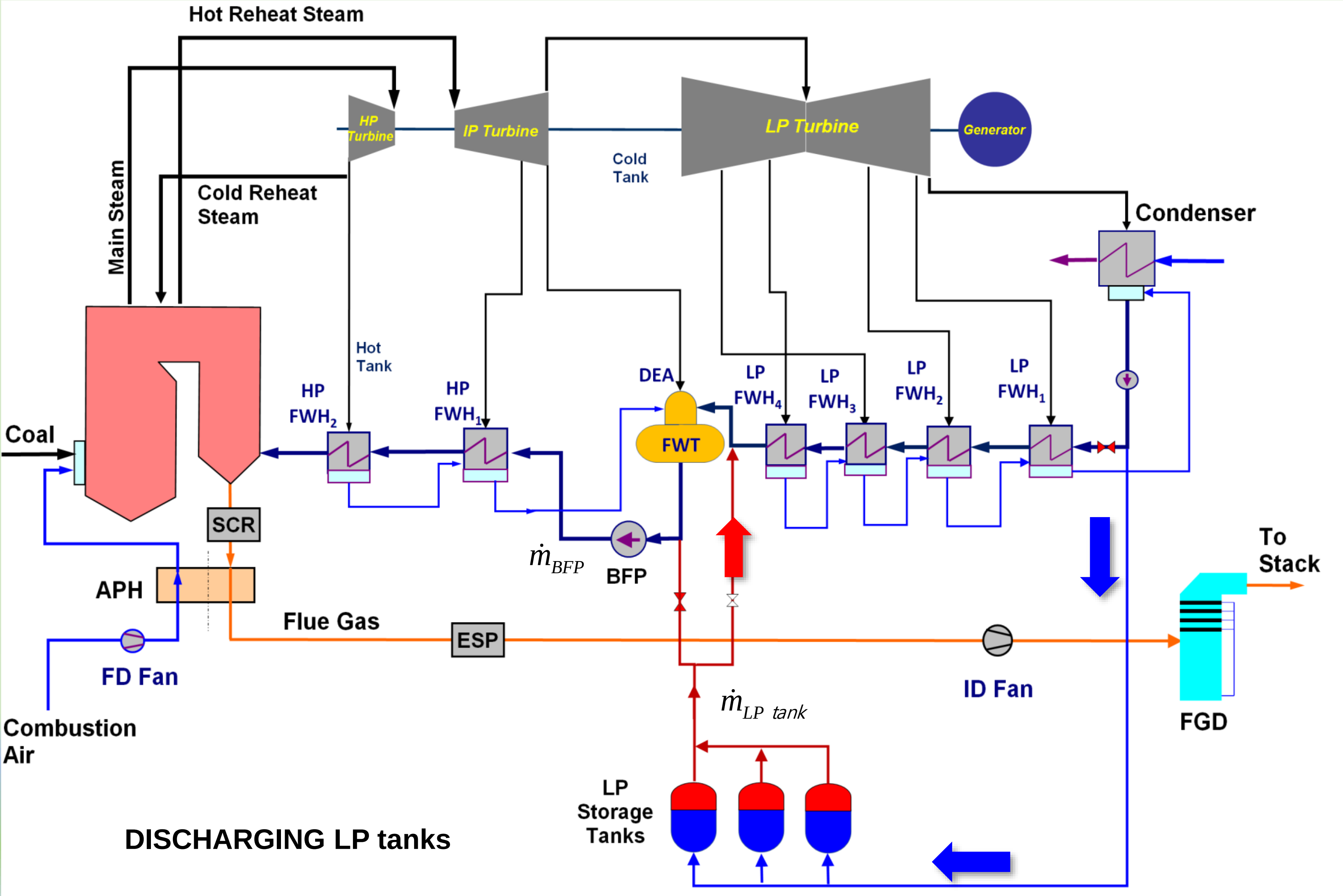
LP Condensate Storage



Charging

- *Steam generator operates at steady-state with constant heat input.*
- *To **decrease** plant power output, storage tanks are filled with hot condensate taken from the outlet stream of the feedwater storage tank (**FWT**).*
- *The condensate flow through the **LP FWHs** increases.*
- *Steam extractions from the **LP turbine** increase, decreasing power output.*
- *Storage tanks operate at low pressure.*
- ***Storage capacity***
  - ***320 MWh$_{th}$** (3 hrs of charging at full load).*
  - ***145 MWh$_{th}$** (3 hrs of charging at minimum load load).*

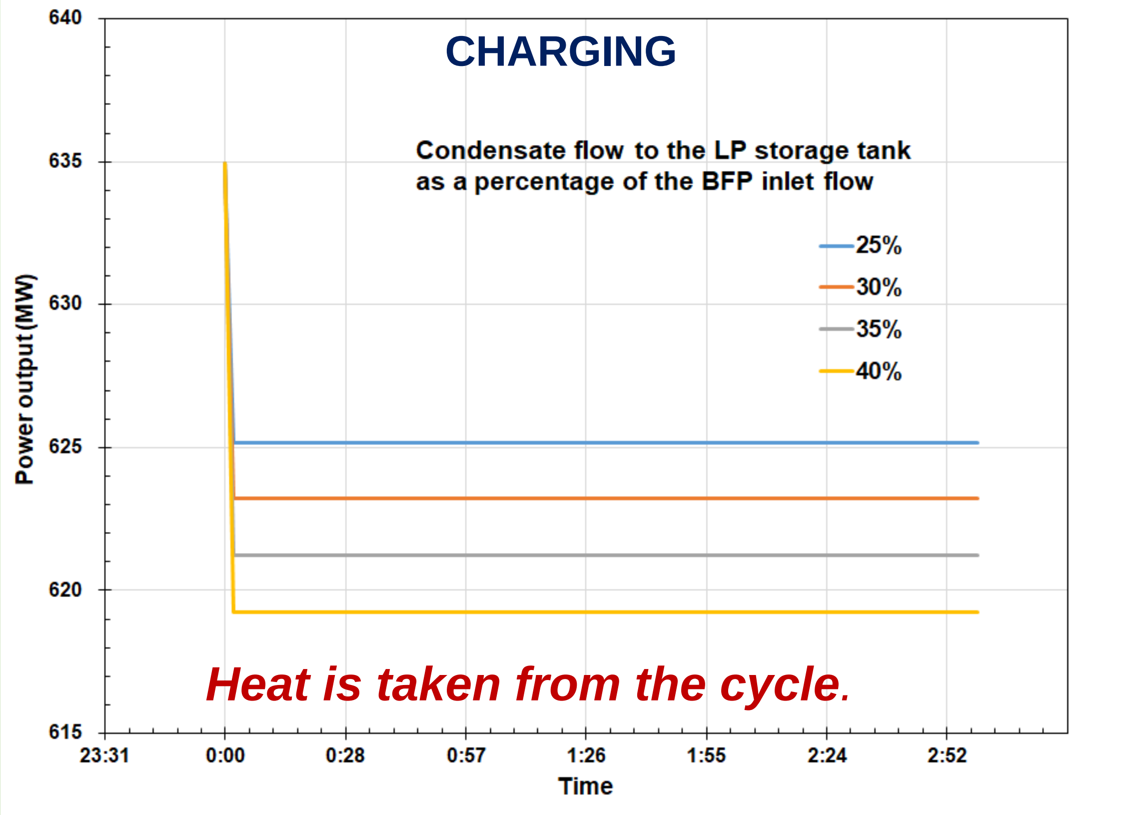
LP Condensate Storage



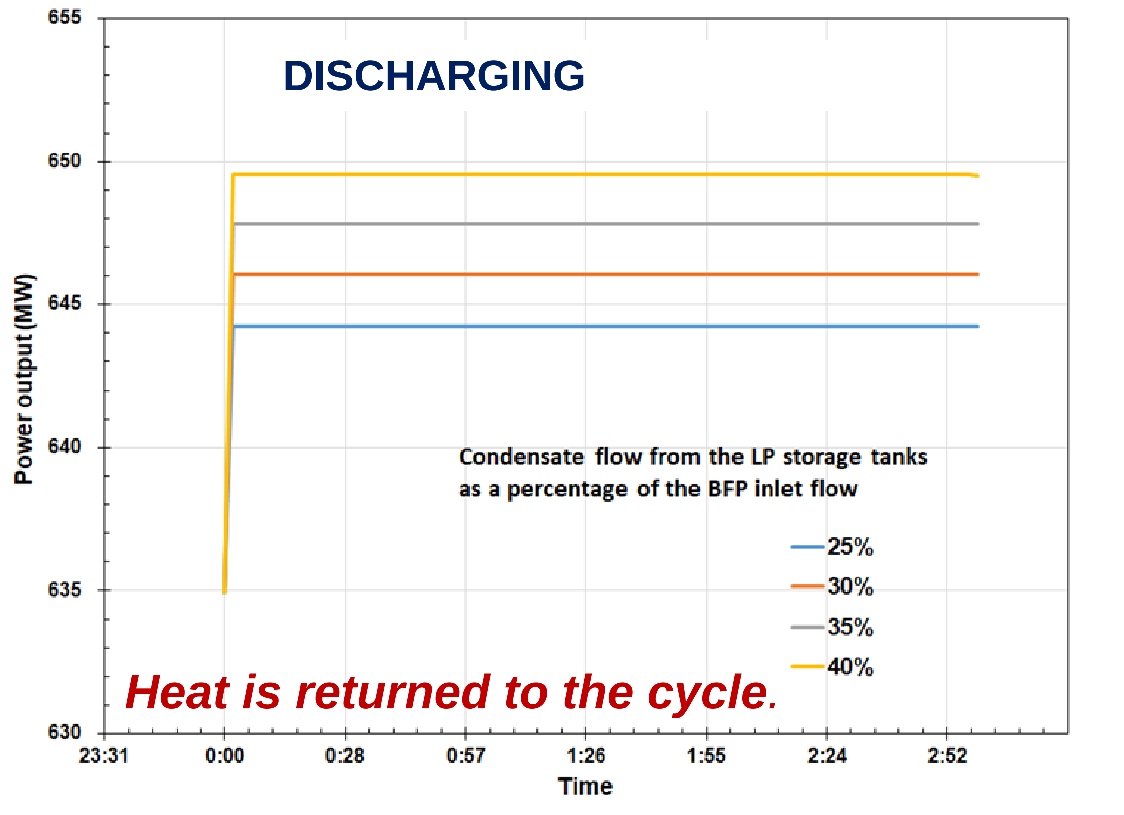
Discharging

- *Steam generator operates at steady-state with constant heat input.*
- *To **increase** plant power output, hot condensate stored in the tanks is discharged into the main condensate line upstream of the deaerator.*
- *Heat is returned to the cycle.*
- *The condensate flow through the **LP FWHs** decreases.*
- *Steam extractions from the **LP turbine** decrease, increasing power output.*

LP Condensate Storage

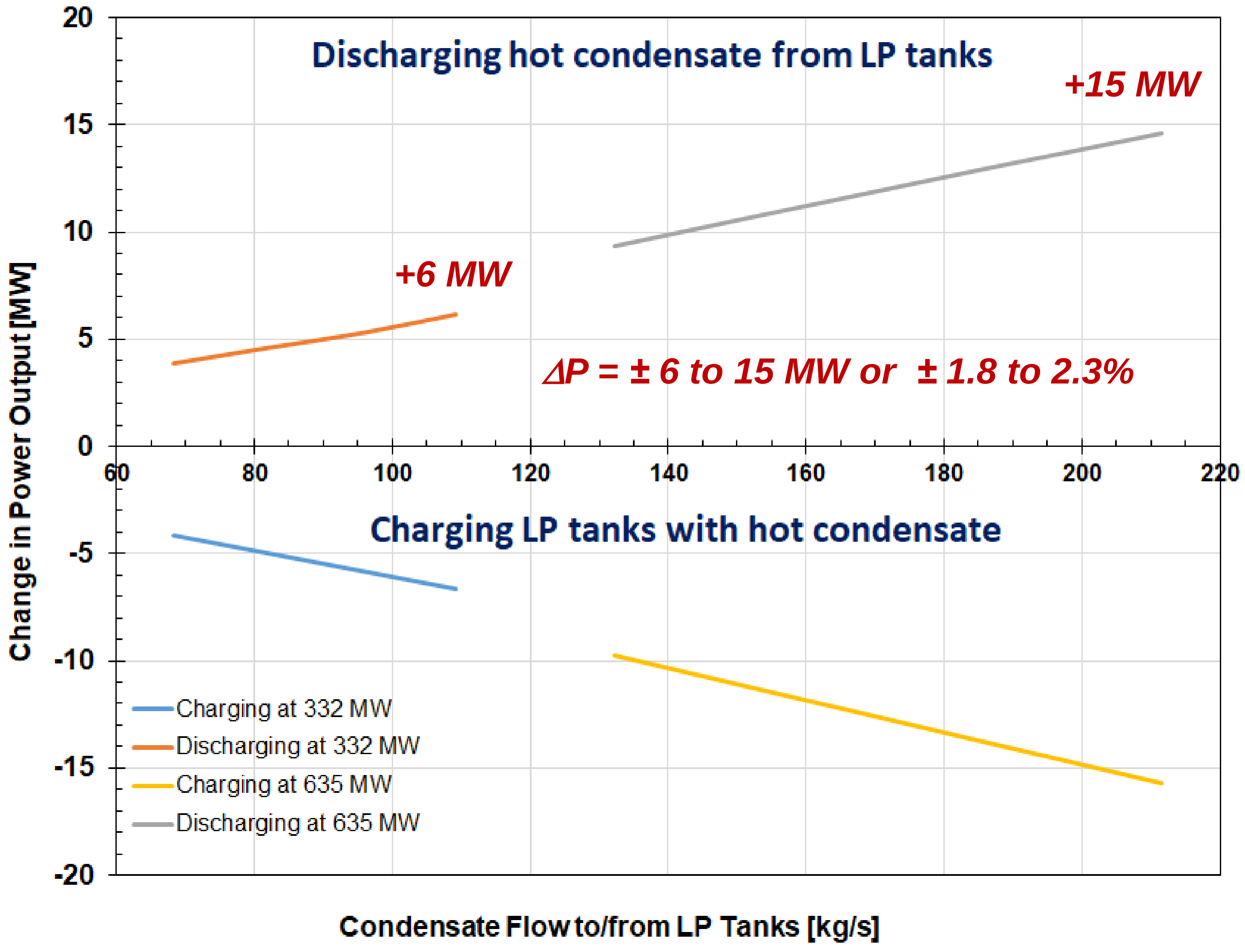


- *Plant power output **increases** almost instantaneously as the hot condensate flow is discharged from the LP tanks to the main condensate line upstream of the deaerator.*
- *Improves plant flexibility and dynamic response.*
- *Power output increase is a linear function of the condensate flow diverted to the **LP** tank.*



- *Plant power output **decreases** almost instantaneously when a portion of the hot condensate flow leaving the feedwater storage tank is diverted to the LP tanks.*
- *Improves plant flexibility and dynamic response.*
- *Power output decrease is a linear function of the condensate flow diverted to the **LP** tank.*

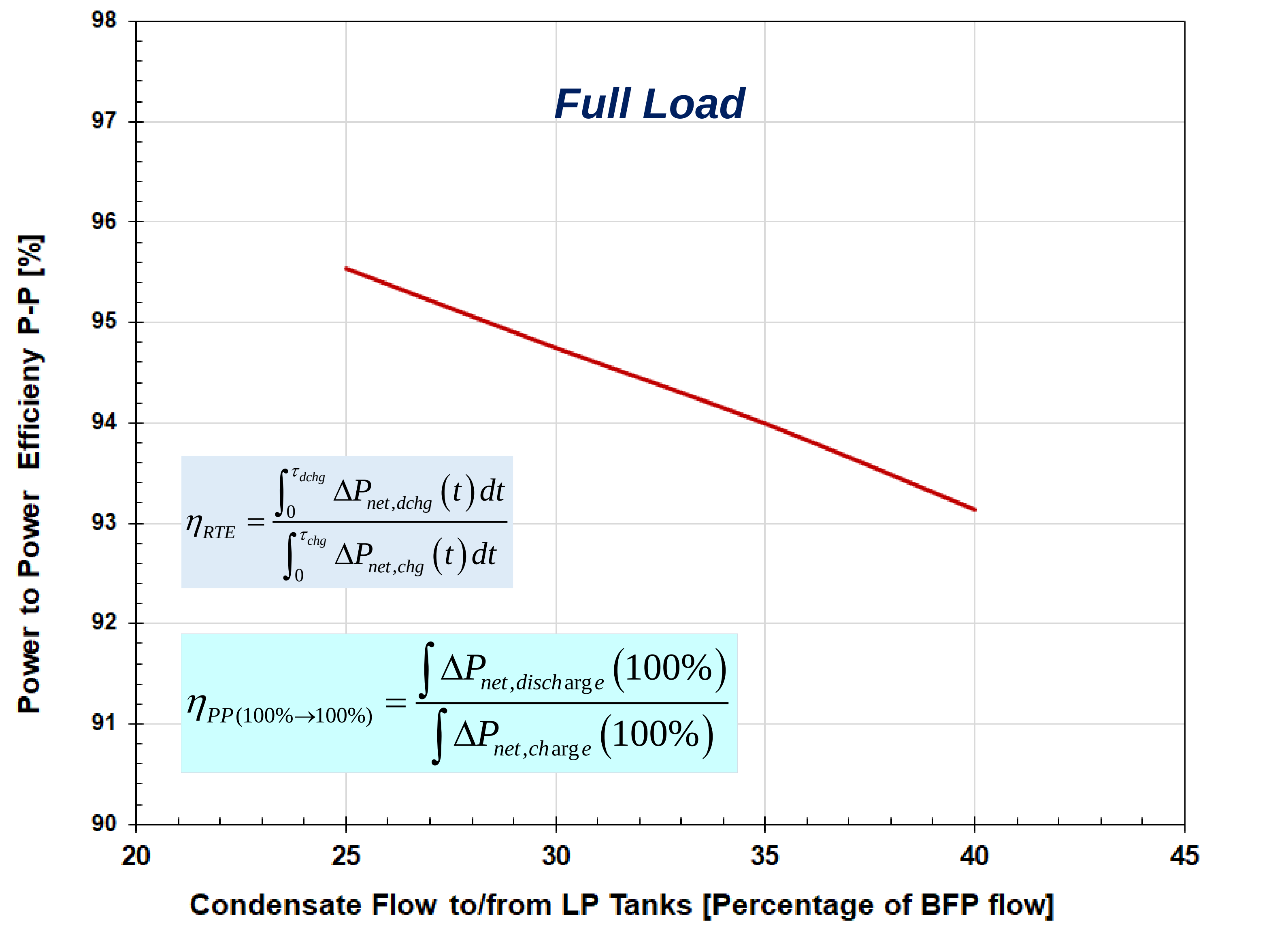
LP Condensate Storage



Charging/Discharging

- *Steam generator operates at steady-state with constant heat input.*
- *LP condensate tanks are charged and discharged for 3 hours.*
- *The integrated LP condensate storage system would, at full load*
  - *allow plant to follow load in the **± 15 MW** range and improve its participation in frequency regulation,*
  - *or to increase maximum power output by **15** MW when power prices are favorable.*
- *Power output at low load (**332 MW**) is affected less compared to the full load (**635 MW**) since the amount of stored and discharged heat at low load is smaller compared to the full load.*

LP Condensate Storage



$$\eta_{RTE} = \frac{\int_0^{\tau_{dchg}} \Delta P_{net,dchg}(t)\,dt}{\int_0^{\tau_{chg}} \Delta P_{net,chg}(t)\,dt}$$

$$\eta_{PP(100\%\rightarrow 100\%)} = \frac{\int \Delta P_{net,discharge}(100\%)}{\int \Delta P_{net,charge}(100\%)}$$

