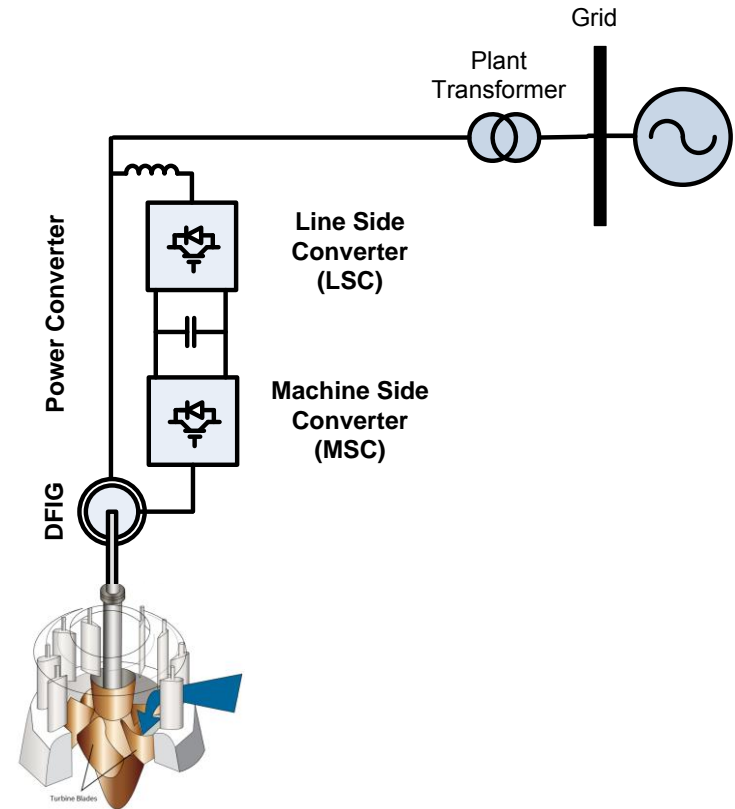


Figure 1: Typical Pumped Storage Plant Arrangement (Source: Alstom Power).



PSH Transient Simulation Modeling

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Pumped Storage Hydropower (PSH) Transient Simulation Modeling:

Developed model to simulate the transient electrical and hydrodynamic behavior of advanced pumped storage hydropower (PSH) plants

The Challenge:

Transient effects are an important consideration when designing a PSH system, yet numerical techniques for hydraulic transient analysis still need improvements for adjustable-speed (AS) reversible pump-turbine applications.

Partners:

Argonne National Lab (ANL): Project management and coordination

Idaho National Laboratory (INL): Hydrodynamic modeling

National Renewable Energy Laboratory (NREL): Electromagnetic transient (EMT) modeling

Next Generation Hydropower (HydroNEXT)

Optimization

- Optimize technical, environmental, and water-use efficiency of existing fleet
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Identify revenue streams for ancillary services

Growth

- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- **Facilitate mechanisms for testing and advancing new hydropower systems and components**
- Reduce costs and deployment timelines of new PSH plants
- Prepare the incoming hydropower workforce

Sustainability

- Design new hydropower systems that minimize or avoid environmental impacts
- Support development of new fish passage technologies and approaches
- Develop technologies, tools, and strategies to evaluate and address environmental impacts
- Increase resilience to climate change

Next Generation Hydropower (HydroNEXT)

