A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe

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A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe

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Abstract

During the first decade of the 21st century 22 new Advanced Pump Storage units with more than 2400 MW of PS capacity have been installed in Europe to help the grid deal with the intermittency of renewable energy associated with wind and solar energy generation. A number of different types of advanced pumped storage plants (advanced conventional, variable speed and Ternary) have been developed with special features to allow fast reaction time for firming the variable nature of renewable energy generation there. The rate of construction of advanced PS plants continues and is even accelerating in the second decade where projections envision additions of 76 units and more than 11,000 MW of pumped storage capacity. In the US, despite the Renewable Portfolio Standard (RPS) initiatives of the individual States and the resulting growth of wind and solar energy generation, no new significant pump storage plants have been commissioned between 2000 and 2010, two units and 40 MW have been commissioned in 2011, none are yet in the detailed project planning or project construction phase and the projections for additions of pumped storage units in the time period 2012 to 2020 are few. This paper will characterize the drivers leading to the significant growth of Advanced Hydro Pumped Storage in Europe and compare and contrast them to the situation in the US. The analysis will look at the basic energy supply, the characteristics of the variability of the renewable resources, the economic and governmental factors influencing the building of pumped storage plants, and the resulting characteristics of the pumped storage solutions.

Background

Pumped Storage Installation Overview: Table 1 displays installed and planned pumped storage units commissioned in OECD Europe[1] arrayed by technology. In the first decade 22 pumped storage units capable of producing 2443 MW of rated power were commissioned. In the period 2011-2020 there are 76 pumped storage units capable of producing 11562 MW commissioned, under construction for commissioning, or planned for building and commissioning. All of the units are modern advanced technology pump storage units. For the entire two decades conventional reversible synchronous speed units comprised 60% of the units commissioned or to be commissioned, 29% of the units were variable speed reversible units, and 11% of the units were Ternary pumped storage machines. For OECD Europe, 96% of the commissioned MW's occur in two regions, namely the Austria/Germany/Switzerland region and the Portugal/Spain region.

1) For purposes of this paper OECD Europe includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

2000 to 2010					%	%	%
# Units	Total	Conventional	Ternary	Varspeed	Conventional	Ternary	Varspeed
OECD Europe	22	12	6	4	55%	27%	18%
US	0	0	0	0	0%	0%	0%
MW		Conventional	Ternary	Varspeed	Conventional	Ternary	Varspeed
OECD Europe	2443	836	547	1060	34%	22%	43%
US	0	0	0	0	0%	0%	0%

2011 to 2020					%	%	%
# Units	Total	Conventional	Ternary	Varspeed	Conventional	Ternary	Varspeed
OECD Europe	76	47	5	24	62%	7%	32%
US	2	2	0	0	100%	0%	0%
MW		Conventional	Ternary	Varspeed	Conventional	Ternary	Varspeed
OECD Europe	11562	6849	303	4410	58%	3%	40%
US	40	40	0	0	100%	0%	0%

Table 1: Comparison of new pumped storage units commissioned or planned to be commissioned in the U.S. and Europe in the years 2000 to 2020 (ref. 1).

In the U.S., on the other hand, in the period 2000-2010 no new units were commissioned; and in the period 2011-2020 there are just 2 units expected to be commissioned comprising 40 MW of rated power. Those units were of the conventional reversible type. Besides the two new units at Lake Hodges, in the U.S. over the period 2000-2020, there have been or will be 980 additional MW of pump storage capacity added through modernization and upgrade of existing PS plants there. This striking difference between the OECD Europe and the U.S. related to pumped turbine installations is graphically depicted in Figure1.