Round trip efficiency

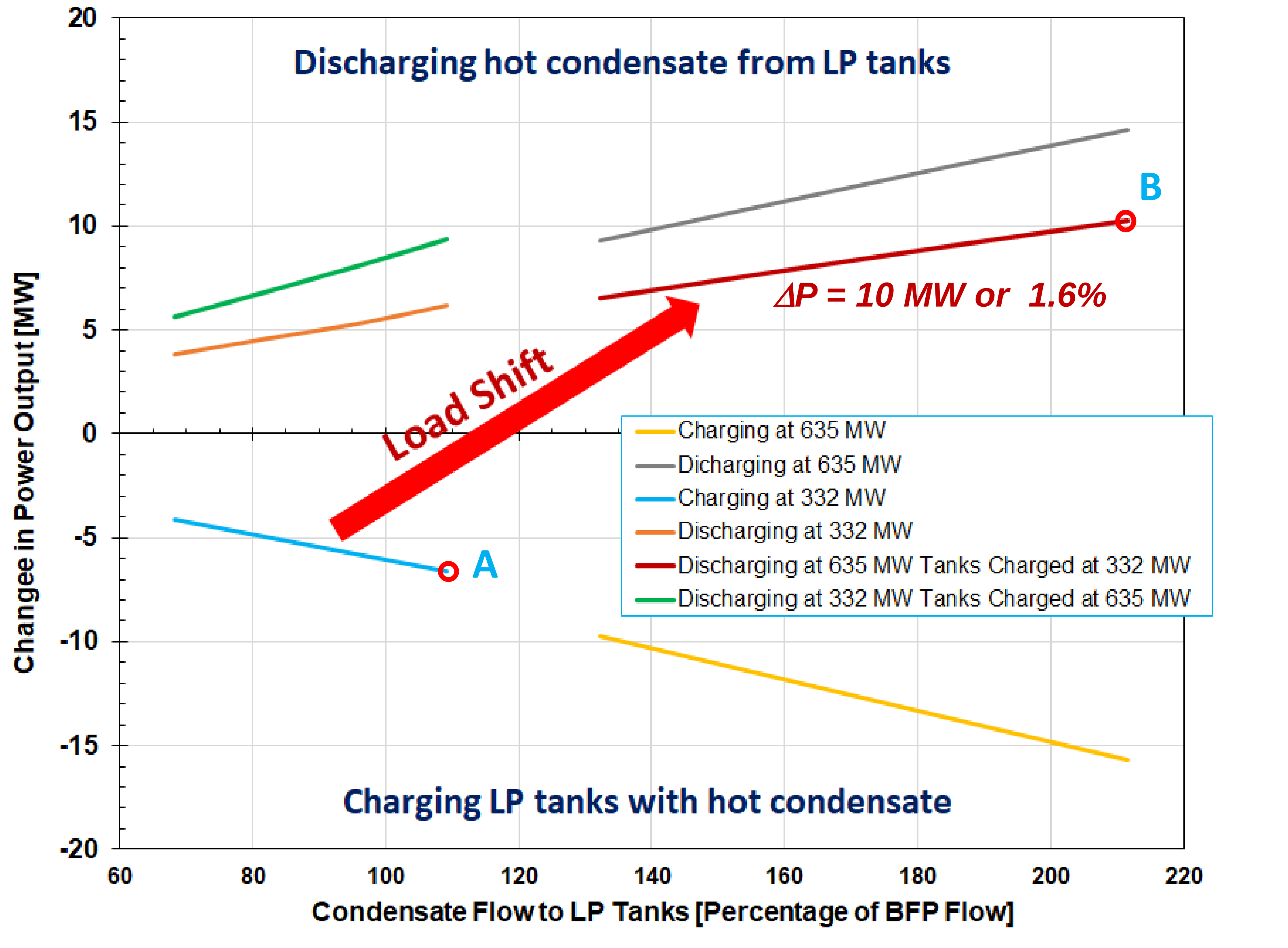
- *Condensate tanks are charged and discharged at full (635 MW_{gross}) load.*
- *Round trip power-to-power efficiency is very high and decreases with the increase in charging / discharging flow.*
- *Since $\Delta P_{net,chg}$ and $\Delta P_{net,dchg}$ are constant, the roundtrip energy-to-energy efficiency can be calculated from*

$$\eta_{RTE} = \frac{\eta_{PP}}{f_z}$$

- *For $f_z = 1$, roundtrip power-to-power and energy-to-energy efficiencies are the same.*

$$\eta_{RTE} = \eta_{PP}$$

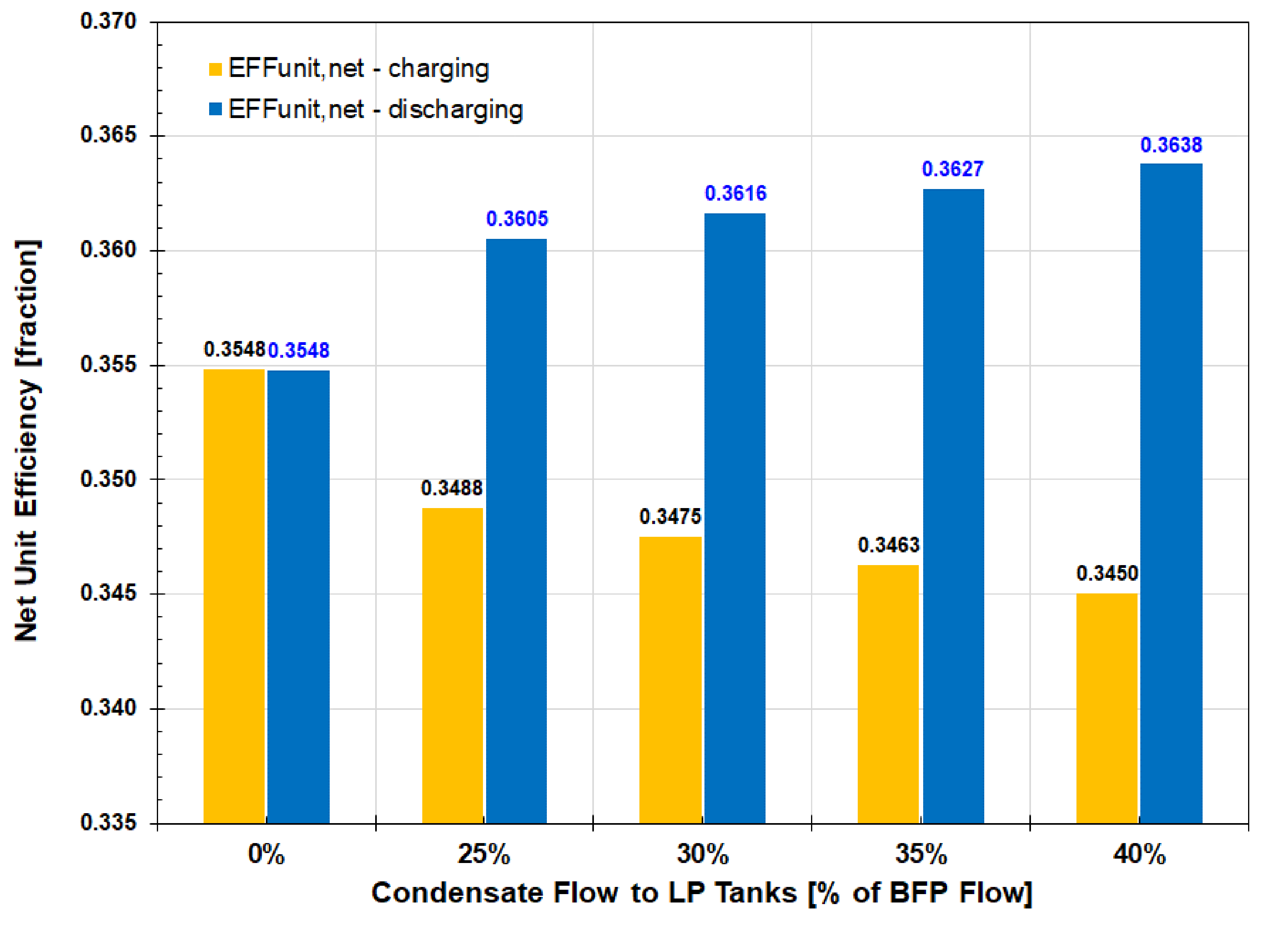
LP Condensate Storage



Load Shift

- *Condensate tanks are charged at low load (336 MW_{gross}) for 3 hours and discharged at full load (635 MW_{gross}).*
- *Power increase due to load shift is smaller compared to the load following since the amount of heat stored at low load is smaller compared to the heat stored at full load.*
- *Discharging time is shorter compared to the charging time, thus $\mathbf{f_z < 1}$ giving $\eta_{RTE} < \eta_{PP}$.*
- *For load shift between points A and B, η_{RTE} = **80%***

LP Condensate Storage

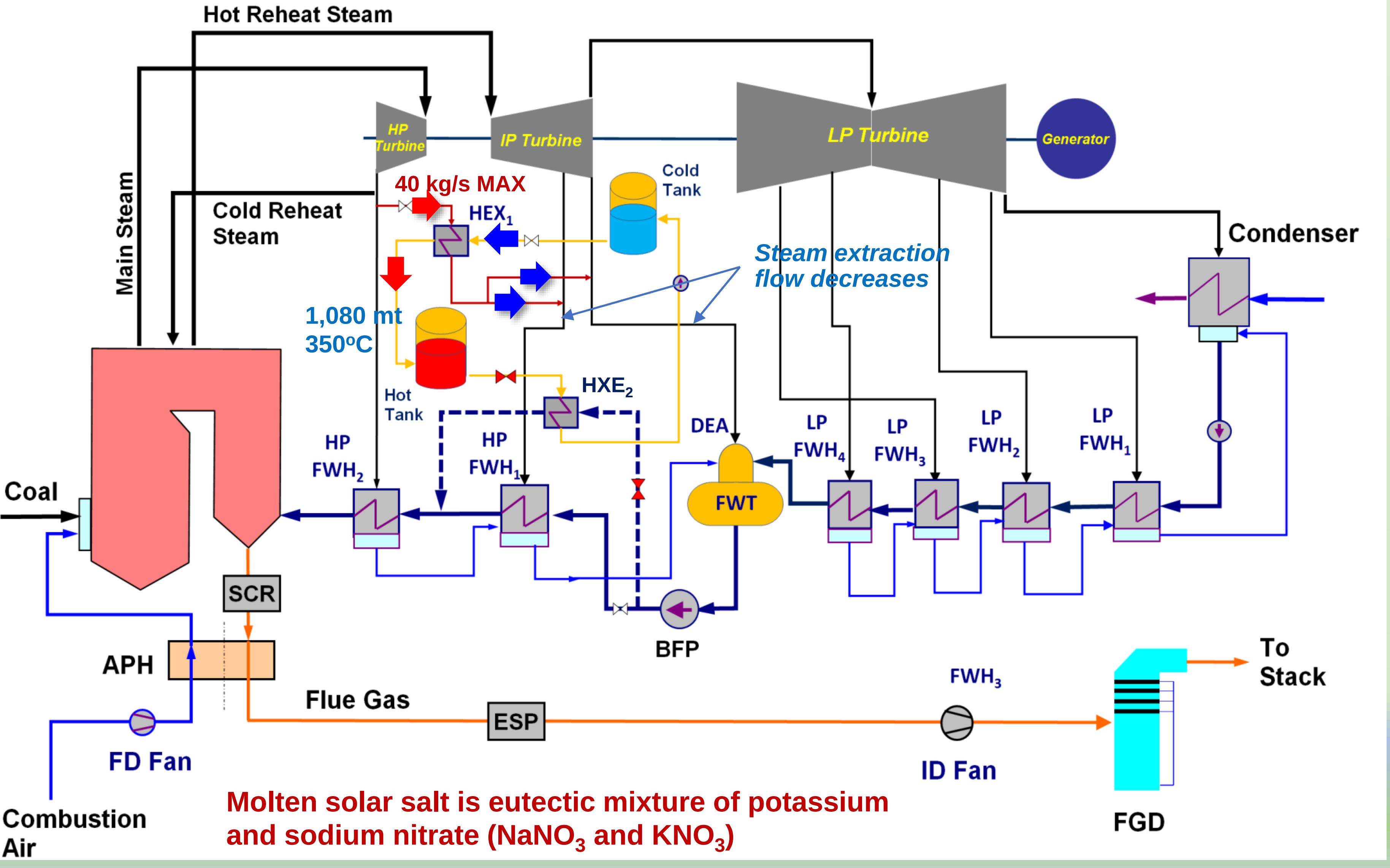


Performance of a Reference Plant with Integrated LP Condensate Tanks

- *Steam generator operates at steady-state with constant heat input.*
- *Condensate tanks are charged and discharged for 3 hours at full and low loads.*
- *Net unit efficiency $\eta_{unit,net}$ decreases during tank charging since stored heat is taken from the steam turbine cycle reducing power output.*
- *Net unit efficiency $\eta_{unit,net}$ increases during tank discharging since stored heat is returned to the steam turbine cycle increasing power output.*
- *At maximum charging/discharging flow, a change in $\eta_{unit,net}$ is approx. **1.8%-points**.*

Two-Tank Molten Solar Salt Thermal Energy Storage (2-Tank MSS TES)

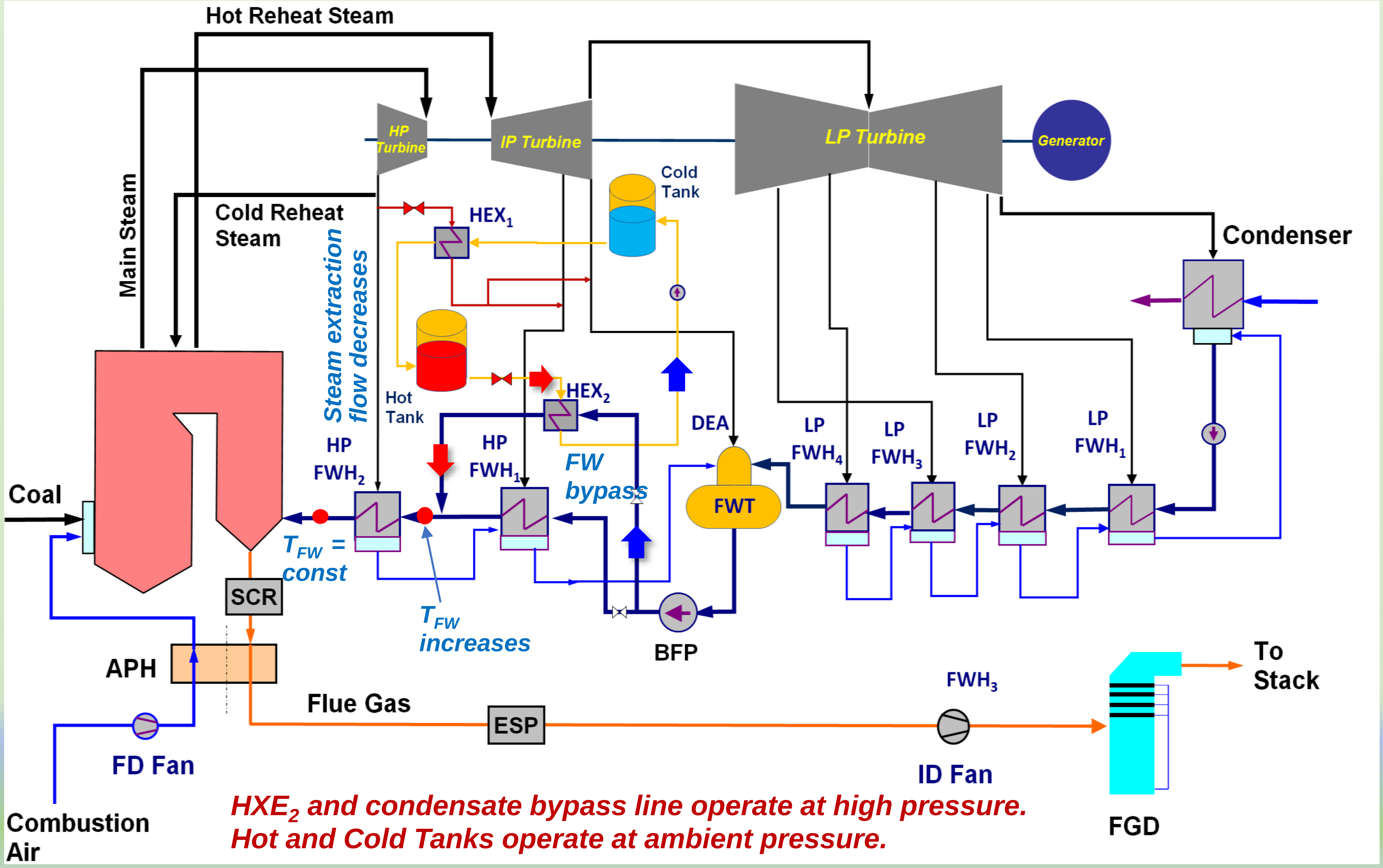
2-Tank Molten Solar Salt TES



Charging

- During TES charging with the **HP exhaust steam**, the plant power output is reduced because of the decreased steam flow through the **IP** and **LP turbines**.
- The heat extracted from the steam turbine cycle is transferred to the molten salt via heat exchanger **HXE$_1$** and stored in the Hot Tank.
- The steam leaving **HXE$_1$** is returned to the steam extraction line for **HP FWH$_1$** and to the deaerator **DEA** replacing portion of the steam extracted from the turbine.
- **Storage capacity**
  - 160 MWh$_{th}$ (3 hrs of charging at full load).
  - 125 MWh$_{th}$ (3 hrs of charging at min load).

2-Tank Molten Solar Salt TES

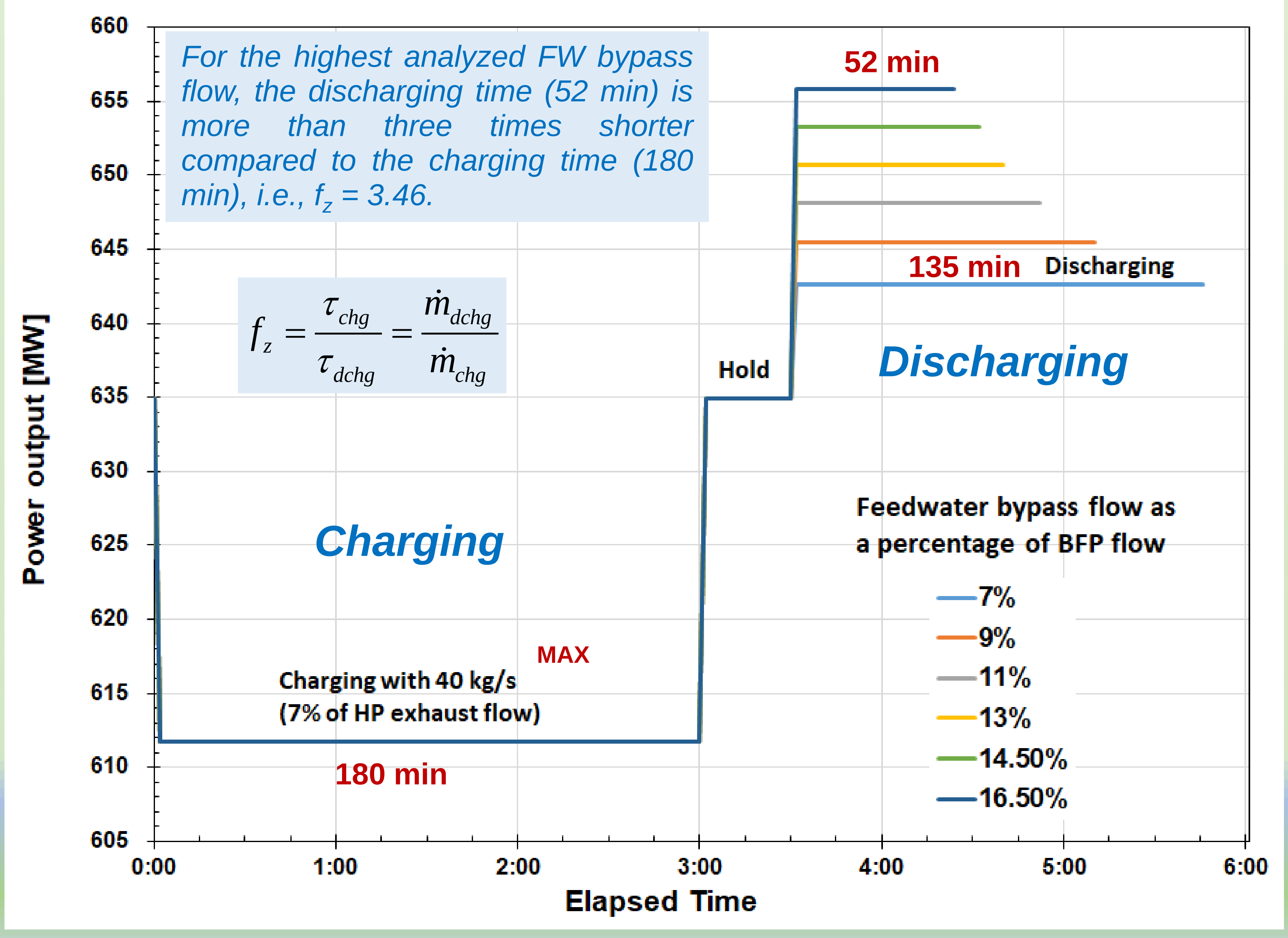


HXE$_2$ and condensate bypass line operate at high pressure.
Hot and Cold Tanks operate at ambient pressure.