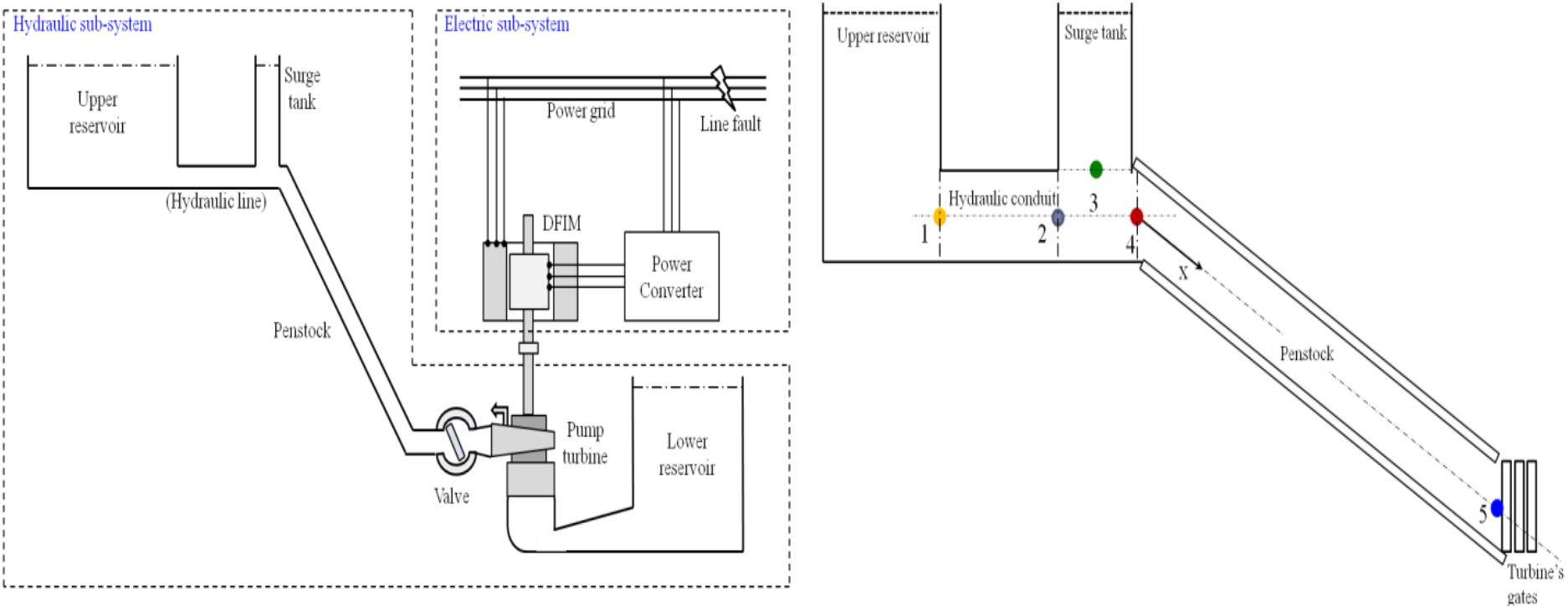
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The Impact

- The project will provide the industry and power system operators with the tools to perform simulations and modeling of transient behavior of advanced PSH technologies, allowing for better understanding of their impacts on the stability of power systems.
- Some impacts, such as the inertial response, are expected to contribute to greater stability of power systems with high penetration of renewable energy generation.
- These tools will facilitate the development of control algorithms customized to specific PSH generators to support the power system grid base on the existing conditions.
- First real-time co-simulation between electrical and hydrodynamic circuits under various dynamic conditions.

