Energy+Environmental Economics

Ternary Pumped Storage Flexible Capacity Assessment

Prepared for Absaroka Energy in response to NorthWestern Energy's 2015 Electricity Supply Resource Procurement Plan

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Arne Olson, Partner
Doug Allen, Managing Consultant
Vivian Li, Associate

Analysis Description

- **Absaroka Energy LLC asked E3 to compare their ternary pumped storage technology to conventional resources in terms of their ability to provide "flexible capacity"**
  - Conventional resources considered: Internal Combustion (Reciprocating) Engine, Frame Combustion Turbine, Aeroderivative Combustion Turbine
- **Flexible capacity does not have a specific definition, so we have looked at each resource's ability to provide**
  - System capacity
  - Ancillary Services

Flexible Capacity Cost Comparison

Nameplate Capacity	Frequency Response	Regulation Up/Down	Spinning Reserves	Non-spinning Reserves
Ability to provide capacity during peak events and contribute to required reserve margins	Most immediate response to deviations in grid frequency served by generator inertia	Provided by generators that are online and have capacity to increase or decrease generation output or load consumption (pumping)	Provided by units that are synchronized to the grid and, upon dispatch, able to ramp up within specified time frame	Provided by units that need not be synchronized to the grid, but are able to ramp up generation within specified time frame upon dispatch

Capital Cost Analysis
$\text{Product Specific Cost}\left(\frac{\$}{\text{kW}}\right) = \frac{\text{Capital Costs}^{*}\ (\frac{\$}{\text{kW}})}{\text{Product Specific Usable Capacity (\%)}}$

** Capital costs considered in this analysis include infrastructure costs as detailed in the 2015 NWE Electricity Supply Resource Procurement Plan*

Cost Comparison

- **For each capacity product, we describe the ability of the different generating technologies to supply that product**
- **We then calculate the product-specific cost per kW by technology**
  - Allows for more balanced comparison of "capacity cost" than a simple $/kW installed cost
- **This comparison focuses on *costs per unit of flexible capacity only*, and does not include an analysis of potential revenues**

Comparison Scope

- **This analysis looks solely at the comparative capital costs (per installed kW) of the different technologies**
  - Accounts for each technology's ability to provide different capacity services
  - Does not account for
    - Fuel / Variable Operating costs
    - Revenues from participation in energy markets
    - Potential impacts of carbon price or air quality operating restrictions
    - Carbon benefits of absorbing renewable overgeneration for later use

Assumptions

		Ternary Pumped Storage	Natural Gas Simple Cycle†		
Operating Characteristic	Units	Pumped Storage Hydro (PS)*	Internal Combustion Engine (ICE)	Aeroderivative Combustion Turbine (Aero)	Frame Combustion Turbine (Frame)
Technology	-	Ternary Unit	Warsila 18V50SG	GE LMS100	GE 7EA
Capacity	MW	150	18	93	79
Capital Costs◊	$/kW	$2,439	$1,756	$1,684	$1,459
Ramp Rate	MW/min	300	4	10	4
Start Time	min	0.4 – 1.5	not reported	not reported	not reported
Shut-down Time	min	2Δ	not reported	not reported	not reported
Min Run Time	Hours	not reported	1	8	8
Min Down Time	Hours	not reported	1	7	7
Operating Range	[min –max, as % of capacity]	-100% (pumping) – +100% (generating)	21%-100%	53%-100%	13%-100%

* *Data provided by Absaroka*

† *All Data taken from Thermal Resource Operating Parameters section of the NorthWestern Energy 2015 Electricity Supply Resource Procurement Plan*