Discharging

- *During TES discharging, **HXE$_2$** is used to transfer heat from the hot molten salt leaving the hot tank to the feedwater (FW) bypass.*
- *The cold molten salt leaving **HXE$_2$** is pumped to the cold tank*
- *FW flow bypassing **HP FHW$_1$** is heated by hot salt in **HEX$_2$**.*
- *The hot FW bypass leaving **HXE$_2$** is returned to the main feedwater line between **HP FWH$_1$** and **FWH$_2$**.*
  - *FW temperature at HP FWH$_2$ inlet increases*
- *Reduction in steam extraction for **HP FWH$_2$** results in higher power output of the IP turbine.*

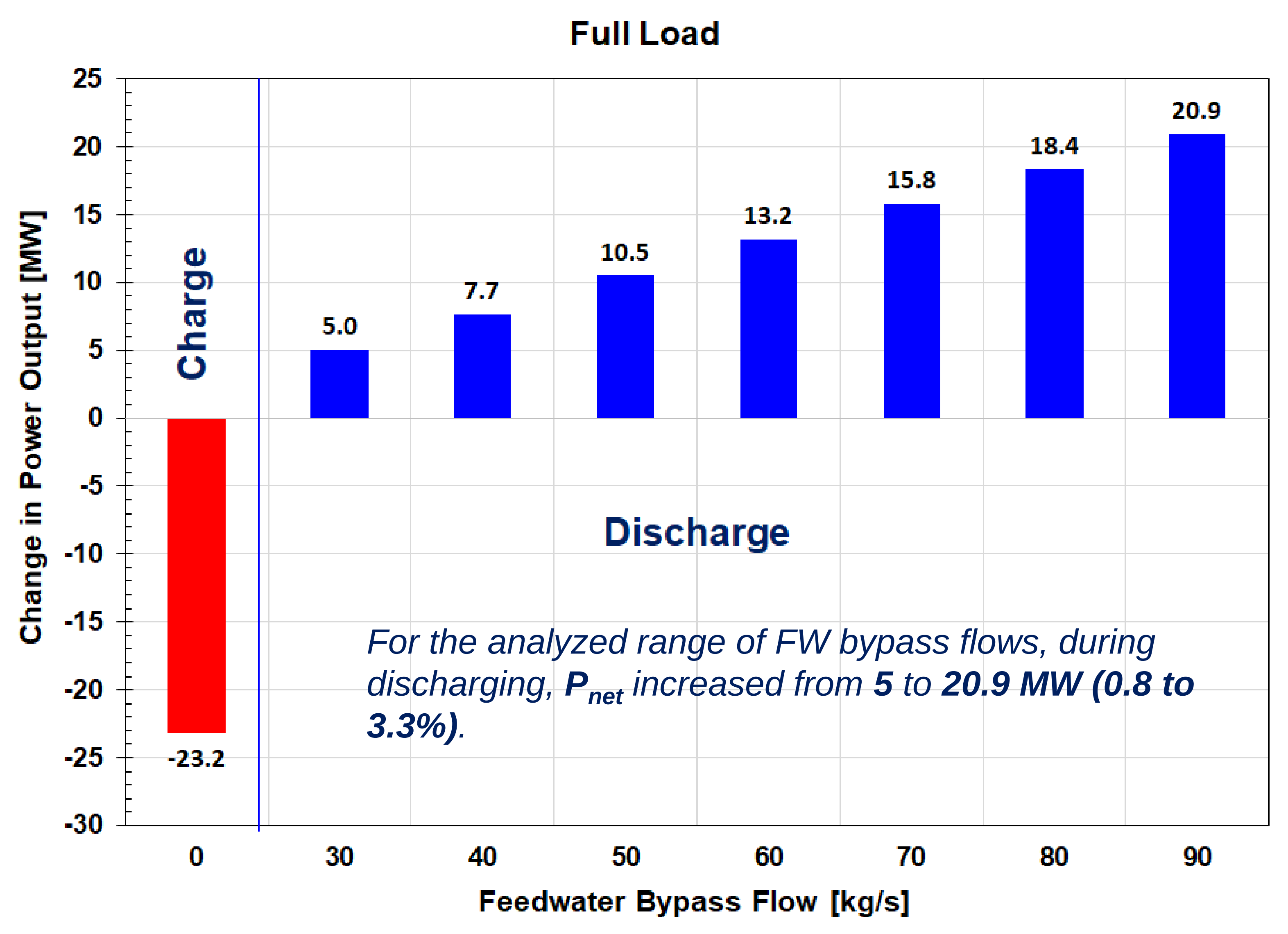
2-Tank Molten Solar Salt TES



Charging and Discharging

- *The effect of TES system charging and discharging on the plant power output at full load as a function of elapsed time.*
- *The system is charged for **3 hours** using charging steam flow rate of **40 kg/s**, placed on hold for **30 minutes**, and then discharged using a range of feedwater bypass flows.*
  - *Tank storage capacity is 1,080 mt.*
- *The plant power output decreases almost instantaneously when charging steam is taken from the HP turbine discharge and stays constant during TES charging.*
- *As stored heat is returned to the cycle during TES discharging, plant power output increases virtually instantaneously.*
- *The heat storage capacity can be increased by increasing charging time*

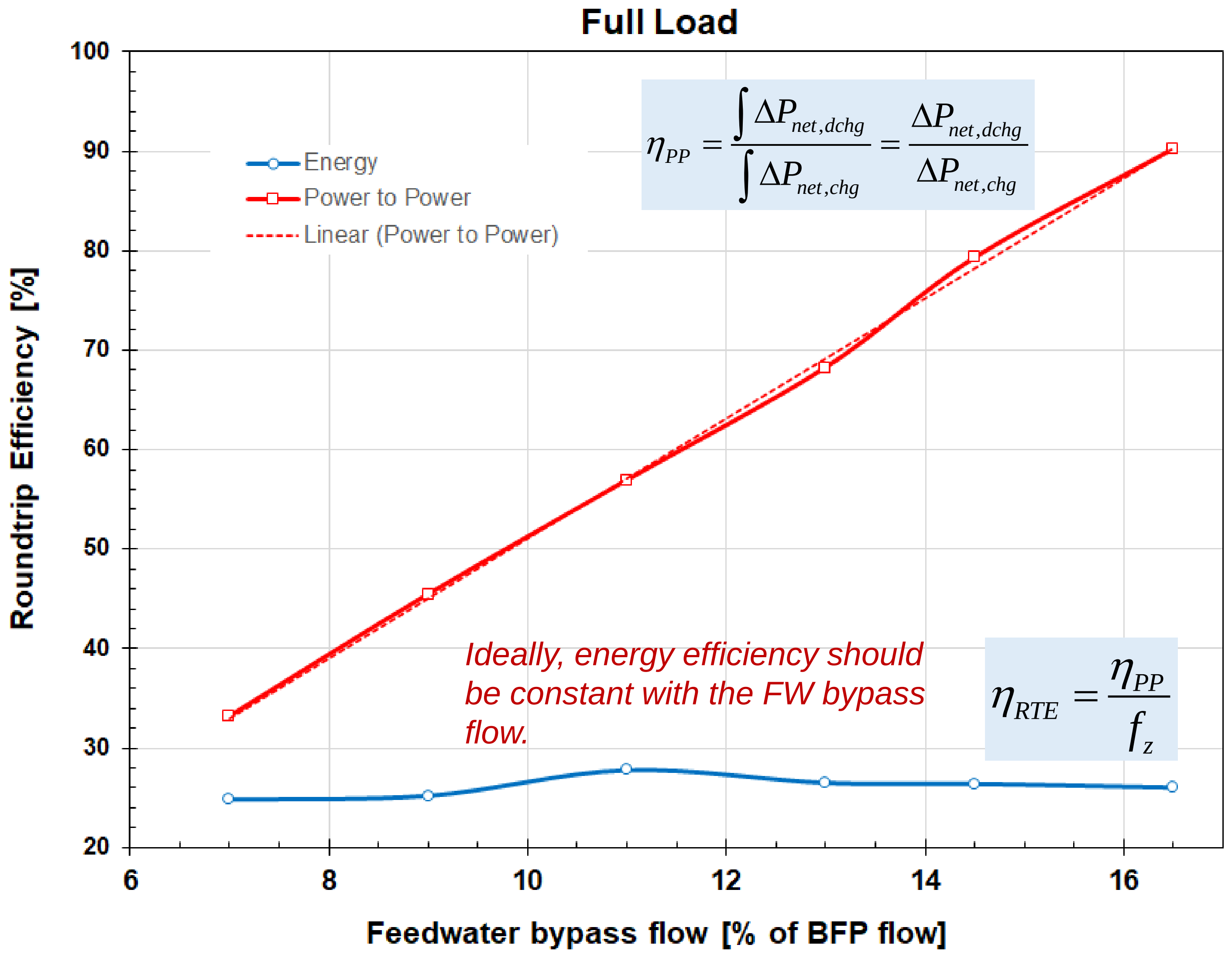
2-Tank Molten Solar Salt TES



Charging and Discharging at Full Load

- *FW bypass flow was varied parametrically from 40 to 90 kg/s.*
  - *Corresponds to 7 to 16.5% of the FW flow at the Boiler Feedwater Pump (BFP) discharge.*
- *During charging, net power output* P_{net} *decreases by* ***23.2 MW (3.6%)****.*
- *The increase in* P_{net} *is a linear function of the FW bypass flow during discharging.*
  - *For the analyzed range of FW bypass flows,* P_{net} *increases from* ***5*** *to* ***20.9 MW (0.8*** *to* ***3.3%)*** *during discharging.*
- *At full load, the integrated 2-tank MSS TES system would allow power plant to*
  - *follow load in the* ***± 20 MW*** *range and improve its participation in frequency regulation*
  - *or to increase maximum power output by* ***20 MW*** *when power prices are favorable.*

2-Tank Molten Solar Salt TES



$$\eta_{PP} = \frac{\int \Delta P_{net,dchg}}{\int \Delta P_{net,chg}} = \frac{\Delta P_{net,dchg}}{\Delta P_{net,chg}}$$

$$\eta_{RTE} = \frac{\eta_{PP}}{f_z}$$

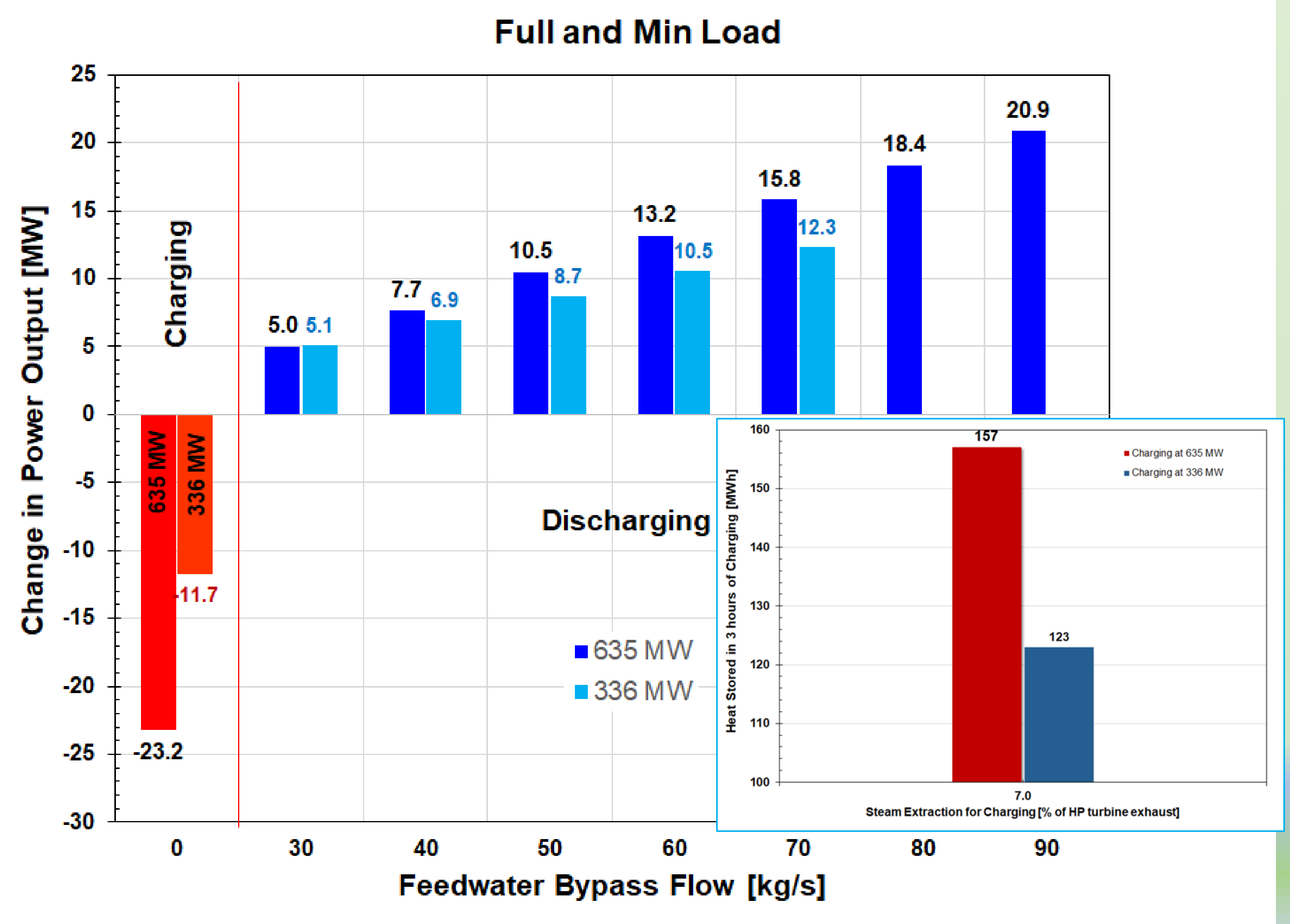
Roundtrip Efficiency

- *The roundtrip energy-to-energy and power-to-power and efficiencies η_{RTE} and η_{PP} for full load operation as functions of the FW bypass flow.*
- *The increase in FW bypass flow results in*
  - *higher $\Delta P_{net,dchg}$*
  - *higher η_{PP}*
  - *higher discharge flow of hot molten salt m_{dchg}*
  - *shorter discharge time τ_{dchg}*
  - *higher f_z*

$$\tau_{dchg} = \frac{\dot{m}_{chg}}{\dot{m}_{dchg}} \tau_{chg} \qquad f_z = \frac{\tau_{chg}}{\tau_{dchg}} = \frac{\dot{m}_{dchg}}{\dot{m}_{chg}}$$

- *For a constant storage tank volume, discharging time is inversely related to the discharge flow.*
- *η_{RTE} is constant.*

2-Tank Molten Solar Salt TES



Charging and Discharging at Full and Min Loads

- *Since, for the same charging time, less heat can be stored at the min load compared to full load, the absolute change in power output achievable by TES charging and discharging at min load is smaller.*

  Low load

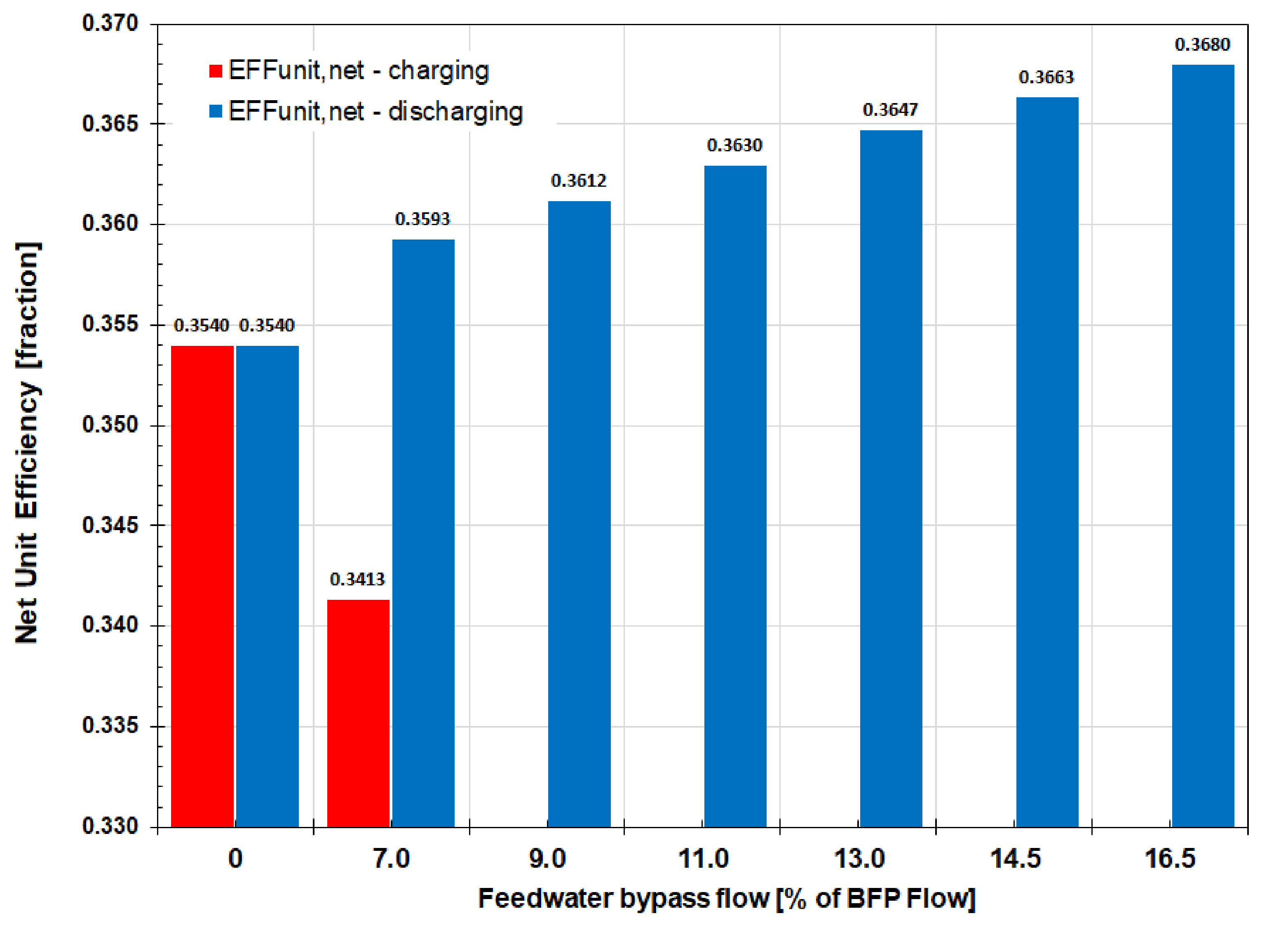
  +12.3 / -11.7 MW** or **+ 3.7 /- 3.6%

  Full load

  ± 20.9 / -23.2 MW or + 3.3% / - 3.5%

- *These results correspond to FW bypass of 70 kg/s at min load (336 MW_{gross}), and FW bypass flow of 90 kg/s at full load (635 MW_{gross}).*

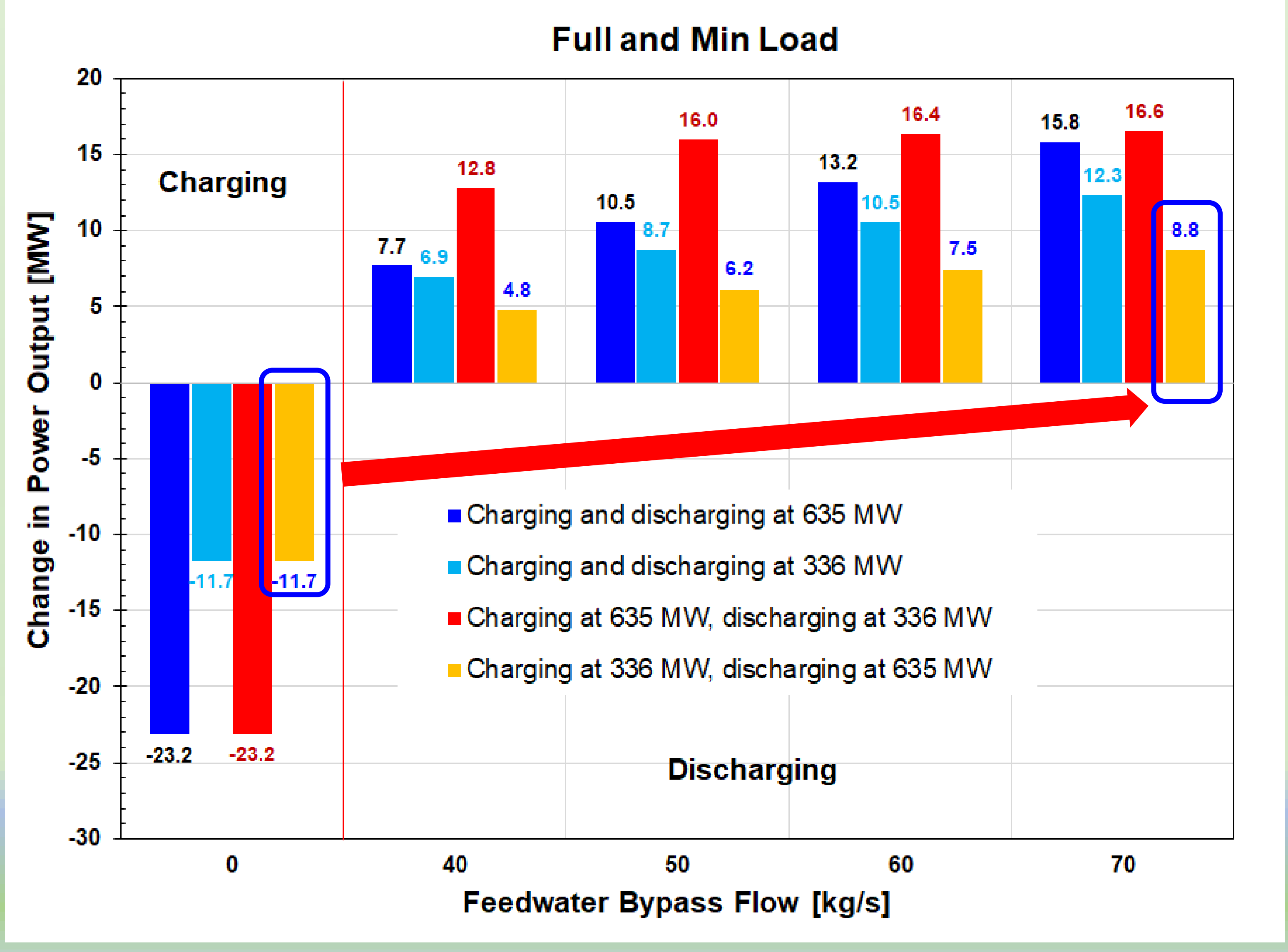
2-Tank Molten Solar Salt TES



Performance of a Reference Plant with Integrated 2-tank MSS TES

- *The effect of TES charging and discharging on the **net unit efficiency** is presented as a function of the feedwater bypass flow.*
- *For a constant heat input, taking heat from the steam turbine cycle decreases cycle and unit performance (decreases efficiency).*
- *Returning heat to the turbine cycle during TES discharging improves performance and increases efficiency.*
- *Lager feedwater bypass flow has a larger effect on performance and efficiency.*
- *The change in net unit efficiency during TES charging and discharging at highest analyzed feedwater bypass is approximately equal to **2.7%-points**.*