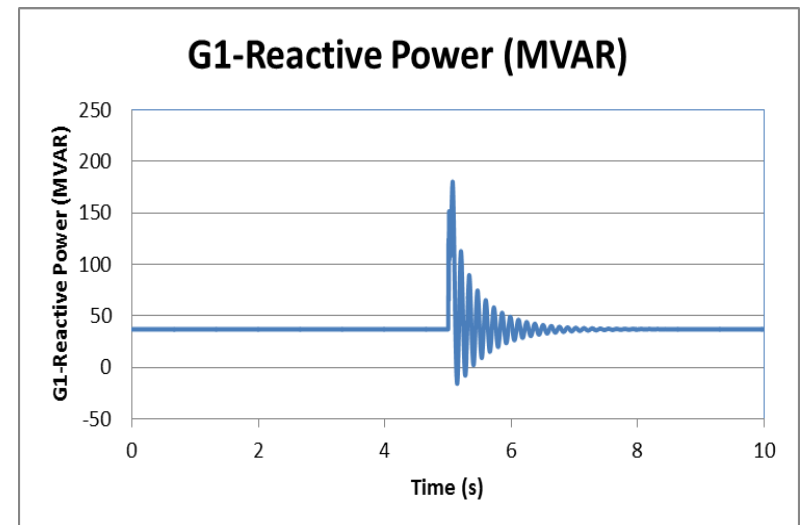
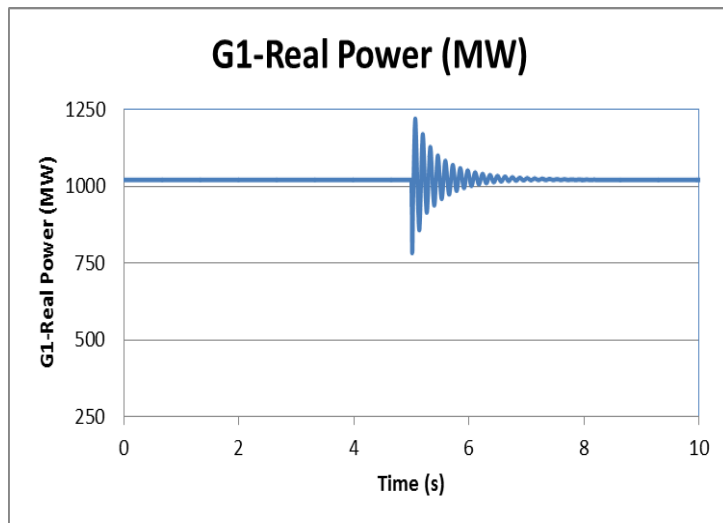
- Two primary subsystems within a typical AS-PSH are shown:
 - Hydraulic subsystem (solved at various boundaries)
 - Electric subsystem (includes transmission network and converters)
- Modes of operation - normal generation, normal pumping, idle, etc.



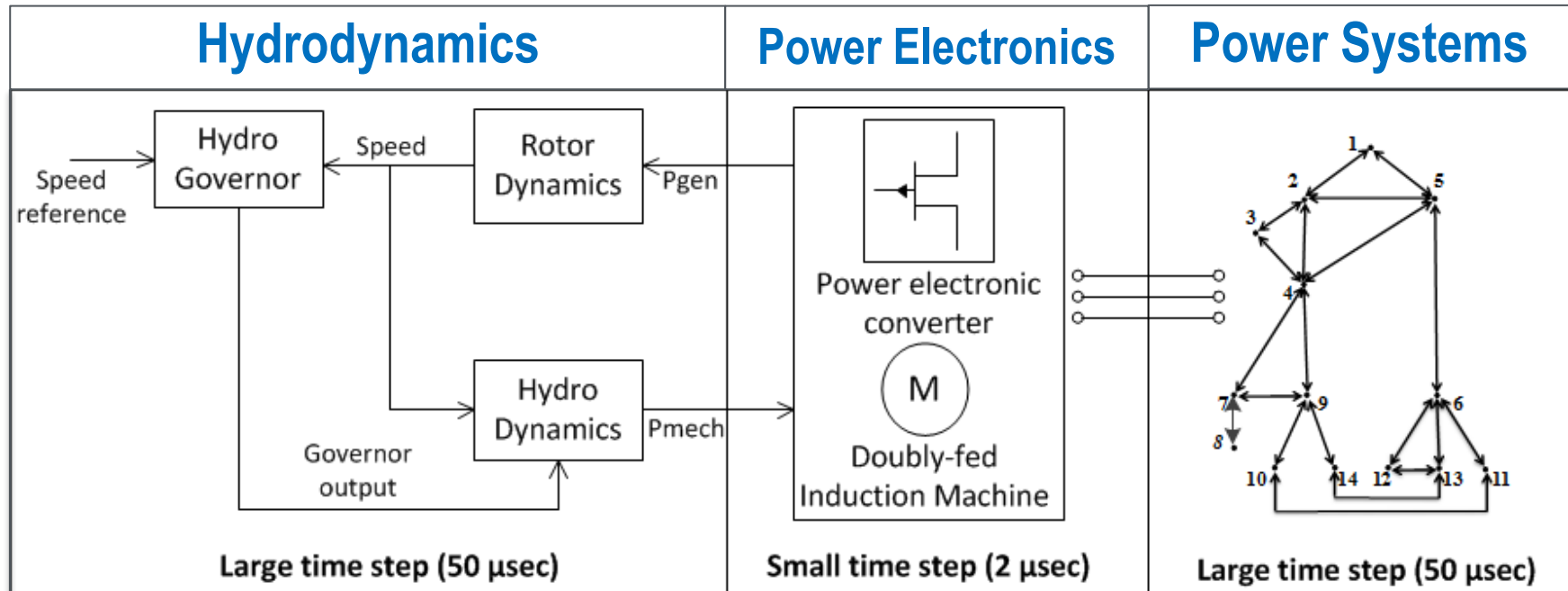
Hydrodynamic Model: Physics-based, vendor-neutral model that can provide a dynamic and transient response in real time