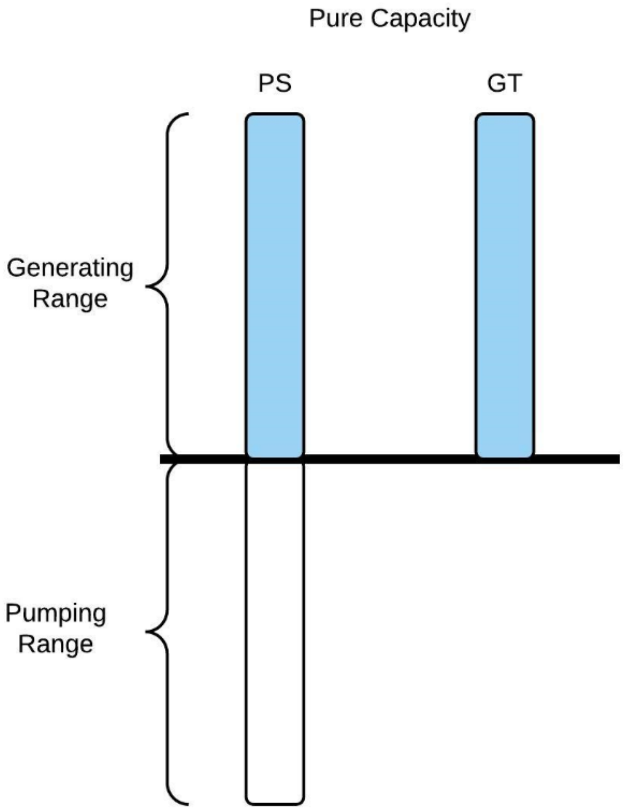
Δ *Assuming "transfer mode" as the final state of rest*

◊ *Includes "Infrastructure" costs as described in NWE's Procurement Plan*

Nameplate Capacity

- Usable capacity provided by the unit (as listed in the NWE Procurement Plan)
- Reflects the unit's contribution to reserve margins / system capacity
- Amount of capacity available to meet peak capacity needs

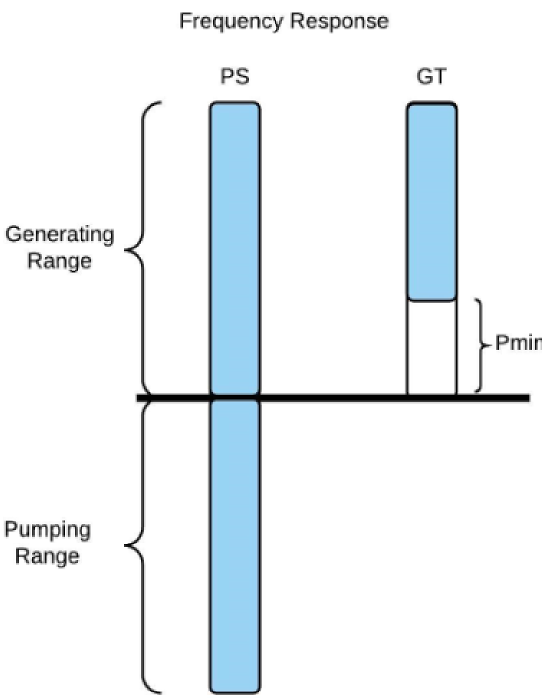
	Capacity Assumptions	Capital Costs (2018 $/kW)
PS	Generation rated power = 150 MW Pumping rated load = 150 MW	$2,439
ICE	Generation rated power = 18 MW	$1,756
Aero	Generation rated power = 93 MW	$1,684
Frame	Generation rated power = 79 MW	$1,459



Flexible Capacity: Frequency Response

- Primary control - most immediate response to deviations in grid frequency
- Served by generator inertia
- Provided primarily by frequency responsive loads and synchronous generators

	Capacity Assumptions	Usable Capacity Range (% of Nameplate)*	Capital Costs (2018 $/kW)
PS	• Inertia of turbine and generator provides frequency response • Some markets offer fast-frequency regulation products	200%	$1,220
ICE	• Primary response requirement for generators with governor function may exist • WECC specifies droop settings for conventional generators	79%	$2,223
Aero		47%	$3,583
Frame		87%	$1,677

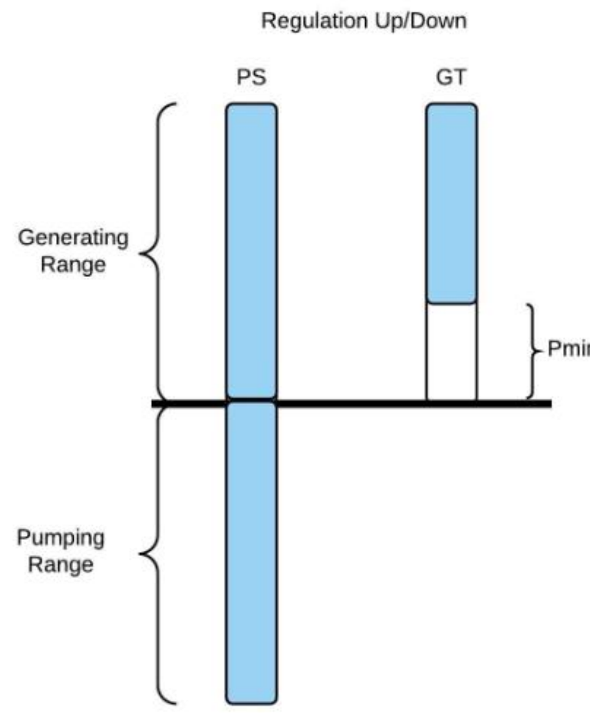


Assuming operating state is at optimal position for providing frequency response [ex. GT at Pmin]