2-Tank Molten Solar Salt TES

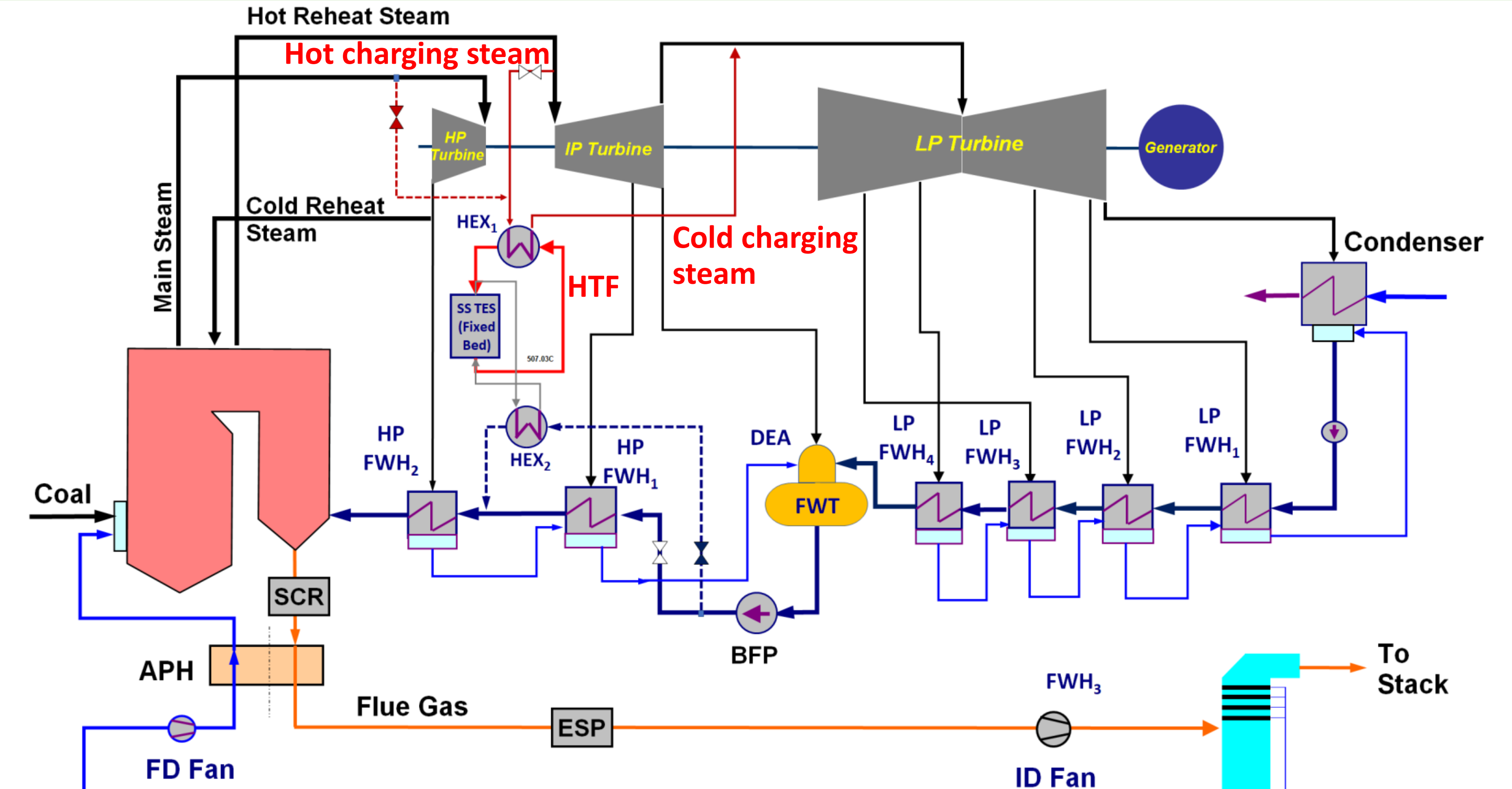


Load Shift

- *2-tank MSS TES is charged at min load (336 MW_{gross}) for 3 hours and discharged at full load (635 MW_{gross}).*
- *Power increase due to load shift is a linear function of the FW bypass flow.*
- *The net power increase of **8.8 MW (1.4%)** during discharging at full load is achieved with the FW bypass flow of 70 kg/s.*
- *The corresponding power decrease during charging at min load is **11.7 MW (3.5%).***
- *η_{PP} is **96.6%***
- *η_{RTE} is low, approx. 25%*
- *The molten salt flow during discharging is considerably higher compared to the charging flow,*
  - *Discharging time is shorter compared to the charging time*
  - *η_{RTE} is low.*

Fixed Bed Thermal Energy Storage (FB TES)

Fixed Bed TES



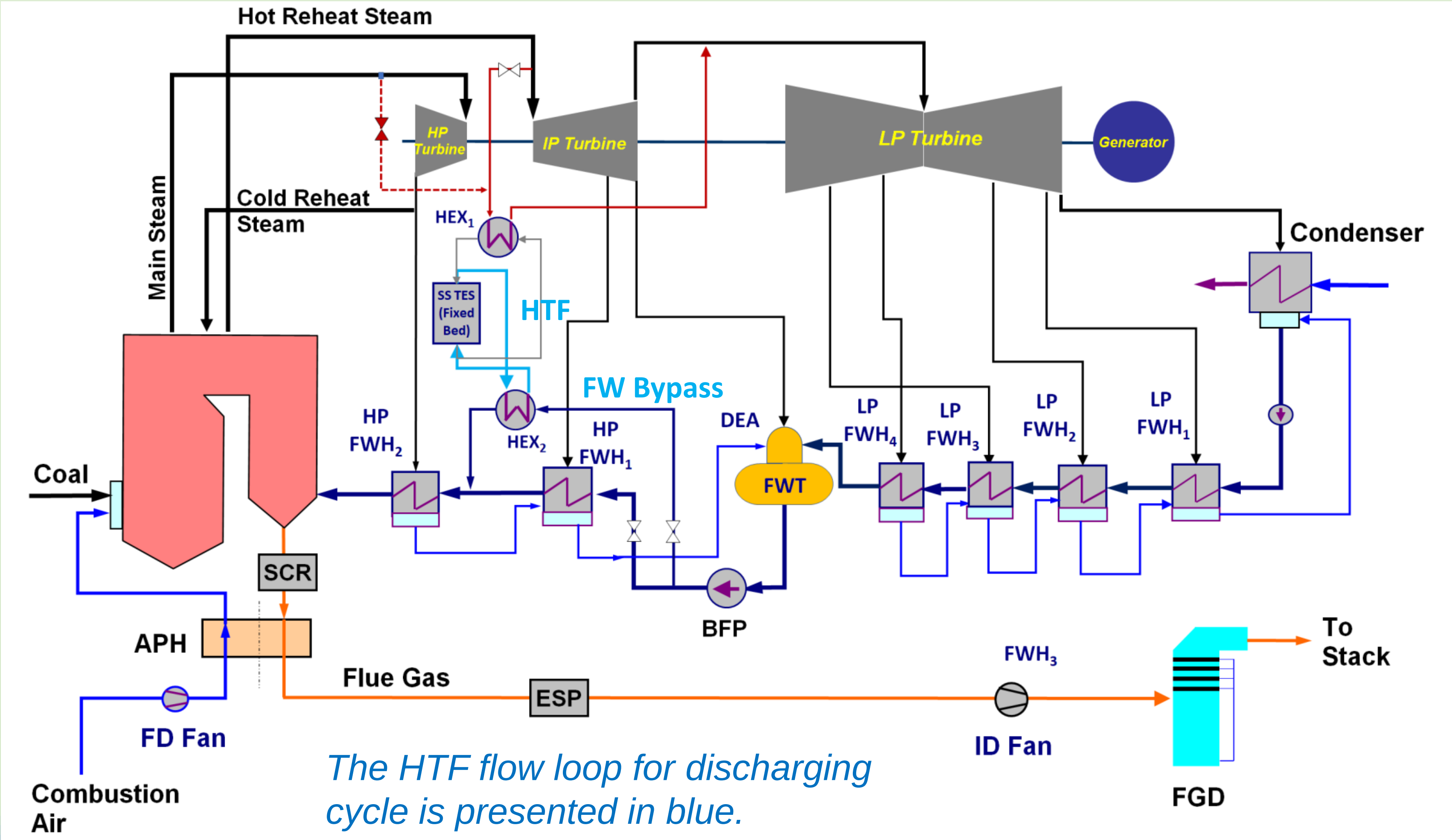
*Total heat storage capacity (6 fluidized beds), 2000 mt of quartzite rock ~ **175 MWh***

A fixed bed thermal energy storage system (FB TES) was selected for the analysis because of the low cost of the heat storage medium, simple operation, and easy scaleup. In a FB TES system, heat is stored in a solid material, such as rocks, ceramics, and other solids.

Charging

- *FB TES is charged when the plant power output needs to be decreased.*
- *Hot reheat steam is used for FB charging.*
- *Heat from the charging steam is transferred to heat transfer fluid (HTF) in **HEX$_1$**.*
- *Cold charging steam is returned to the **LP** turbine inlet.*
- *During bed charging (heat storage phase), hot HTF enters FB from the top, flows through the stationary bed of solids, transfers heat to the heat storage medium, and exits at the bottom of the bed at lower temperature.*
- *The HTF flow loop for charging cycle is presented in red.*

Fixed Bed TES



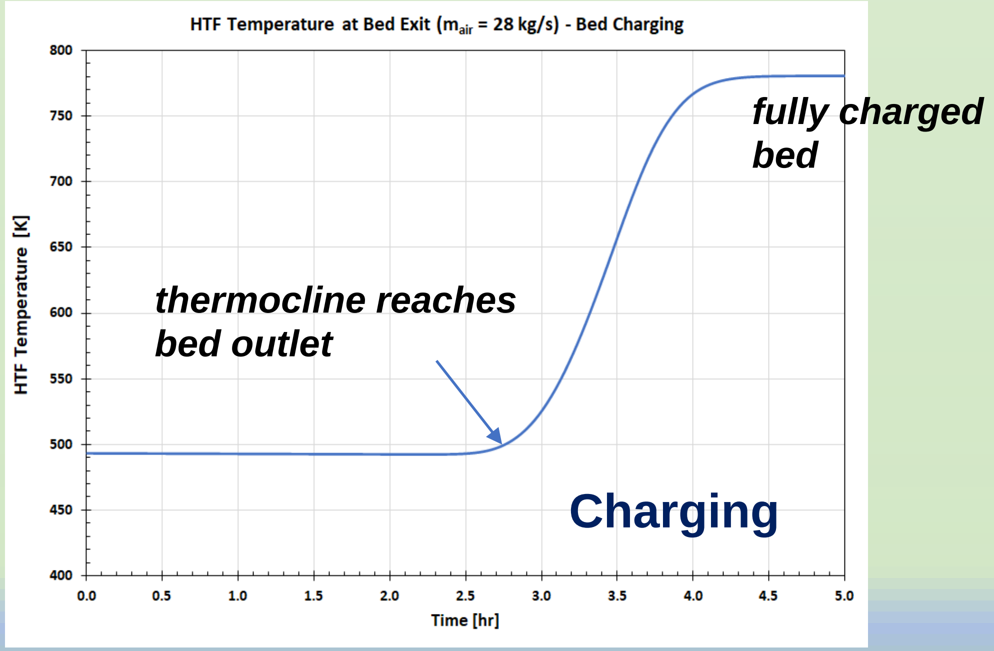
Discharging

- *FB TES is discharged when the plant power output needs to be increased.*
- *During bed discharging, cold HTF leaving **HEX$_2$** enters FB from the bottom and flows through the stationary bed of solids. Stored heat is transferred to HTF increasing its temperature.*
- *Hot HTF exits FB at the top and flows through **HEX$_2$**, transferring heat to the FW bypass.*
- *Cold HTF leaving **HEX$_2$** returns to the FB for reheating.*
- *This mode of operation creates a hot temperature zone in the upper part of the FB and low temperature zone at the bottom part, i.e., establishes a **thermocline**.*

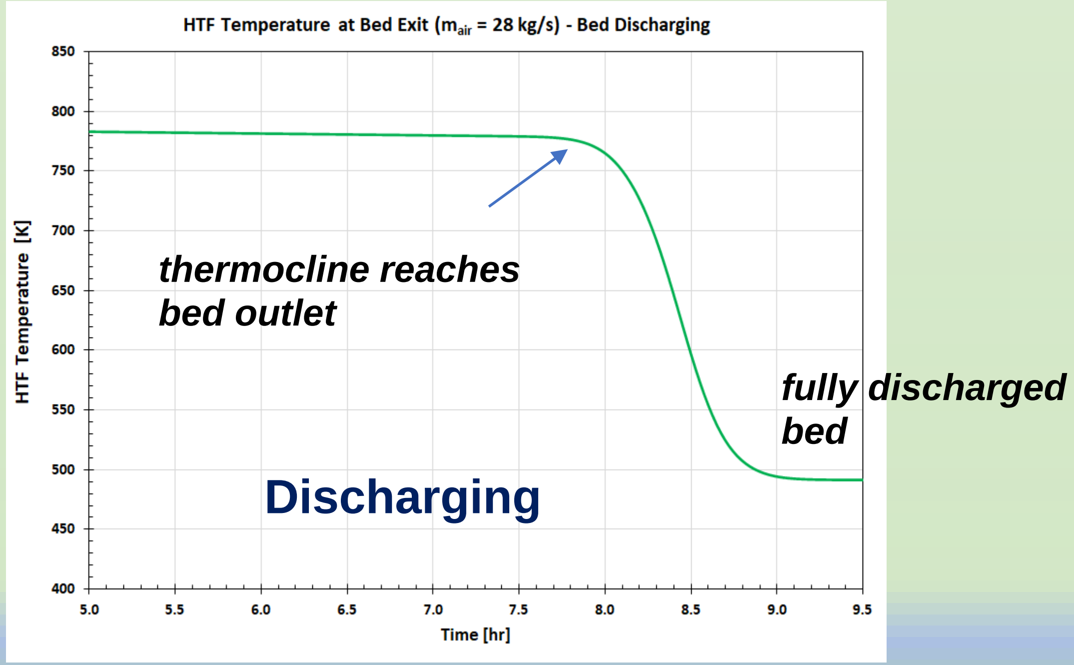
*A **thermocline**, i.e., temperature difference between the top and bottom portions of the FB, allows one storage tank (vessel) to operate as two storage tanks, one at high temperature, the other one at low temperature.*

Fixed Bed TES

- ***The FB TES model was integrated with the EBSILON Professional model of the reference plant to determine the effect of integrated FB TES on power plant performance.***
  - *During **charging**, hot HTF enters FB from the top, flows through the stationary bed of solids, transfers heat to the heat storage medium, and exits at the bottom of the bed at lower temperature.*
  - *During **discharging** hot HTF exits FB at the top and flows through HEX_2, transferring heat to the FW bypass. Cold HTF leaving HEX_2 returns to the FB for reheating.*

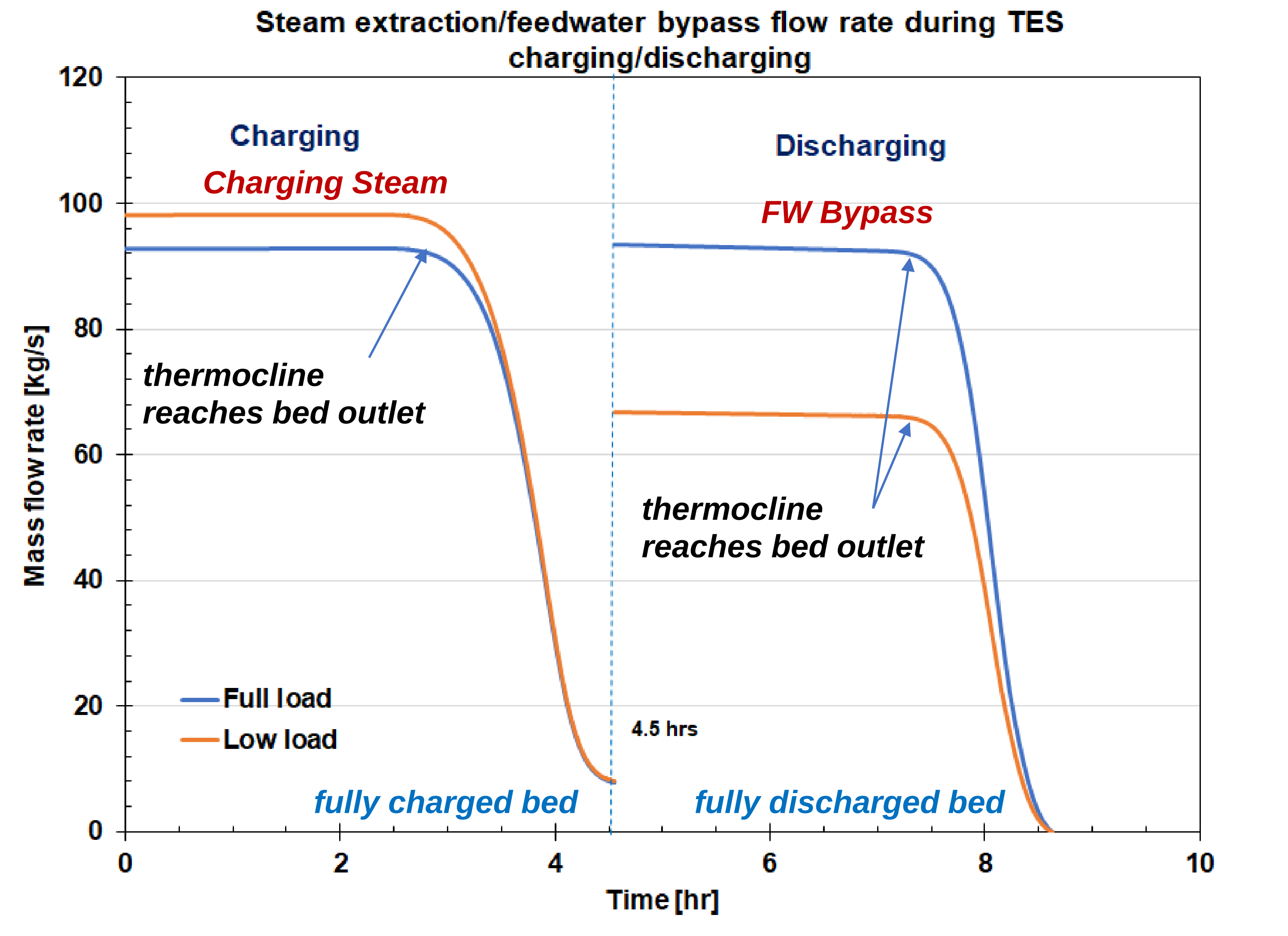


*HTF temperature at bed outlet starts to **increase** as thermocline propagates to the bed outlet and reaches maximum value when bed is **fully charged**.*



*HTF temperature at bed outlet starts to **decrease** as thermocline propagates to the bed outlet and reaches minimum value when bed is **fully discharged**.*

Fixed Bed TES

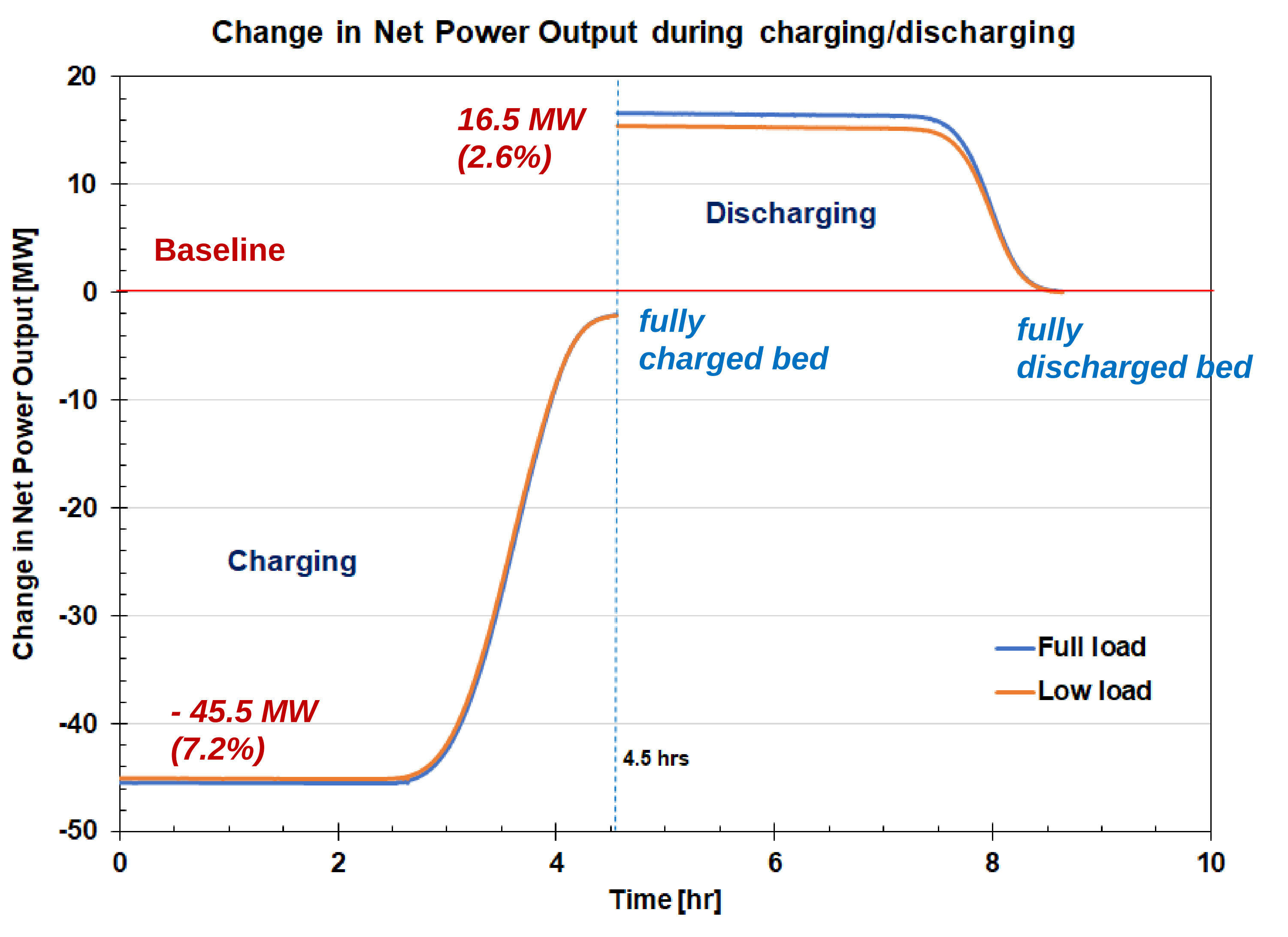


For reference HTF flow of 28 kg/s

Performance of Reference Plant with Integrated FB TES

- *As a result of transient performance of the FB TES system, flow rates of the charging steam and FW bypass flow are not constant during charging/discharging but vary with time.*
- *An increase in HTF temperature at bed outlet during **bed charging** results in a decrease in the charging steam flow rate (left side of the figure).*
- *HTF reaches minimum value for a fully charged bed.*
- *During **bed discharging**, a decrease in HTF temperature at bed outlet results in a decrease in discharged heat.*
- *FW bypass flow decreases to maintain constant FW temperature at boiler inlet $T_{FW,in}$ = **const.** (right side of the figure).*
- *FW bypass flow reaches zero for a fully discharged bed.*