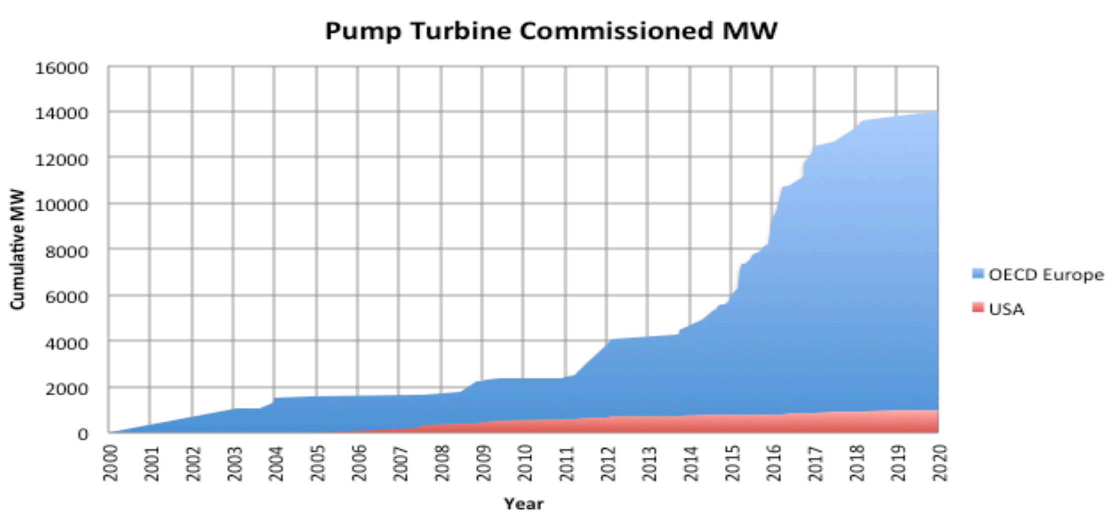

Figure 1: Pump storage commissioned, or expected to be commissioned in OECD Europe and the U.S. (cumulative MW vs. year of commissioning (ref. 1).)

Electricity Generation: In both OECD Europe and in the U.S. a growth of electric energy generation has been taking place in response to demand. Using the IEA International Energy Outlook (IEO) 2011 as a data source (ref. 2), Figure 2 compares electrical power net generation between the two regions. As it can be seen from Figure 2, both OCED Europe and the U.S. have similar electrical power generation capabilities in the period.

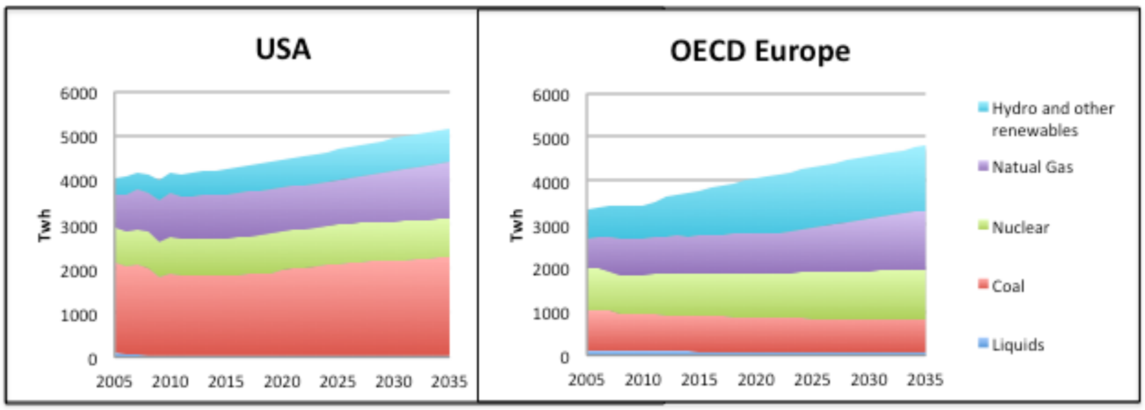

Figure 2: Electrical power net generation split by generation technology (ref. 2).

Renewable Electricity Generation: As a means to manage carbon emissions and to mitigate their effect on global warming, European and U.S. governments started incentivizing installation of renewable electric generation in addition to hydropower with European countries starting earlier than the U.S. governments (state and federal). In OECD Europe, the policies of the individual countries have been decisive in influencing their electrical energy generation evolution. Various incentives including feed in tariff policies with long time frame phase out have been well used. In the U.S., the policies of the individual States play a significant role; but in the U.S., the incentives of the federal government, in particular those associated with federal tax credits, have also been of significant influence. Tax incentives and feed in tariff's in the U.S. have been transient at best, with unknown periods of validity and expiration.

As a consequence the European renewable electric energy generation from wind, solar and biomass started growing earlier, today is ahead of the that generation in the U.S., and is forecast to increase more in the future in Europe than in the U.S. based on current governmental incentives (Figure 3). As indicated in the IEO2011 review, renewable energy is OECD Europe's fastest-growing source of electricity generation in the IEO2011 Reference Case increasing by 2.5% per year through 2035. OECD Europe's leading position worldwide in wind power capacity is maintained through 2035, with growth in generation from wind sources averaging 6.4% per year, even though the Reference Case assumes no enactment of additional legislation to limit greenhouse gas emissions. Strong growth in offshore wind capacity is underway, with more than 800 megawatts added to the grid in 2010, representing a 51% increase over the amount of capacity added in 2009.