Flexible Capacity: Regulation Up/Down

- Secondary control - occurs within seconds to minutes via automatic generation control
- Provided by generators who are online and have capacity to increase or decrease output

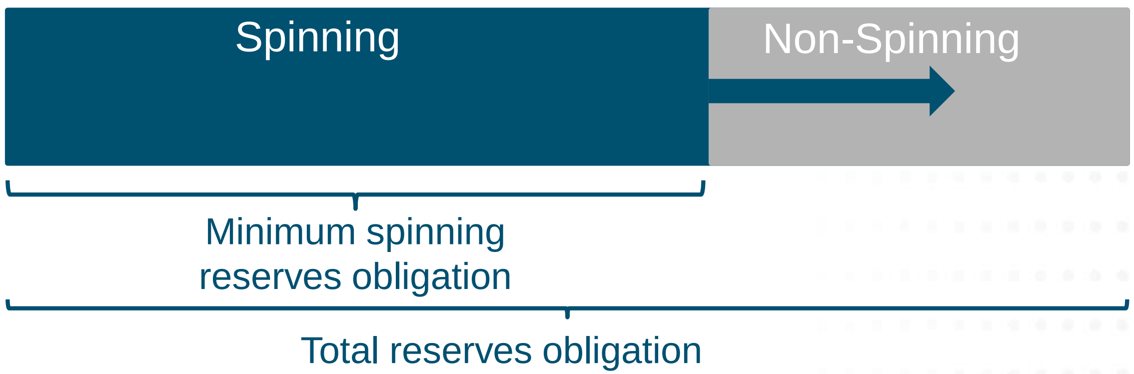
	Capacity Assumptions	Usable Capacity Range (% of Nameplate)*	Capital Costs (2018 $/kW)
PS	• Capacity to increase/decrease system output by reducing/increasing generation or load • Fast switching between modes doubles the effective range unit.	200%	$1,220
ICE	Capacity of conventional generators to provide regulation up and down is limited by ramp rate and minimum power generation levels.	79%	$2,223
Aero		47%	$3,583
Frame†		87%	$1,677



*Assuming operating state is at optimal position for providing frequency response [ex. GT at Pmin]
†Frame units are not usually used for Regulation given their limited operating flexibility

Spinning vs. Non-Spinning Reserves

- **Spinning/Non-spinning reserves are used to meet the same operating reserve obligation**

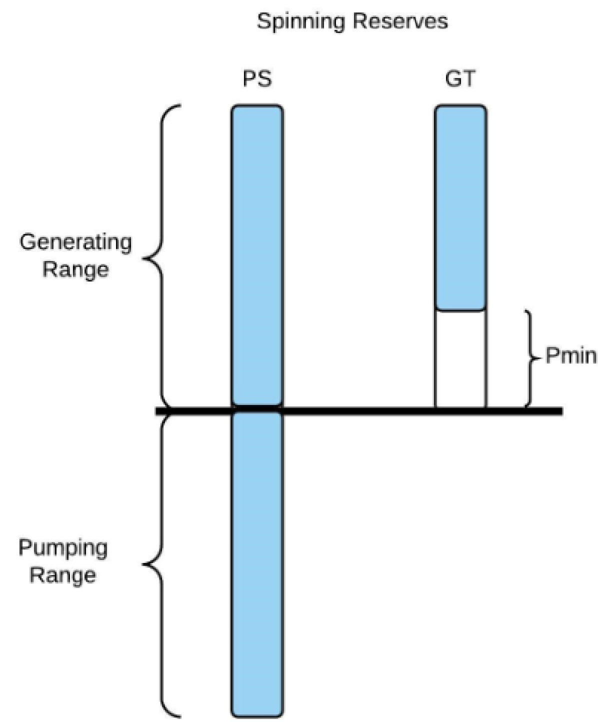


- **Fast response of ternary pumped storage units allows for provision of either spinning or non-spinning reserves, even when in charging mode**