Fixed Bed TES



For reference HTF flow of 28 kg/s

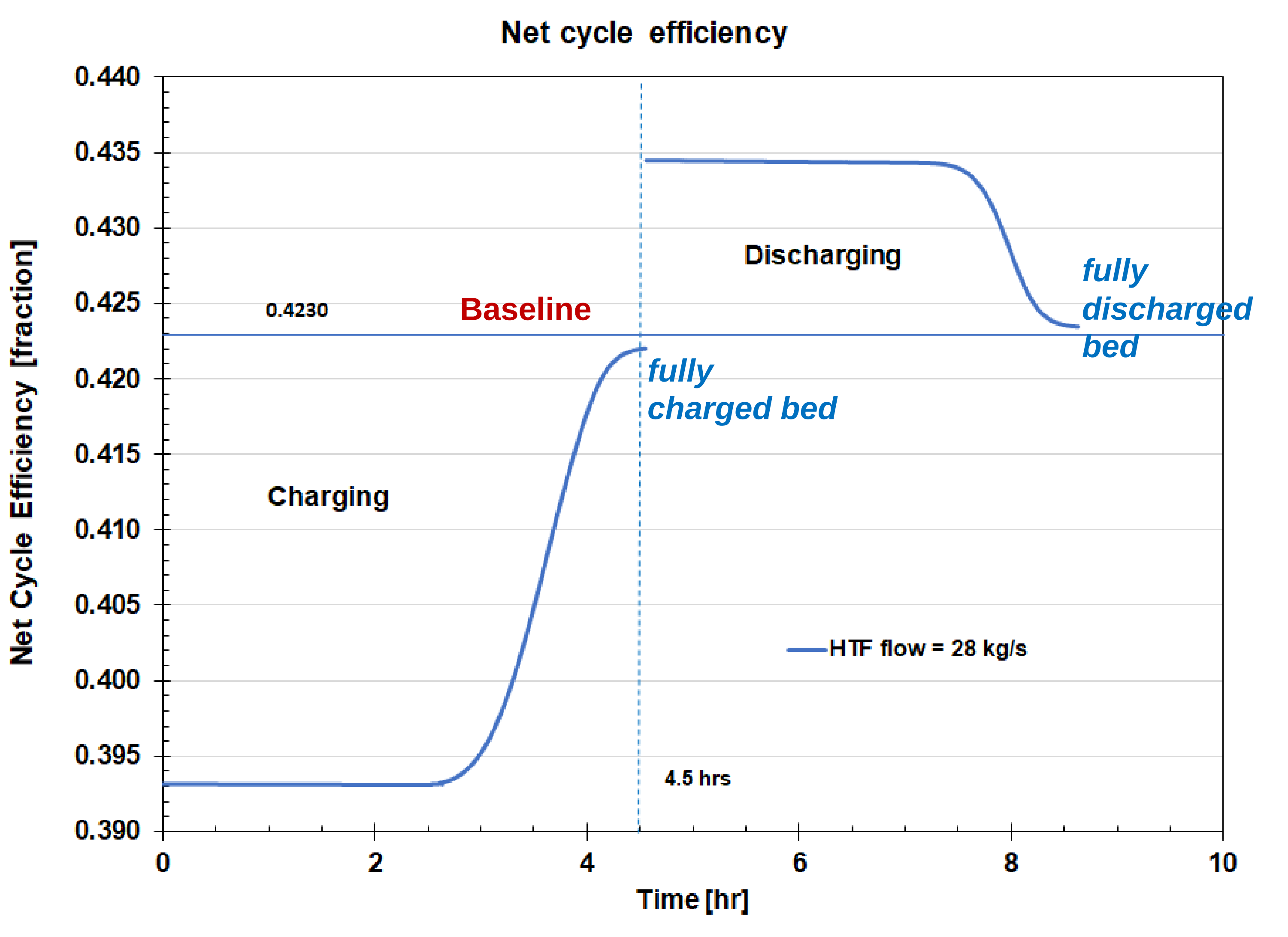
Performance of Reference Plant with Integrated FB TES

- *Variations in charging steam flow rate during bed charging and FW bypass flow during bed discharging affect operation of the steam turbine cycle and power output.*
- *Plant power output is not constant as it was the case with previously analyzed TES systems but varies with charging / discharging time and HTF flow.*

For the reference HTF flow rate of 28 kg/s

- *Maximum decrease in net power output during bed charging is **45.5 MW (7.2%)**.*
- *Maximum increase in power output during bed discharging is **16.5 MW (2.6%)**.*
- *The change in net power output varies as flow rates of charging steam and FB bypass vary during bed charging / discharging.*

Fixed Bed TES

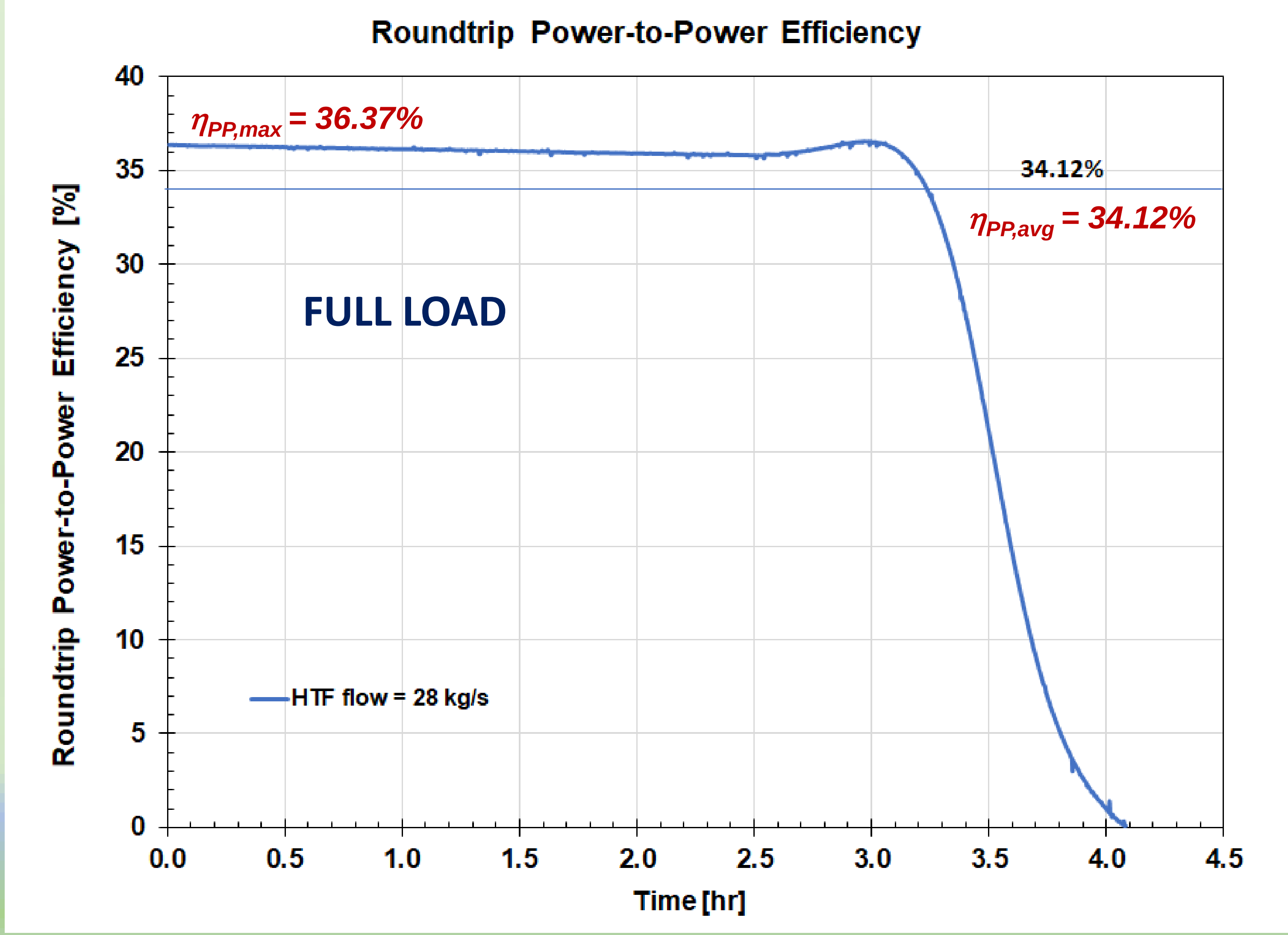


For reference HTF flow of 28 kg/s

Performance of a Reference Plant with Integrated FB TES

- *Heat input **HI** is maintained constant.*
- *During **bed charging** net cycle efficiency $\eta_{cycle,net}$ is lower compared to baseline since heat is taken from the cycle and stored in TES resulting in lower net power output P_{net}.*
- *During **bed discharging**, stored heat is returned to the steam turbine cycle resulting in higher net power output P_{net} compared to baseline and higher net cycle efficiency $\eta_{cycle,net}$.*
- *As the bed is getting closer to the fully charged or discharged condition, $\eta_{cycle,net}$ rapidly changes approaching baseline value for the fully charged or discharged bed.*
  - *The maximum efficiency decrease during charging is 3%-points.*
  - *The maximum increase during discharging is approximately 1.2%-points.*

Fixed Bed TES



For reference HTF flow of 28 kg/s

Roundtrip Efficiency

- *Variation in net power plant output during bed charging and discharging results in variation of roundtrip efficiency.*
- *For the analyzed case, the value of η_{PP} is close to the maximum value for approximately 3 hours, for as long as ΔP_{net} values corresponding to bed charging and discharging are approximately constant.*
- *As the bed is getting closer to the fully charged or discharged condition and flow rates of charging steam and FW condensate begin to decrease, the value of η_{PP} rapidly decreases approaching zero for the fully charged or discharged bed.*
- *For full load and refence HTF flow of 28 kg/s*

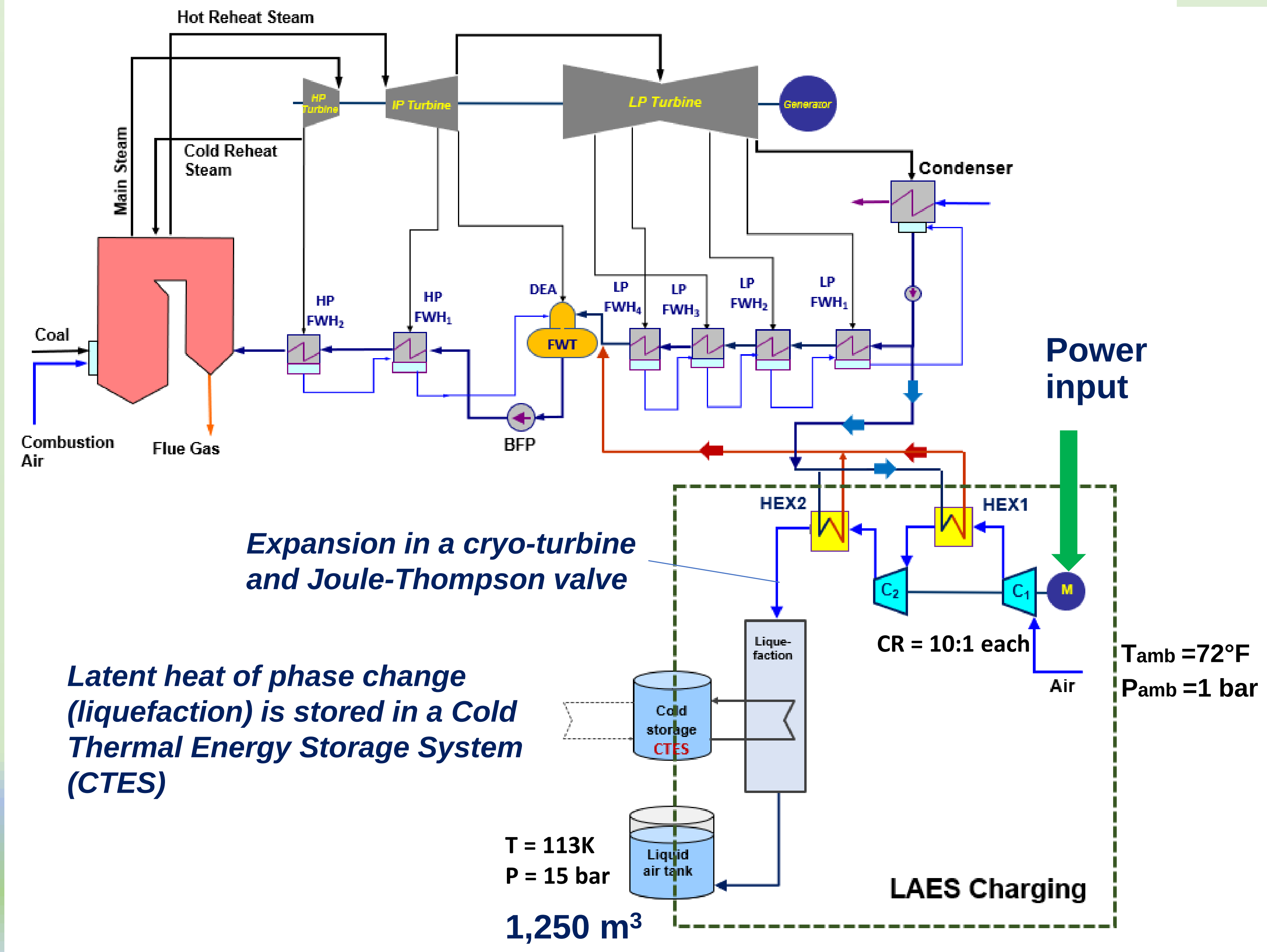
$$\eta_{PP,max} = 36.7\%$$

$$\eta_{PP,avg} = 34.1\%$$

$$\eta_{RPE} = 31.5\% < \eta_{PP}$$

Liquid Air Energy Storage (LAES)

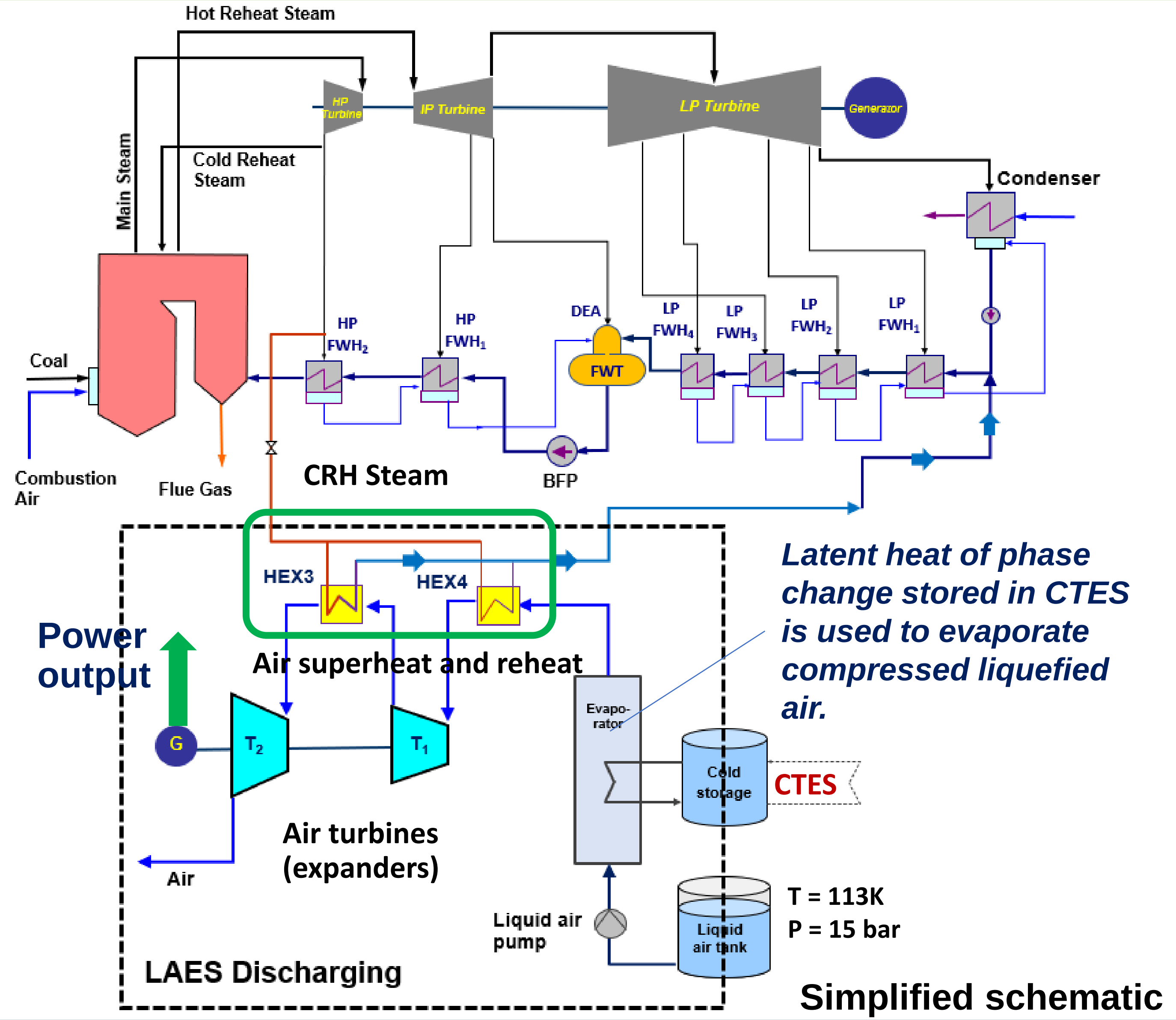
Liquid Air Energy Storage (LAES)



Charging

- ***LAES is charged when the plant power output needs to be decreased.***
- *After dehumidification, ambient air is compressed, liquified, and stored in a liquid air storage tank.*
  - *A two-stage compression system with intercooling was selected for this analysis.*
- *Compression heat is used to preheat the condensate bypass flow in intercoolers **HEX_1** and **HEX_2**.*
  - *The preheated condensate merges with main condensate flow upstream of **DEA**.*
- *The condensate bypass decreases the main condensate flow through the **LP FWHs 1** to **4**, and steam extractions from the LP turbine, resulting in a power increase of the LP turbine.*
  - *This increase is offset by the electric power taken from the generator needed to drive air compressors.*
  - *Net power output of the **integrated power plant-LAES system** (Integrated System) decreases.*

Liquid Air Energy Storage (LAES)

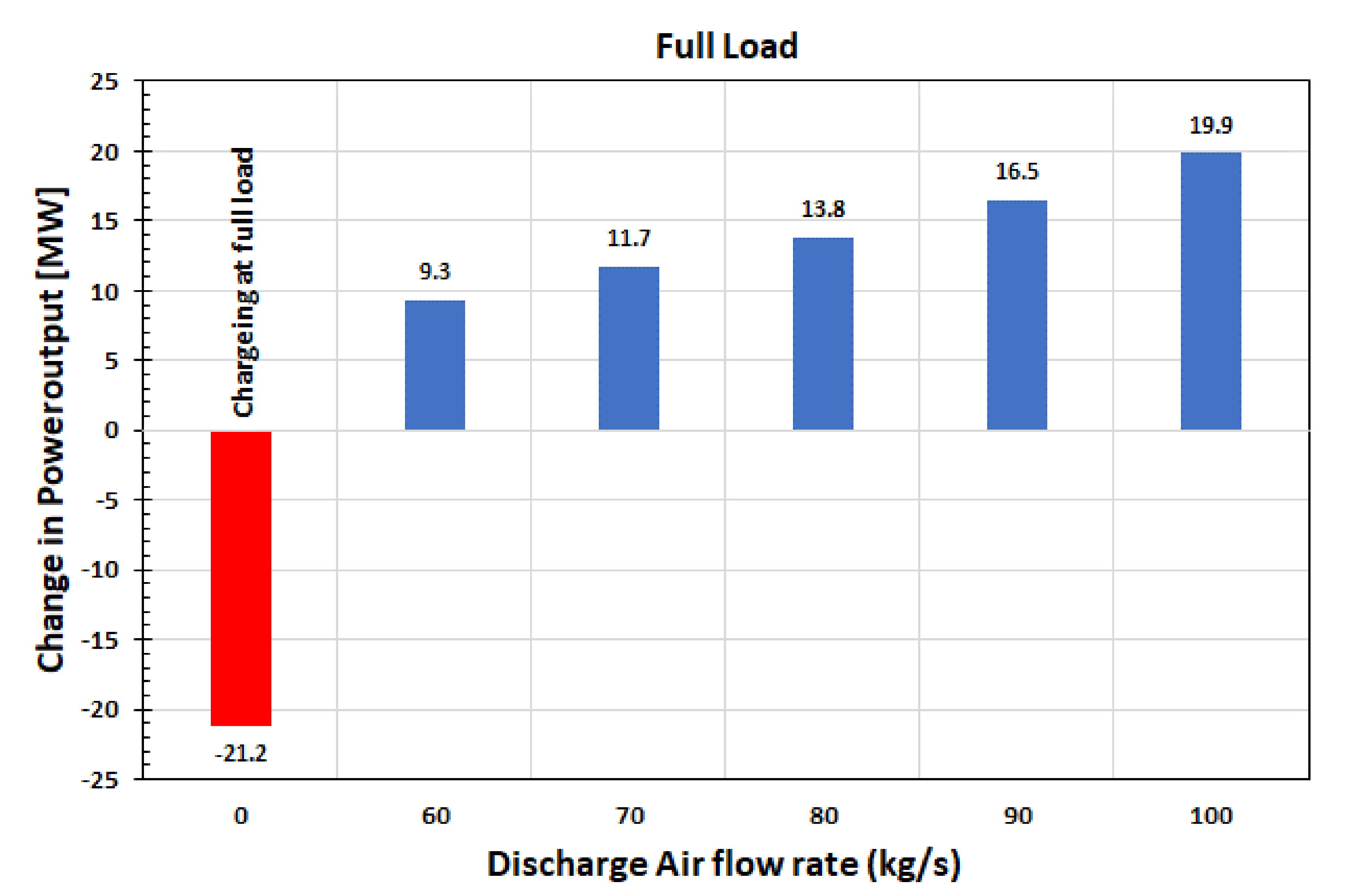


Simplified schematic

Discharging

- ***LAES is discharged when the plant power output needs to be increased.***
- *Liquefied air stored in a liquid storage tank is discharged from the tank, and its pressure is increased by the liquid air (cryogenic) pump.*
- *After evaporation in the evaporator, saturated air is superheated in* ***HEX_4*** *and expanded in air turbine* ***T_1****. Turbine exhaust is reheated in a reheater* ***HEX_3*** *prior its expansion in air turbine* ***T_2****.*
  - *In the presented simplified configuration, heat for the heat exchangers* ***HEX_3*** *and* ***HEX_4*** *is supplied by the steam extracted from the HP steam exhaust, resulting in a decrease in turbine power output.*
  - *This decrease is offset by the electric power output generated air turbines* ***T_1*** *and* ***T_2****.*
  - *Net power output of the* ***integrated power plant-LAES system (Integrated System)*** *increases.*
- *In a more complex and efficient configuration, a combination of the* ***IP*** *and* ***LP*** *turbine extractions and additional HEXs are used to minimize a decrease in the steam turbine power output.*