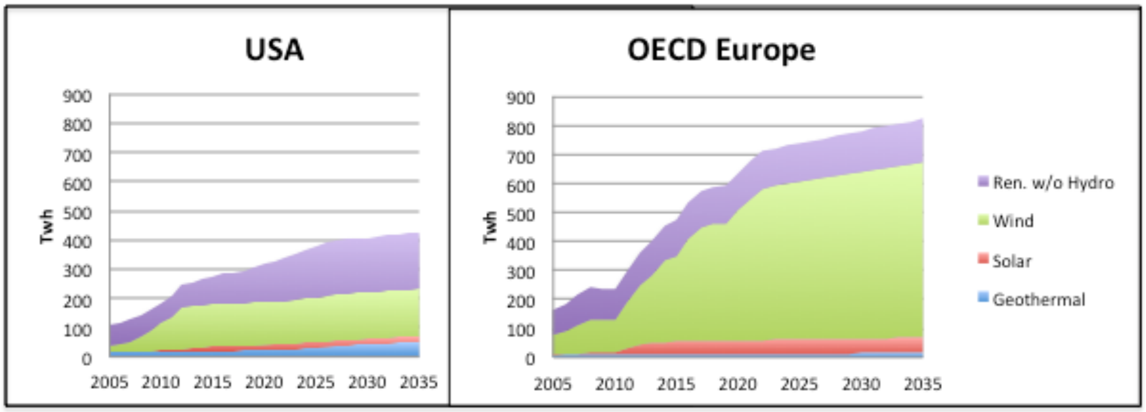

Figure 3: Renewable electrical power net generation without hydro split by sector (ref. 2).

According to reference 3, the growth of non-hydropower renewable energy sources in OECD Europe is encouraged by some of the world's most favorable renewable energy policies. The European Union set a binding target to produce 21 % of electricity generation from renewable sources by 2010 and reaffirmed the goal of increasing renewable energy use with its December 2008 "climate and energy policy", which mandates that 20% of total energy production must come from renewables by 2020. Some of the individual countries have set even more aggressive goals through their National Renewable Energy Action Plans (NREAP). Current laws are expected to lead to the construction of more renewable capacity than would have occurred in their absence. In addition, some individual countries provide economic incentives to promote the expansion of renewable electricity. For example, Germany, Spain, and Denmark—the leaders in OECD Europe's installed wind capacity—have enacted feed-in tariffs that guarantee above-market rates for electricity generated from renewable sources and, typically, last for 20 years after project commissioning. As long as European governments support such price premiums for renewable electricity, robust growth in renewable generation is likely to continue.

Projections of wind and solar energy in Europe (ref. 4) show expectations of significant growth in the EU27, especially in the regions Spain/Portugal and Germany/Denmark/Austria/Switzerland (Table 2), regions where most of the PS growth in Europe is occurring.

Wind + Solar % of electricity consumption in Europe		
	2010	2020
EU27	6%	16%
Spain/Portugal	17%	25%
Germany/Denmark/Austria/Switzerland	13%	21%

Table 2

In the U.S. the stimulation of renewables continues through the Renewable Portfolio Standards (RPS) passed as law in the various states. These RPS standards require that a certain percentage of the electricity generated (typically, though not universally, electricity sales) in the states must come from renewable sources (Figure 4). As of June 2010, mandatory RPS policies requiring states to procure a percentage