Flexible Capacity: Spinning Reserves

- Tertiary control - system operator dispatches reserves in response to contingencies
- Provided by units that are synchronized to the grid and able to ramp up within specified time frame

	Capacity Assumptions	Usable Capacity Range (% of Nameplate)*	Capital Costs (2018 $/kW)
PS	• Fast ramp rate and mode switching allows for fast response to operator dispatch • Unit in generation, idling, or pumping mode • Can increase/decrease load or generation • Can switch from one mode to another	200%	$1,220
ICE	• Limited by ramp rate, start-up times (hot-start)	79%	$2,223
Aero		47%	$3,583
Frame		87%	$1,677

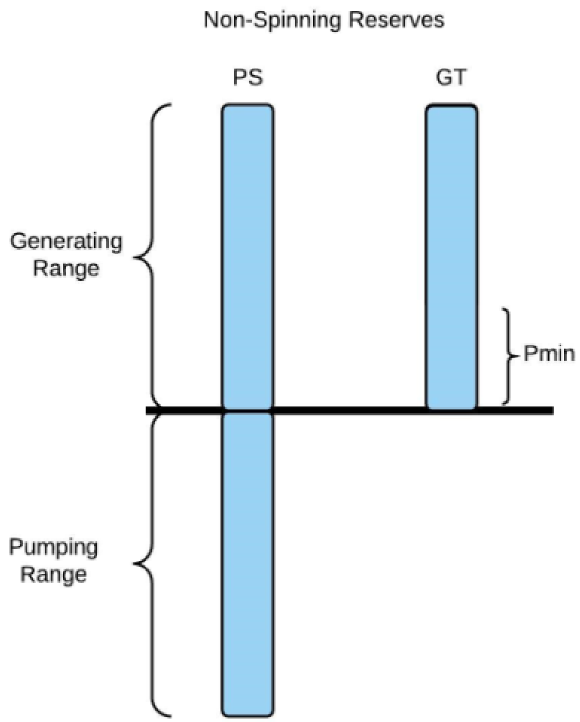


**Assuming operating state is at optimal position for providing frequency response [ex. PS pumping, GT at Pmin]*

Flexible Capacity: Non-Spinning Reserves

- Tertiary control - system operator dispatches reserves in response to contingencies
- Provided by units that *are not necessarily* synchronized to the grid, but able to ramp up generation within specified time frame
- Required response time is slower than spinning reserves

	Capacity Assumptions	Usable Capacity Range (% of Nameplate)*	Capital Costs (2018 $/kW)
PS	• Unit in standby mode • If dispatched, can quickly ramp up capacity	200%	$1,220
ICE	• Capacity and participation limited by ramp rate, start up time (cold-start)	100%	$1,756
Aero		100%	$1,684
Frame		100%	$1,459



**Assuming operating state is at optimal position for providing frequency response [ex. PS pumping, GT not on]*

Additional Flexible Capabilities

Operating Characteristic	Gordon Butte Pumped Storage Ternary Unit	Aeroderivative CT	Frame CT	ICE
Additional cost for each start	Minimal	Yes	Yes	Yes
Estimated median cold start cost*	n/a	$32/MW	$103/MW	Not provided
Can absorb overgeneration?	Yes	No	No	No
Black start?	Yes	Yes**	Yes**	Yes**

*Intertek APTECH (2012). Power Plant Cycling Costs. http://wind.nrel.gov/public/wwis/aptechfinalv2.pdf

**Siemens (2006). Black Start Studies. https://w3.usa.siemens.com/datapool/us/SmartGrid/docs/pti/2006June/Black_Start_Studies.pdf

Conclusions

+ **Compared to the conventional resources described in NWE's 2015 IRP filing, Ternary Pumped Storage can provide the following services at a cheaper per-kW installed price:**
  - Frequency Response
  - Regulation Up / Down
  - Spinning Reserve
  - Non-Spinning Reserve
+ **Beyond the ability to provide flexible and peak capacity considered here, this analysis does not reflect a pumped storage facility's ability to store energy for use later, which enables**
  - Absorption of overgeneration
  - Arbitrage of energy price spreads
  - Increased transmission system utilization