Liquid Air Energy Storage (LAES)

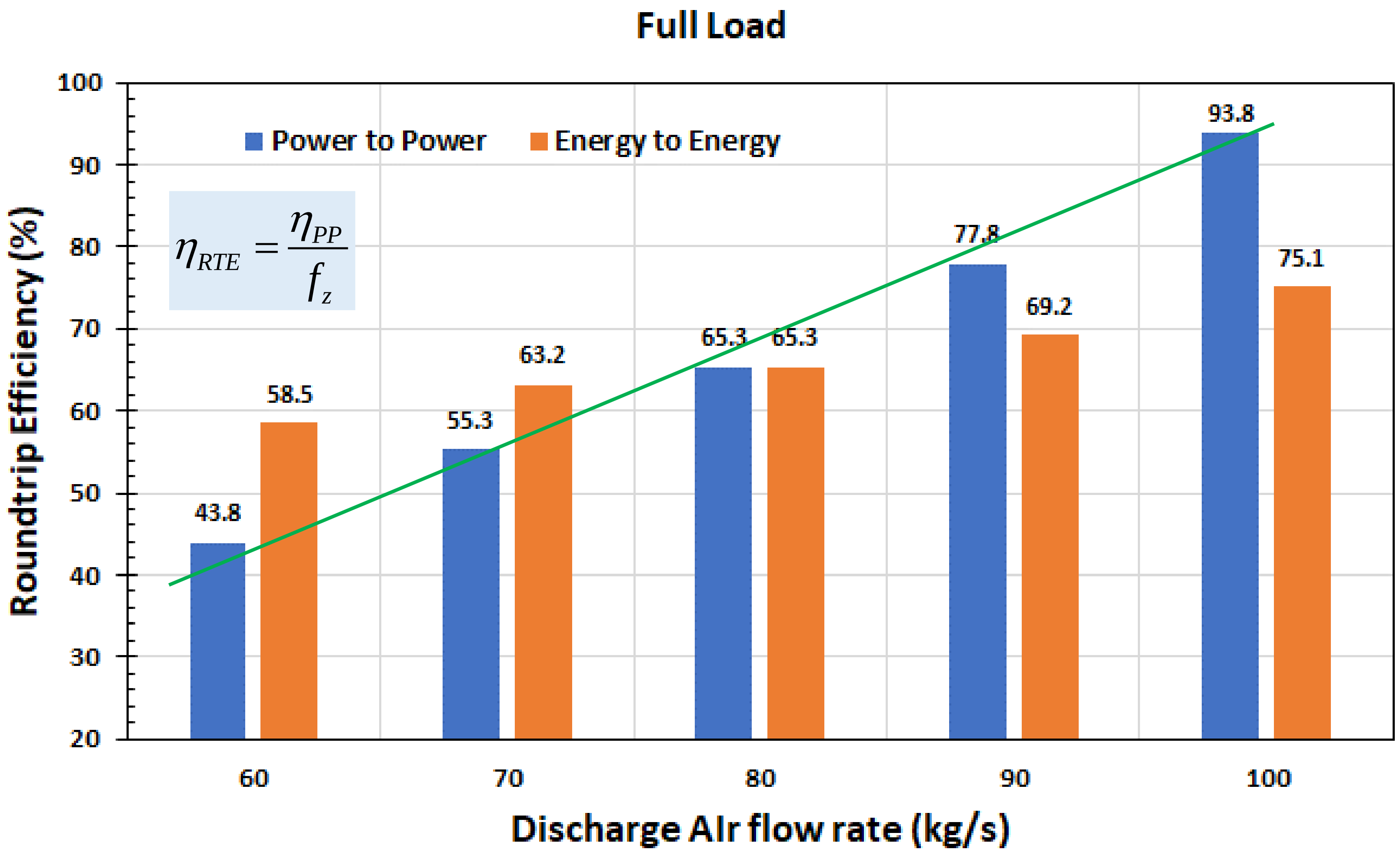


Reference charging flow rate 80 kg/s

Full load Charging and Discharging

- *For the reference charging flow rate of 80 kg/s, the net plant power output decreases by* ***21.2 MW****, or* ***3.9%*** *of the full load power output.*
- *During the LAES discharging, the net power output increases linearly with the flow rate of liquid air.*
- *As the discharging liquid air flow rate increases from* ***60*** *to* ***110 kg/s****, the net plant power output increases linearly from* ***9.3*** *to* ***19.9 MW****, or* ***1.7*** *to* ***3.6%*** *from the base power output.*
- *For the LAES discharging flow of 80 kg/s (f_y = 1), the net plant power output increases by* ***13.8 MW*** *or* ***2.5%****.*
- *At full load, the integrated LAES system would allow power plant to*
  - *follow load in the* ***± 20 MW*** *range and improve its participation in frequency regulation*
  - *or to increase maximum power output by* ***20 MW*** *when power prices are favorable.*

Liquid Air Energy Storage (LAES)

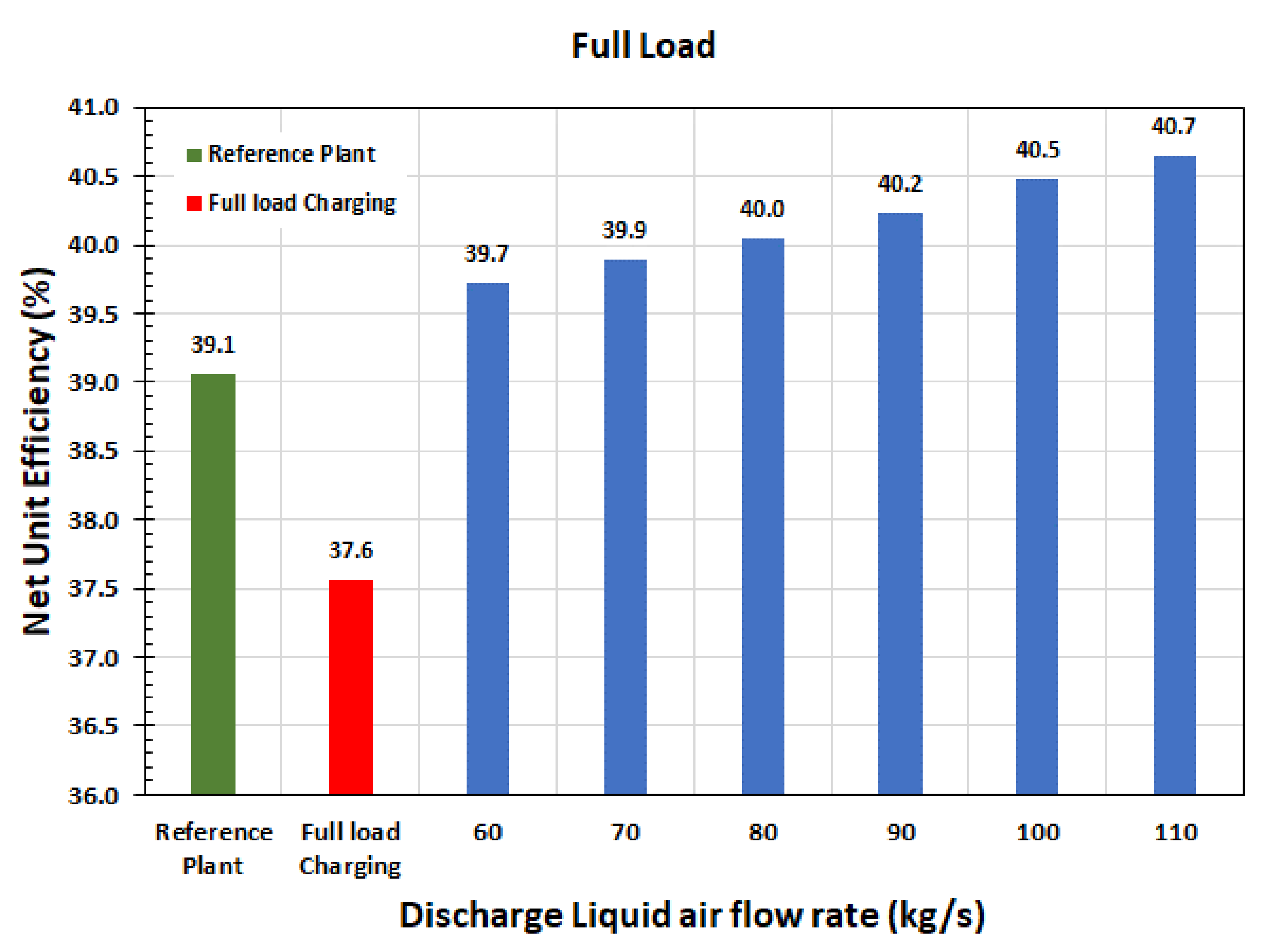


Reference charging flow rate 80 kg/s

Roundtrip Efficiency

- *The power-to-power and energy-to-energy roundtrip efficiencies increase linearly with discharging air flow rate.*
  - *During LAES discharging the plant net power output increases linearly with the discharge air flow rate.*
- *For the discharging liquid air flow rate of 100 kg/s, the power-to-power roundtrip efficiency* $\boldsymbol{\eta_{PP}}$ *is very high, approximately 94% and is higher compared to* $\boldsymbol{\eta_{RTE}}$*.*
- *The rate of increase in power-to-power roundtrip efficiency is higher compared to the energy-to-energy roundtrip efficiency.*
  - *For discharging air flow of 80 kg/s (f_z = 1),* $\eta_{PP} = \eta_{RTE}$*.*
  - *For discharging air flow rate higher than 80 kg/s (f_z > 1),* $\eta_{RTE} < \eta_{PP}$*.*

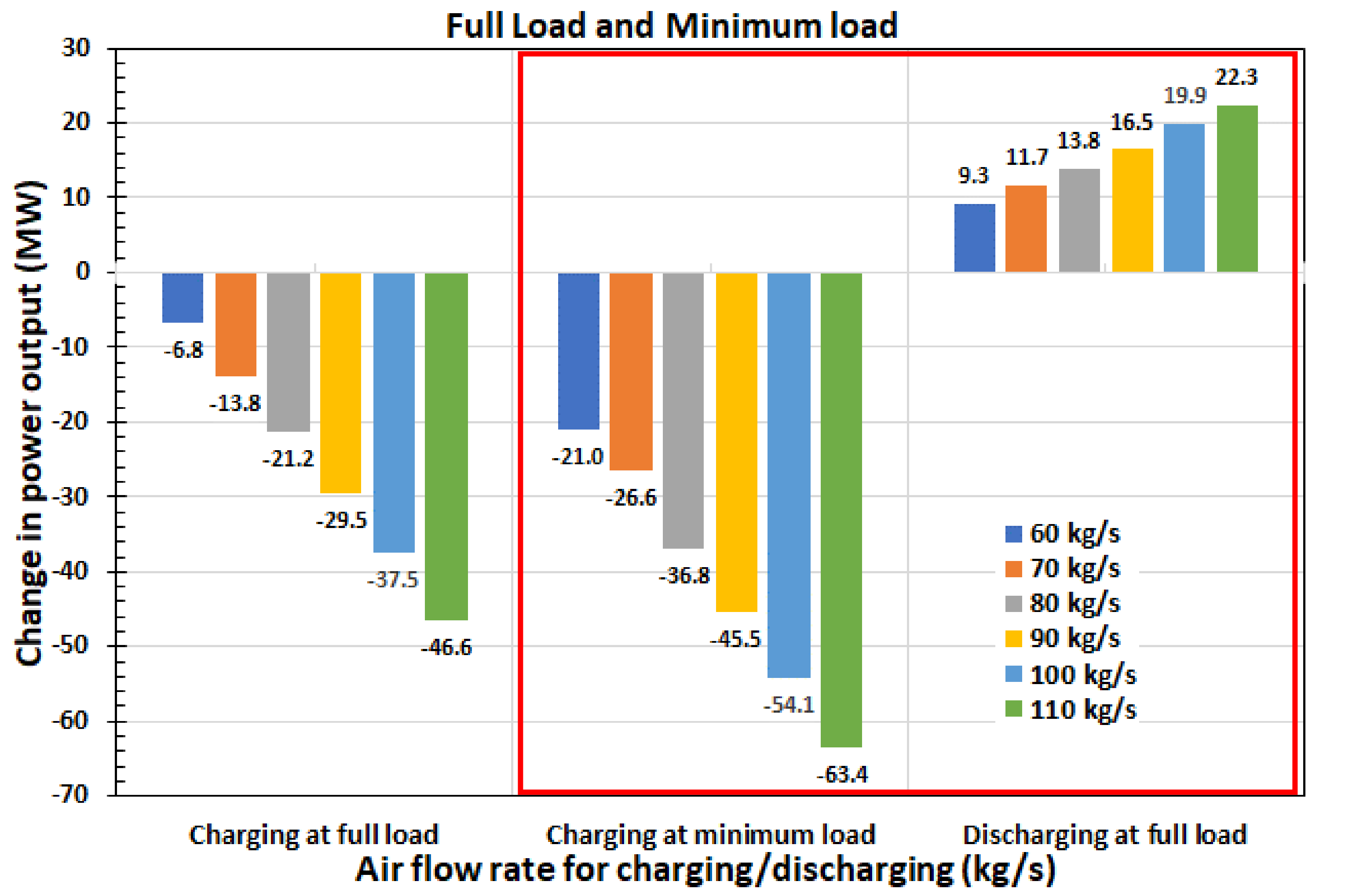
Liquid Air Energy Storage (LAES)



Performance of a Reference Plant with Integrated LAES

- *A constant heat input was considered. during the charging and discharging.*
- *Using electrical energy from the main el. generator to run the compressors for LAES **charging** decreases unit efficiency and increases net unit heat rate.*
  - *Increase in LP turbine power output due to lower steam extractions for LP FWHs, partially offsets a decrease in net power output.*
- *During LAES discharging, the power output of air turbines increases net plant power output.*
  - *Higher net unit efficiency*
  - *Steam extractions from IP and LP turbines for air superheating and reheating partially offset efficiency improvement.*
- *Net unit efficiency η_{net} decreases by **1.5%-points** during LAES charging.*
- *During LAES discharging, η_{net} increases from **0.6** to **1.6%-points** during, depending on the discharge air flow.*

Liquid Air Energy Storage (LAES)



The value of η_{RTE} may be increased by charging LAES at the minimum load with a low charging flow for a long time and discharging it at the full load at high discharging flow for a short time, i.e., at a high value of f_z.

Load Shift

- LAES is charged at min load for 3 hours and discharged at full load.
- Net power change during charging / discharging is a linear function of the charging /discharging air flow.

Charging/discharging flow = 80 kg/s

- Decrease in ΔP_{net} during charging at min load is **36.8 MW (3.5%).**
- Increase in ΔP_{net} during discharging at full load is **13.8 MW (2.5%)**.
  - η_{PP} is 37.5%, η_{RTE} is 65.3%
- A decrease in power output at min load is larger compared to the full load.
  - At lower load, net unit power output is lower, while for the same air flow rate, power input to air compressors is the same.
  - At minimum load, LAES has larger effect on plant performance compared to the full load.

Summary of TES Performance

Effect of TES Charging/Discharging on Net Plant Power Output and TES Roundtrip Efficiency

Operation at Full Load

	Charging				Discharging				Roundtrip Efficiency							
TES System	ΔP_{chg}	$\Delta P_{chg,AVG}$	ΔP_{chg}	$\Delta P_{chg,AVG}$	ΔP_{dchg}	$\Delta P_{dchg,AVG}$	ΔP_{dchg}	$\Delta P_{dchg,AVG}$	$\eta_{RTE,P\text{-}P,MAX}$	$\eta_{RTE,P\text{-}P}$	$\eta_{RTE,E\text{-}E}$	**Notes**	Storage Volume	Storage Capacity	Charging Time	Discharging Time
	MW	MW	%	%	MW	MW	%	%		%	%			MWh_{th}	min	min
LP Condensate Storage	-15.7		-2.5		14.6		2.3			93.1	93.1	Condensate flow to LP tanks = 40% of BFP flow (211.6 kg/s)	2,285 t	318	180	180
	-9.8		-1.5		9.3		1.5			95.5	95.5	Condensate flow to LP tanks = 25% of BFP flow (132.3 kg/s)	1,428 t	201	180	180
Molten Solar Salt Storage	-23.2		-3.6		20.9		3.3			90.1	26.1	FW Bypass flow = 90 kg/s (16.5% of BFP flow)	1,080 t	157	180	70
	-23.2		-3.6		15.8		2.5			68.1	26.5	FW Bypass flow = 70 kg/s (13% of BFP flow)			180	52
LAES	-21.2		-3.9		13.8		2.5			65.1	65.3	Charging/Discharging flow = 80 kg/s (f_z = 1)	1,250 m^3	136	180	224
	-21.2		-6.8		19.9		3.6			93.9	75.1	Charging flow = 80 kg/s, Discharging flow = 100 kg/s (fz = 1.25)			180	180
FB TES	-45.5	-40.1	-7.2	-5.70	16.6	13.7	2.6	2.2	36.5	34.2	31.5	HTF Flow = 28 kg/s	2,000 mt	175	270	270 (160*)
	-66.3	-48.4	-10.4	-7.62	23.4	19.0	3.7	3.0	35.3	39.2	30.4	HTF Flow = 40 kg/s	2,000 mt		210	120

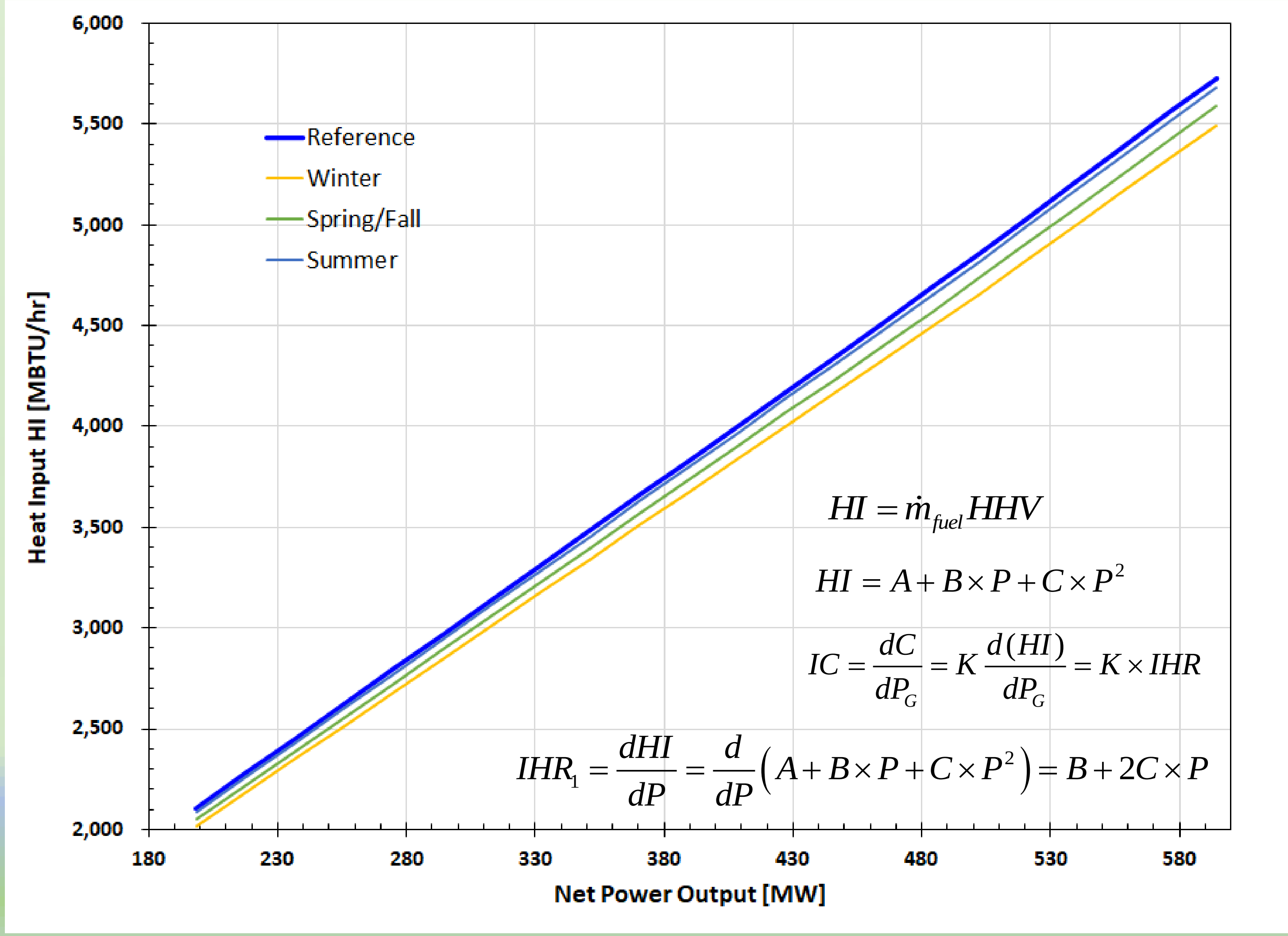
Operation at Minimum Load

	Charging				Discharging				Roundtrip Efficiency							
TES System	ΔP_{chg}	$\Delta P_{chg,AVG}$	ΔP_{chg}	$\Delta P_{chg,AVG}$	ΔP_{dchg}	$\Delta P_{dchg,AVG}$	ΔP_{dchg}	$\Delta P_{dchg,AVG}$	$\eta_{RTE,P\text{-}P,MAX}$	$\eta_{RTE,P\text{-}P}$	$\eta_{RTE,E\text{-}E}$	**Notes**	Storage Volume	Storage Capacity	Charging Time	Discharging Time
	MW	MW	%	%	MW	MW	%	%		%	%			MWh_{th}	min	min
LP Condensate Storage	-6.6		-2.0		6.2		1.85			92.7	92.7	Condensate flow to LP tanks = 40% of BFP flow (109.2 kg/s)	1,179 t	144	180	180
	-4.1		-1.3		3.9		1.2			93.0	93.0	Condensate flow to LP tanks = 25% of BFP flow (68.2 kg/s)	737 t	90	180	180
Molten Solar Salt Storage	-11.7		-3.5		12.3		3.7			104.9	28.3	FW Bypass flow = 24% BFP flow (70 kg/s)	1,080 t	123	180	180
	-11.7		-3.5		15.9		4.7			135.7	28.4	FW Bypass flow = 31% BFP flow (90 kg/s)			180	180
LAES	-36.8		-6.7		12.2		6.7			33.2	33.2	Charging/Discharging flow = 80 kg/s (f_z = 1)	1,250 m^3	135	224	224
	-36.8		-9.8		19.2		9.8			52.2	41.8	Charging flow = 80 kg/s, Discharging flow = 100 kg/s (fz = 1.25)			224	180
FB TES	-45.0	-35.8	-7.1	-5.7	15.4	12.8	2.4	2.0	34.2	35.6	29.7	HTF Flow = 28 kg/s	2,000 mt	175	270	270 (160*)