- Simulates several different modes of operation of AS-PSH
- Co-simulates the hydrodynamics with other domains (i.e., electrical, mechanical, and thermal) as needed
- Demonstrates participation in both real time energy and ancillary service market
- Provides an environment for Controller-Hardware-In-the-Loop (CHIL), Hardware-In-the-Loop (HIL), and Power-Hardware-In-the-Loop (PHIL) to serve as a verification and validation platform.

EMT Dynamic Model: Simulates balanced and unbalanced conditions (e.g. single line to ground fault) as compared to existing Positive Sequence dynamic model of the AS-PSH. The program is an open source program, thus allowing modification to the control block diagrams and algorithms to resolve various issues (e.g. sub-synchronous resonance, power oscillations).

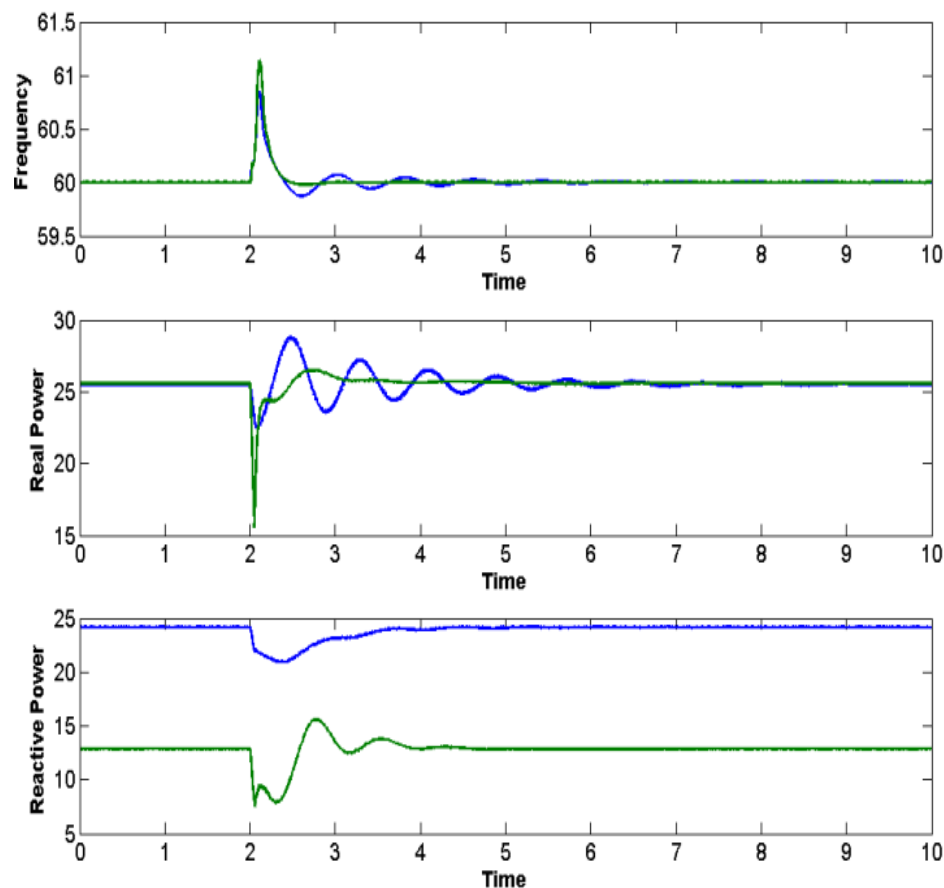
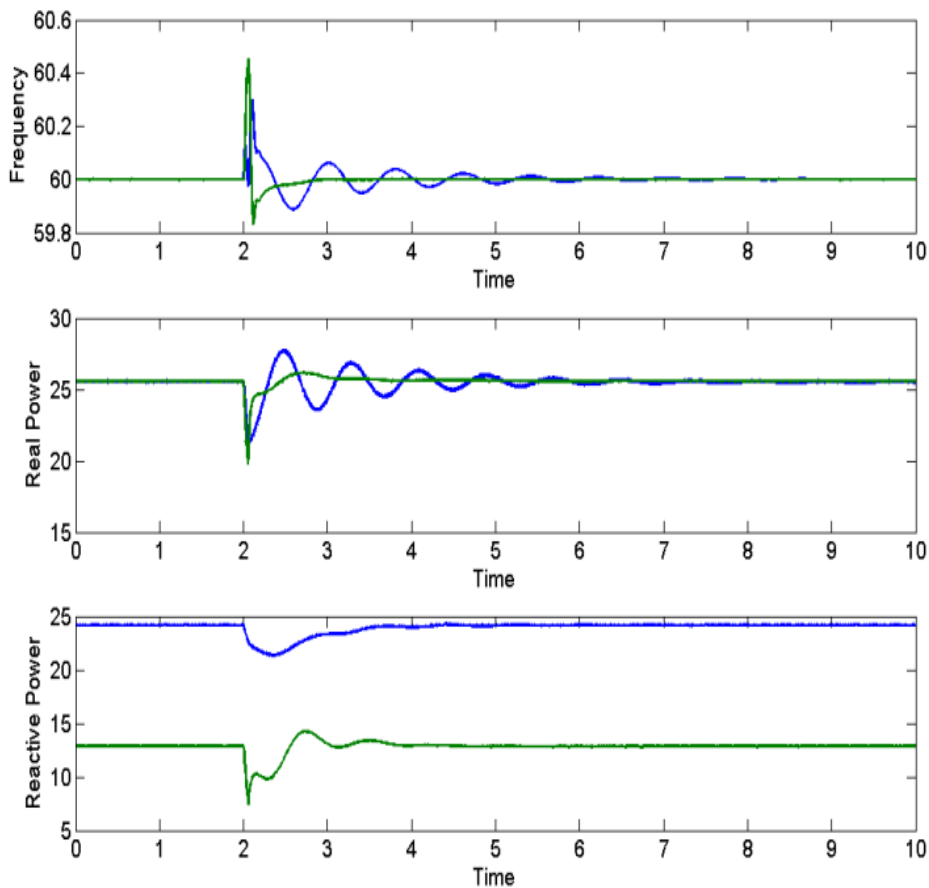


- Real-time physics-based model of the AS-PSH hydro circuit, power electronic converter, converter controls
- IEEE 14 bus test system with AS-PSH and conventional hydro simulated in real time for generating responses
 - Fault conditions applied at bus no. 2.