Economic Performance

Economic Performance

Heat Input – Reference plant: winter, summer and fall/spring



$$HI = \dot{m}_{fuel} HHV$$

$$HI = A + B \times P + C \times P^2$$

$$IC = \frac{dC}{dP_G} = K \frac{d(HI)}{dP_G} = K \times IHR$$

$$IHR_1 = \frac{dHI}{dP} = \frac{d}{dP}\left(A + B \times P + C \times P^2\right) = B + 2C \times P$$

Economic Model

- *The economic dispatch model for the Reference plant w/o ITES was developed by the Customized Energy Solutions (CES) using information on the reference plant performance and the* ***actual market price data and trading rules*** *for the energy market the plant is operating in.*
  - *The Reference plant represents a "state of the art" design of a 645 MW_{gross} subcritical unit at 2,400 psia, 1,000 ^{o}F main steam (MST) and 1,000 ^{o}F hot reheat steam (HRHT) temperature.*
  - *Coal: Eastern Bituminous*
  - *Air pollution control system for* ***SO_x***, ***NO_x***, *and* ***PM*** *control.*
- *Two energy markets were considered,* ***MISO*** *and* ***PJM***. *The dispatch model was used to establish baseline economic performance of the reference plant in these two markets.*

Economic Performance

- *Economic analysis is being performed by the **Customized Energy Solutions, Ltd (CES)** a professional engineering company specializing in analysis of economic performance of power generation facilities and assets in different energy trading markets managed by ISOs (Independent System Operators).*
- *There are seven ISOs in the U.S.. All except Texas ISO, ERCOT are subject to FERC jurisdiction. Other regional ISOs are PJM, MISO, CAISO, SPP and NE ISO, and NY ISO.*
  - *The analysis was performed for the MISO and PJM markets.*
- *A description of ISO roles and definitions of the critical ISO procured services is given in the next slide to help understand how a power plant (with or without integrated energy storage) receives its revenue and what the role of an integrated energy storage system will be.*
- *As the electric utility industry was deregulated, utilities in some regions of the U.S. transferred the responsibility of managing the high-voltage transmission lines to independent transmission operators, known as **Independent System Operators (ISO)** and **Regional Transmission Operators (RTOs)**. Besides sending electricity over the transmission lines, the ISO or RTOs maintain the quality and reliability of the electricity as specified by the North American Electric Reliability Corporation (NERC).*

Economic Performance

- *To maintain a smooth operation of the transmission grid, ISO/RTO procure services through competitive bidding from third parties to stabilize the electrical grid system.*
- *Besides procuring **Capacity** and **Energy**, ISOs also procure **Ancillary Services (A/S)** that are a collection of secondary services purchased by ISO/RTOs to help insure the reliability and availability of energy to consumers.*
- ***Energy storage systems (ESS) are unique** as they consume electricity when charging and generate electricity when discharging in response to signals from the ISO/RTO. However, ESSs must meet the same standards in terms of speed, ramp rates, quantity and quality that the ISOs require of other resources.*
- *ISO/RTOs have realized that ESSs have some unique capabilities and have **recently altered some rules** that accommodate some of their capabilities. ISO/RTOs are also aware of limitations of ESS that vary with the various ESS technologies.*
- ***ESS must adhere to the strict criteria set by ISO for procuring Energy, Capacity and Ancillary Services such as frequency control, regulation, spinning and non-spinning reserves.***
- *With the added capability of an ESS to store and the deliver (dispatch) electricity at will, the ESS can also engage in a strategy to buy electricity when it is priced low and then sell it back to the grid when it is priced high. This practice known as **arbitrage**.*

Economic Performance: *Services commonly procured by ISO*

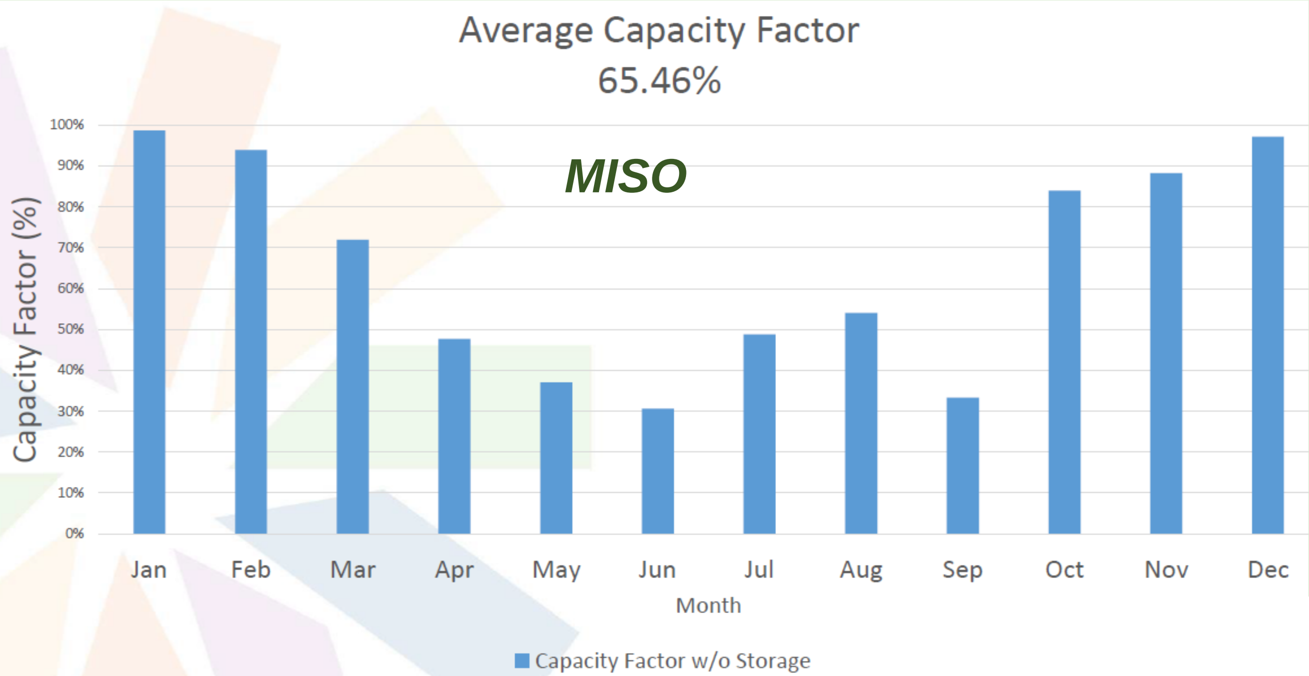
- *Primary Frequency Response (PFR)*
- *Arbitrage*
- *Ancillary services (A/S)*
  - ***Frequency Regulation***

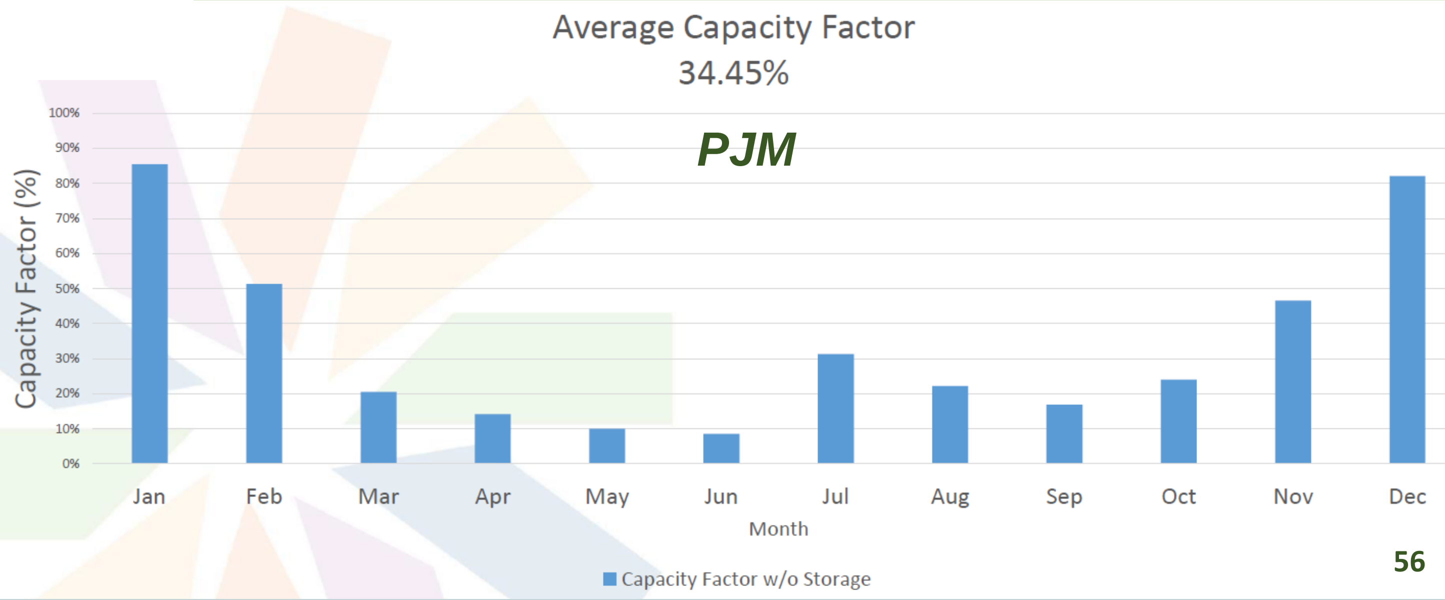
    A commonly used ancillary service by electrical grid operators for managing second-to-second imbalance between electricity generation and electricity demand (consumption). ISOs generally procure two separate services for managing frequency. Regulation Up (inject power to the grid) and Regulation Down (pull power from the grid) upon a signal from the grid.
  - ***Spinning Reserve** (on-line reserve capacity synchronized to the grid's frequency)*
  - ***Non-Spinning Reserve***

***Energy Markets**:*

- *ISOs operate two types of energy markets: **(1)** Day-Ahead Hourly Market (**DAM**) where energy is procured 24 hours later; **(2)** Real-Time Market (**RTM**) where ISO procure energy to the dispatch cycle every few seconds and committed a few minutes to a few hours ahead for the same day use.*
- *Revenue options from the above-described services were modeled using the Reference plant model and the **CoMETS** model.*
  - ***Competitive Markets Evaluation Tool for Storage (CoMETS)** is a proprietary code developed by CES based on a mixed integer linear modeling (MILP) optimization engine, used to determine optimal hourly dispatch of the Energy Storage System to maximize potential market revenues subject to participation in various market segments and under relevant operating constraints.*

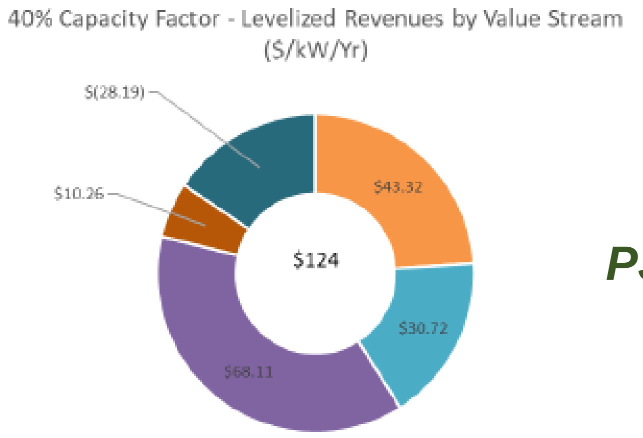
Capacity Factor (CF) of Reference Plant

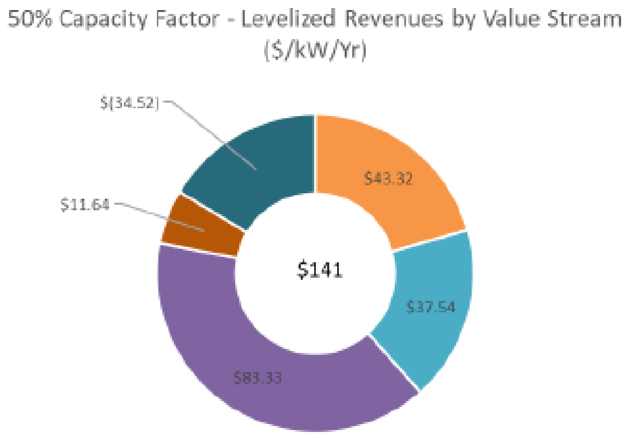


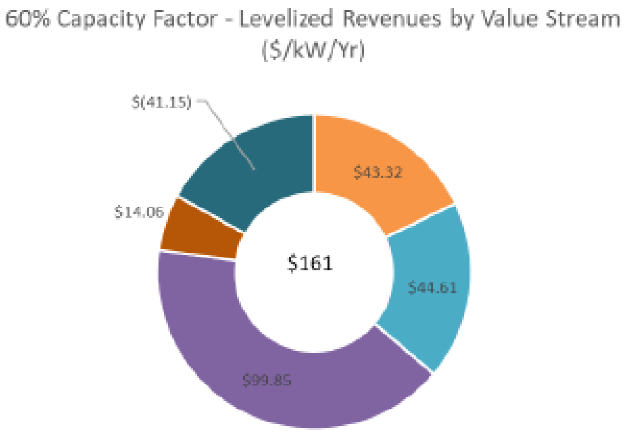


LP Condensate TES

Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF





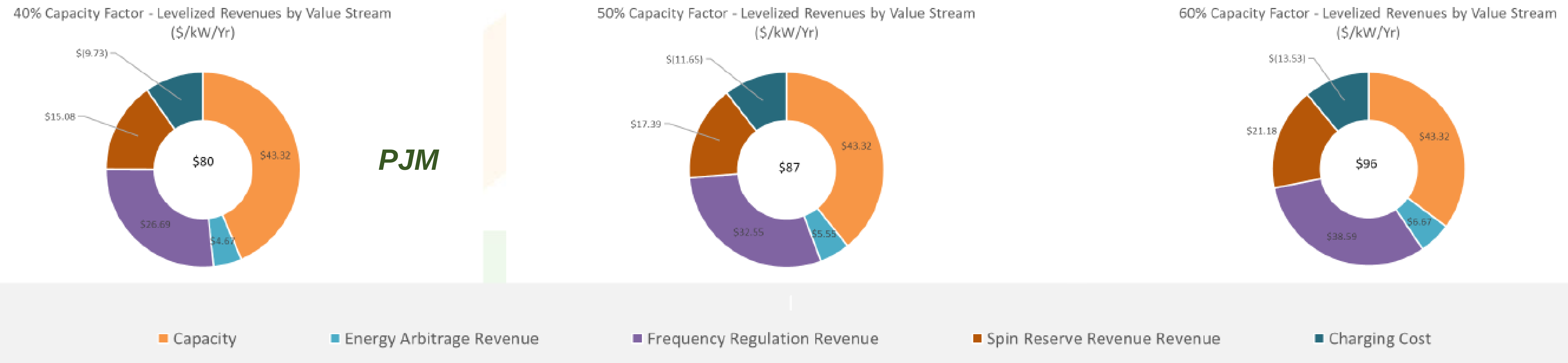


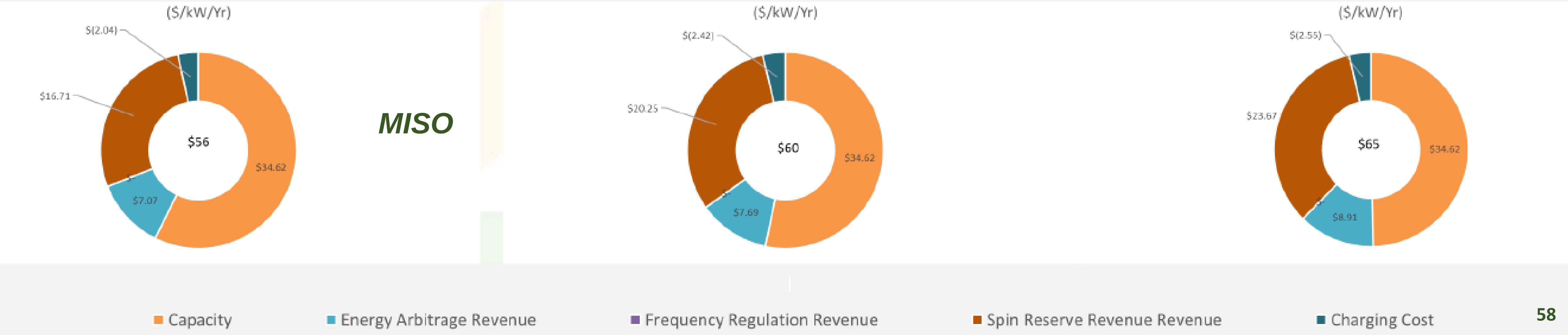
PJM

MISO

2-tank MSS TES

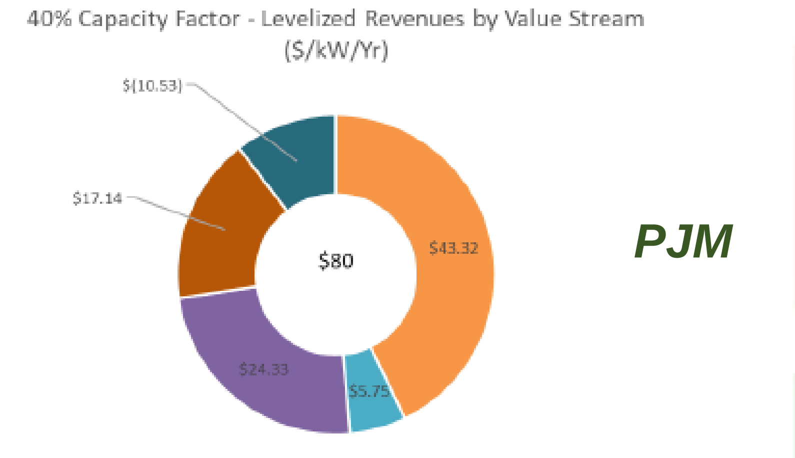
Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF



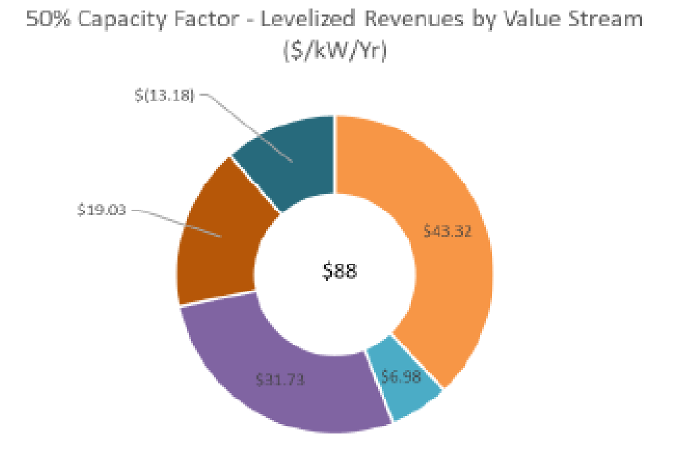


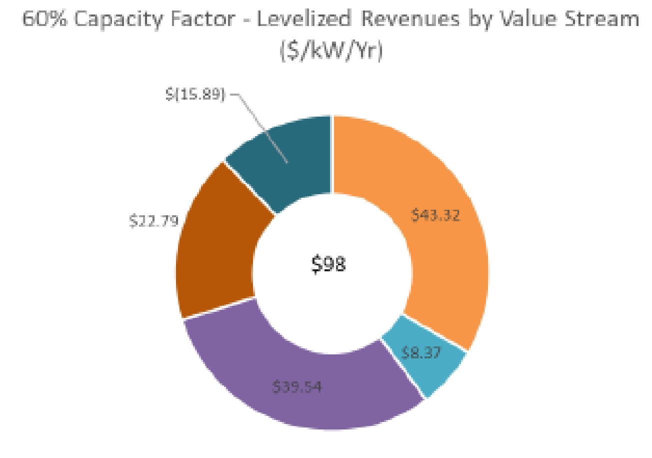
Fixed Bed TES

Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF

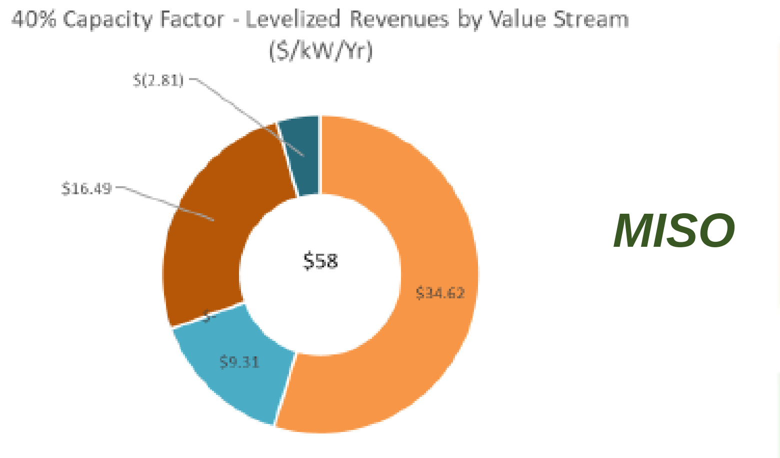


PJM

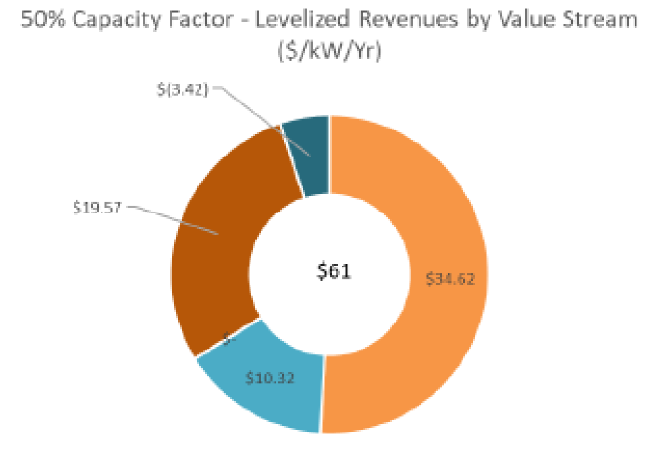


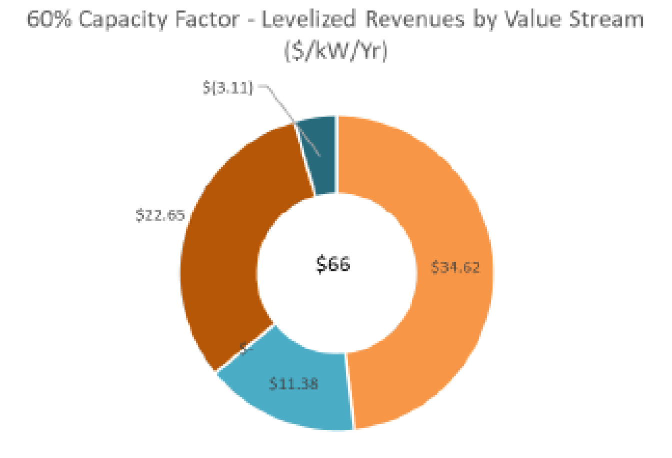


Capacity | Energy Arbitrage Revenue | Frequency Regulation Revenue | Spin Reserve Revenue Revenue | Charging Cost



MISO



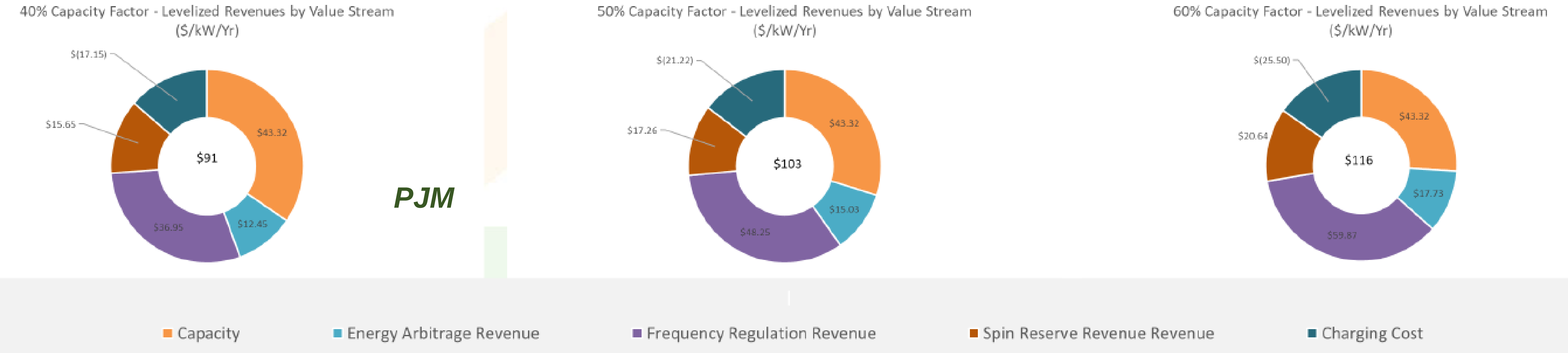


Capacity | Energy Arbitrage Revenue | Frequency Regulation Revenue | Spin Reserve Revenue Revenue | Charging Cost

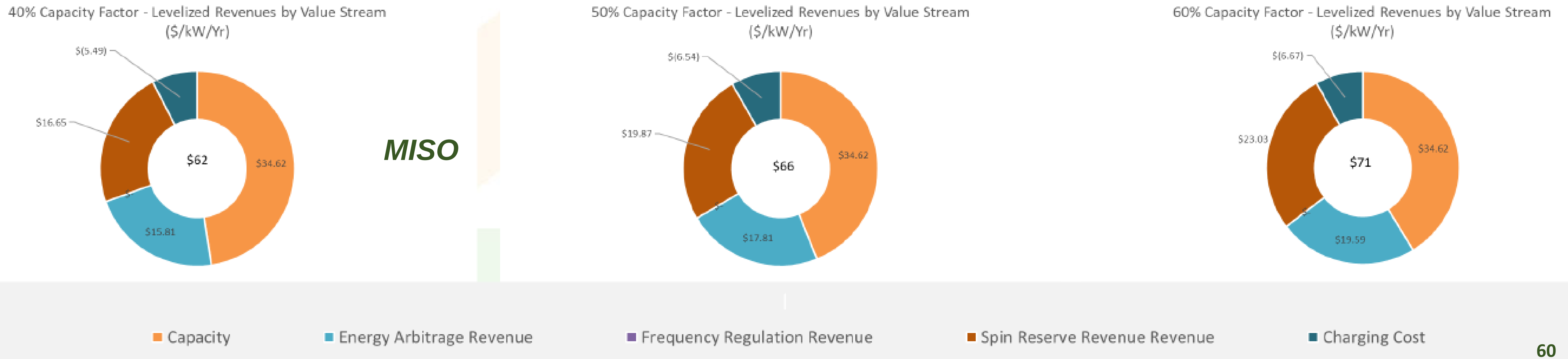
LAES (80 kg/s)

Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF

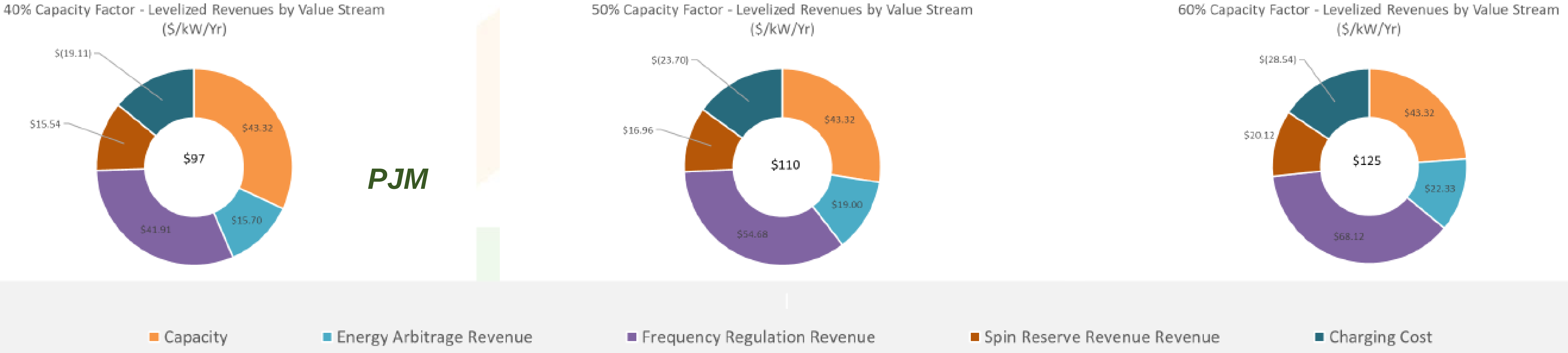
PJM

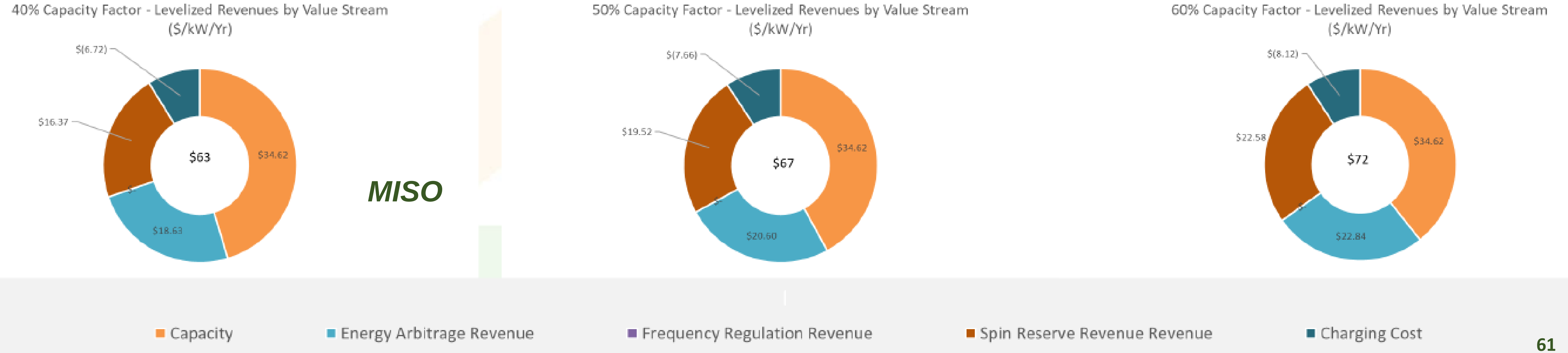


MISO

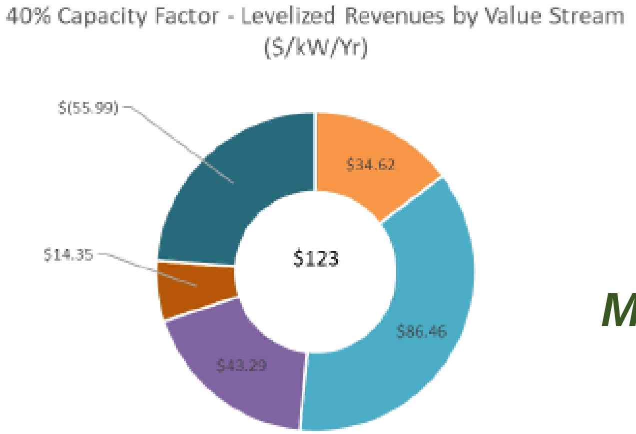


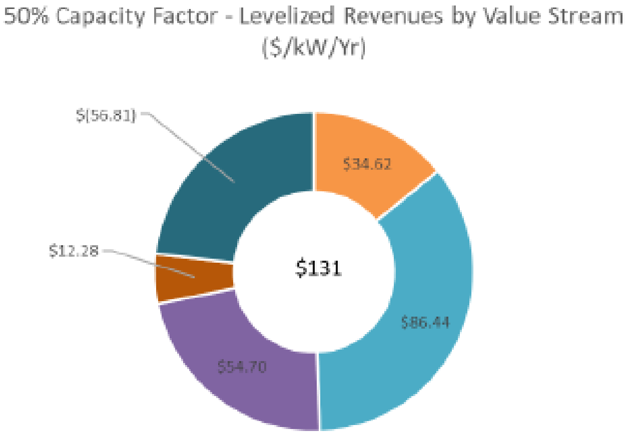
LAES (100 kg/s) *Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF*

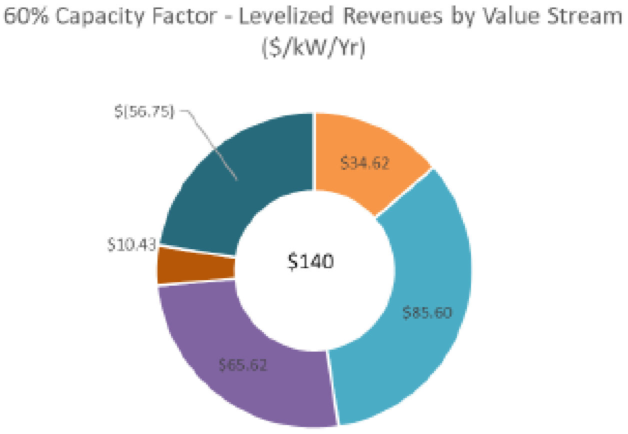




Battery Energy Storage System (BESS)



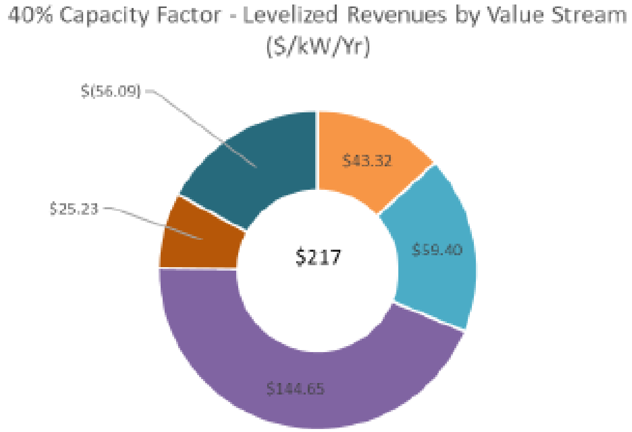


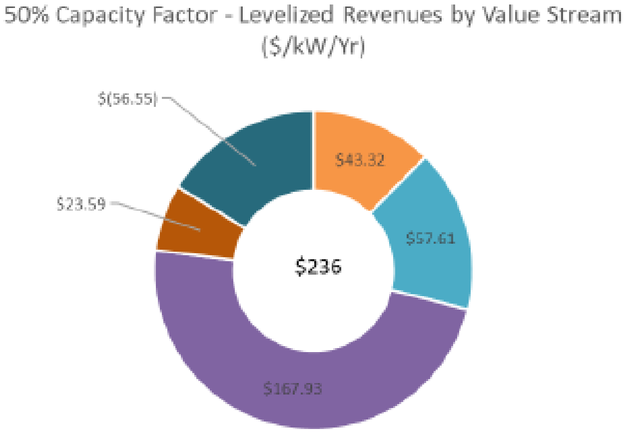


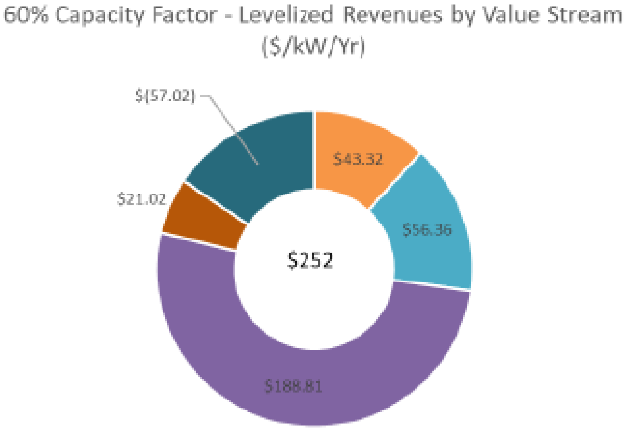
MISO

Levelized revenues by value stream for MISO and PJM energy markets as functions of plant CF

Capacity · Energy Arbitrage Revenue · Frequency Regulation Revenue · Spin Reserve Revenue Revenue · Charging Cost





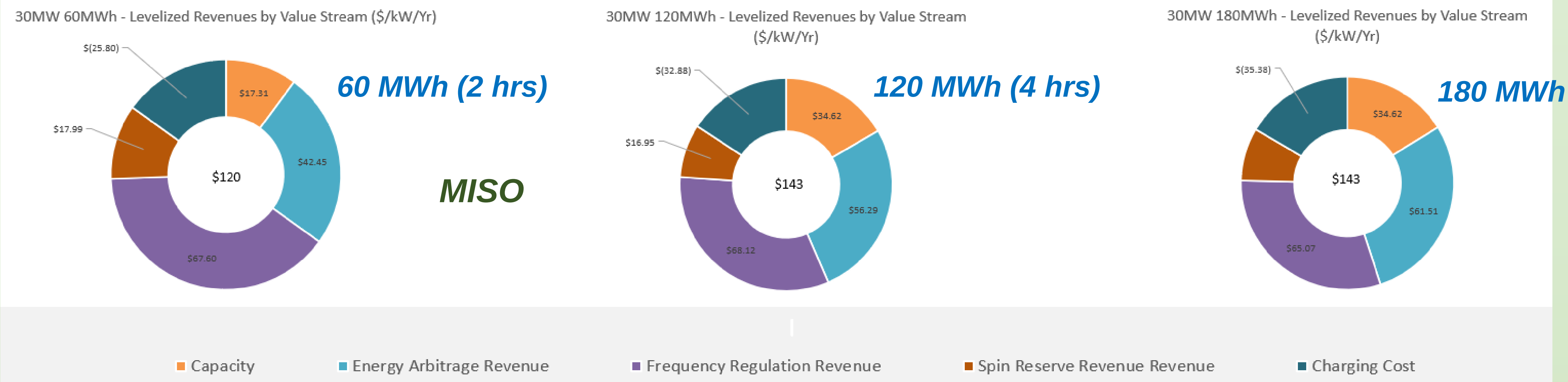


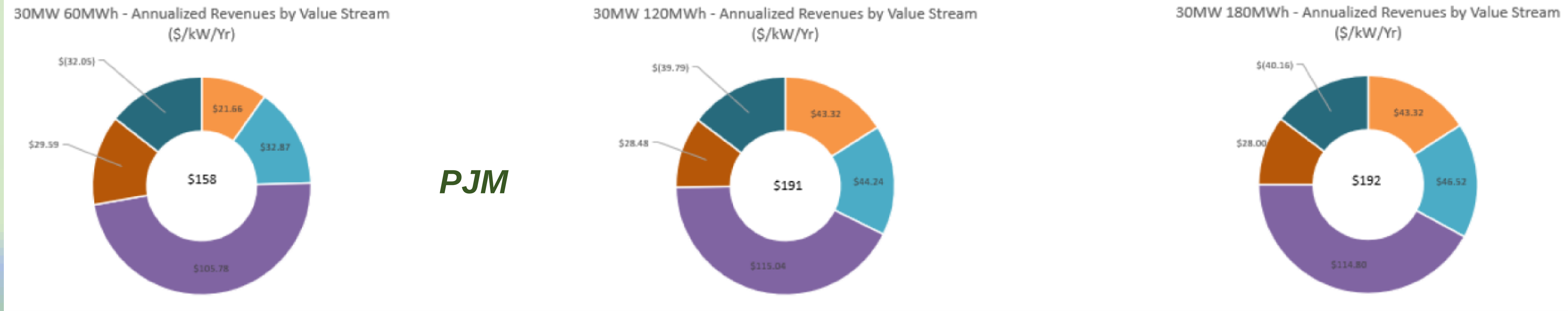
PJM

Capacity · Energy Arbitrage Revenue · Frequency Regulation Revenue · Spin Reserve Revenue Revenue · Charging Cost

Battery Energy Storage System (BESS)

Levelized revenues by value stream for MISO and PJM energy markets as functions of storage capacity





Results for both markets show diminishing return for storage capacities longer than 4 hours.

Capacity · Energy Arbitrage Revenue · Frequency Regulation Revenue · Spin Reserve Revenue Revenue · Charging Cost

Conclusions

- *Five TES designs and their integrations with a steam Rankine cycle (cycle) of coal-fired power plant were investigated to determine their impact on plant operation and flexibility, performance and economics.*
- *Performance of the Reference plant with and without integrated TES system (IES) was simulated over the range of unit loads using detailed models.*
  - *Plant power output and performance decrease during TES charging since heat is taken away from the cycle.*
  - *Plant power output and performance increase during TES discharging as stored heat is returned to the cycle.*
- *TES integration with the cycle improves plant flexibility.*
- *Improvement in plant flexibility primarily depends on TES integration. TES type is also important.*
- *The effect of investigated TES types on plant performance is relatively similar.*
- *TES roundtrip efficiency depends on TES type, integration, and operation.*
- *TES operation has a significant effect on its roundtrip efficiency.*
- *Analysis of economic performance was performed for PJM and MISO energy markets.*
- *Levelized revenues by value stream and other economic parameters were determined for the analyzed IES systems.*
- *The analysis of the results is in progress.*