AS-PSH and Conventional Hydro response to 1LG fault

AS-PSH and Conventional Hydro response to 3LG fault



AS-PSH response in green and conventional hydro-generator response in blue for comparison

- Developed hydrodynamic turbine model and co-simulated electrical and hydrodynamic circuits to study penstock wall elasticity, water hammering, and water compressibility under dynamic conditions
- Performed detailed electromagnetic transient (EMT) modeling of the doubly fed induction generator (DFIG) for AS-PSH
- Models developed capable of capturing sub-cycle events in both domains
- Dissemination at:
 - WECC Model Validation Working Group (MVWG) and Renewable Energy Modeling Task Force (REMTF)
 - Utility Variable-generation Integration Group (UVIG)
 - Modeling and Integration User Group (MIUG),
 - IEEE presentations
 - International Journal of Power and Energy Systems.

- This project was funded for one year:
 - Initiation date: January 2014
 - Completion date: March 2015

Budget History (NREL)

FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$189K	N/A	\$105K	N/A	N/A	N/A

Budget History (INL)

FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$437K	N/A	\$63K	N/A	N/A	N/A

Budget History (ANL)

FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$80K	N/A	\$20K	N/A	N/A	N/A

- The funding expired in Q2-FY2015 and all funding has been costed.

Partners, Subcontractors, and Collaborators:

- WECC Renewable Energy Task Force (REMTF)
- UVIG Modeling and Integration User Group (MIUG)
- IEEE: IEEE Renewable Energy Machines Applications Subcommittee (REMAS), IEEE Task Force on Adjustable Speed Pump Storage Modeling
- Software Vendors (Siemens PTI: PSSE, Nayak: PSCAD), Hydropower Industry

Communications and Technology Transfer:

- “NREL Dynamic Modeling Activities Pump Storage Hydropower Plant,” Modeling and Integration User Group Meeting, UVIG Fall Technical Workshop, San Antonio, TX, October 15-17, 2014
- “Dynamic Modeling of Adjustable-Speed Pumped Storage Hydropower Plant” a technical paper presented at the IEEE Power and Energy Society, General Meeting, July 2015, Denver, CO
- “Dynamic Models for Hydropower and Marine Hydrokinetic Generators”, a webinar presentation at the WECC-MVWG and WECC-REMTF, March 2016
- “Real-Time Co-simulation of Adjustable-Speed Pumped Storage Hydro for Transient Stability Analysis”, 2016 submitted to the International Journal of Power and Energy Systems.

FY17/Current research: None

Proposed future research:

- The AS-PSH can play a role in balancing variable renewable energy generation and can be applicable for a close-loop system utilizing the potential difference between upper-lower reservoirs
- A combination of the potential energy to deliver primary and secondary frequency response, and a capability to deliver a large inertial response will significantly improve the AS-PSH system to become the clearing house of the fast frequency response provider
- The potential of utilizing PSH technologies can be listed as shown in the table here
- Analyze the impacts of providing grid services on the AS-PSH civil structures, loading, and overall plant life for overall dam safety and design
- Prototyping and optimizing advanced power electronic converters for integration with next generation AS-PSH plants.

	PSH Contribution
1	Inertial response
2	Governor response, frequency response, or primary frequency control
3	Frequency regulation, regulation reserve, or secondary frequency control
4	Flexibility reserve
5	Contingency spinning reserve
6	Contingency non-spinning reserve
7	Replacement/Supplemental reserve
8	Load following
9	Load leveling / Energy arbitrage
10	Generating capacity
11	Integration of variable energy resources (VER)
12	Portfolio effects
13	Reduced cycling of thermal units
14	Reduced transmission congestion
15	Voltage support
16	Improved dynamic stability
17	Reduced environmental emissions
18	Energy security
19	Transmission deferral
20	Black start capability

P. Donalek, "Advanced Pumped Storage Modeling," Advanced Pumped Storage Modeling Task Force Meeting, IEEE Power and Energy Society General Meeting, July 31, 2014, National Harbor, MD.