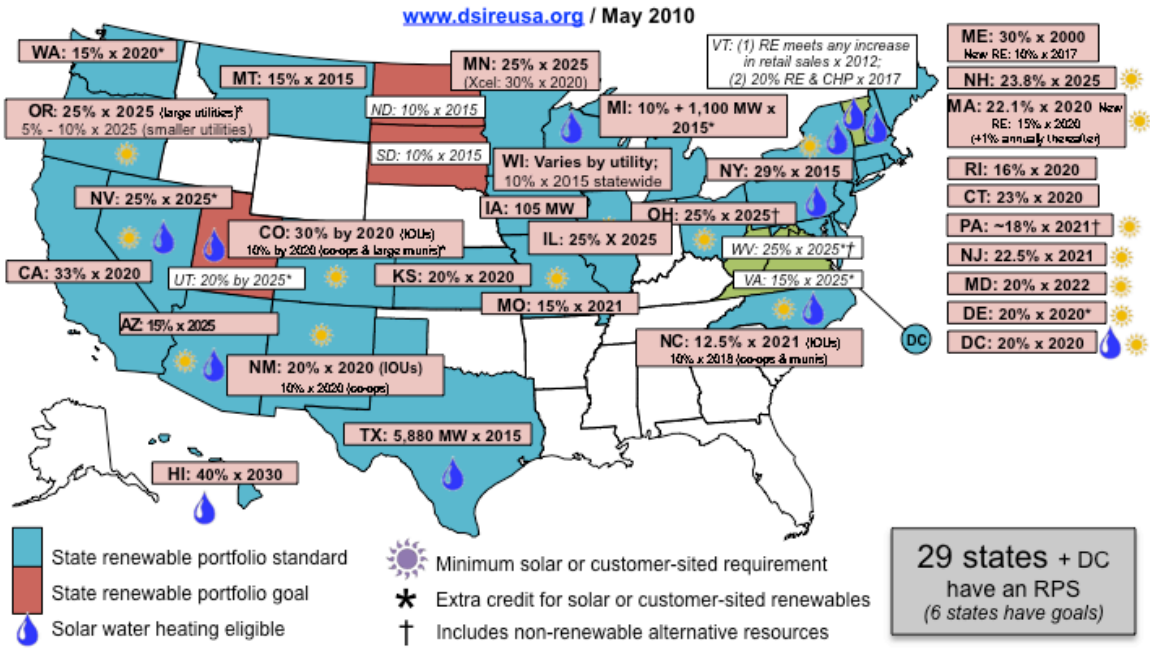

Figure 4: State RPS Portfolio standards as of May, 2010

of generation from renewable energy, have been passed in 31 U.S. states and the District of Columbia, with six additional states approving conditional or non-mandatory renewables goals. In the IEO2011 Reference Case, generation from renewable energy sources in the United States increases in response to requirements in more than half of the 50 states for minimum renewable shares of electricity generation or capacity.

State RPSs would be significantly strengthened if complemented by a federal RPS or energy policy that addresses transmission bottlenecks and siting issues on federal lands, both of which will be critical to sustaining renewables growth toward the middle of the next decade (ref. 5). Although renewable generation in 2035 in the *IEO2011* Reference Case is 17% lower than in the IEO2010 outlook, the share of renewable-based electricity generation is expected to grow from 9.7% in 2008 to 14.3% in 2035 (ref. 3). This is due to a variety of factors including lower electricity demand, a significant increase in the availability of shale gas, and revised technology and policy assumptions.

The projection for electricity generation from other renewables sources has also dropped as a result of lower expectations for biomass co-firing. U.S. Federal subsidies for renewable generation are assumed to expire as specified in the Energy Policy Act. However, if those subsidies were extended a larger increase in renewable generation would be expected (ref 3). So in contrast to some of the renewable energy stimulating regulations in Europe, some of those in the U.S. are neither as long-term nor as consistent.

In the U.S., projected increased generation from renewable energy in the electric power sector, excluding hydropower, accounts for 33% of the overall growth in electricity generation between 2010 and 2035 (ref. 6). Generation from renewable resources grows in response to federal tax credits, state-level policies, and federal requirements to use more biomass-based transportation fuels, some of which can produce electricity as a byproduct of the production process. Growth in renewable generation is supported by many state requirements, as well as new regulations on CO_2 emissions in California. The share of U.S. electricity generation coming from renewable fuels (including conventional hydropower) is projected to grow from 10% in 2010 to 14% in 2020 to 16% in 2035. Looking at wind and solar renewables alone, Table 3 compares OECD Europe with the U.S. based on reference 2 data from IEO2011 and with EU27 data from NREAP (ref. 4)

Wind + Solar % electricity consumption in Europe and U.S.		
	2010	2020
EU27 (Ref 4)	6.0%	16.0%
OECD Europe (Ref 2)	3.5%	12.2%
U.S. (Ref 2)	2.3%	3.6%

Table 3

Clearly, the move to renewable generation, particularly wind and solar, is occurring at a different pace in OECD or EU27 Europe compared to the U.S.

Electricity Generation from Coal: Electrical generation from coal is concerning as a consequence of its greenhouse gas emissions. Coal accounted for 25% of OECD Europe's net electricity generation in 2008; but concerns about the contribution of CO_2 emissions to climate change could reduce that share in the future. In the *IEO2011* Reference Case, electricity from coal slowly loses its prominence in the OECD Europe, declining by 0.5% per year from 2008 to 2035 and ultimately falling behind renewables, natural gas, and nuclear energy as a source of electricity. Coal consumption in the electric power sector is not decreasing uniformly in all countries in OECD Europe, however. Spain's Coal Decree, which went into force in February 2011, subsidizes the use of domestic coal in Spanish power plants. The policy is expected to result in more electricity generation from coal-fired plants at least through 2014, when the subsidy is scheduled to expire (ref. 3).

In the U.S., the government recently enacted legislation, Cross-State Air Pollution Rule (CSAPR), which requires reductions in SO_2 and NO_x emissions in roughly one-half of the States, with an initial target in 2012 and further reductions in 2014. Even so, coal remains the dominant energy source for electricity generation there, but its share of total generation will probably decline from 45% in 2010 to 39% in 2035 in the AEO2012 (ref. 6).

Electricity Generation from Natural Gas: Despite recent political restrictions on the availability of Russian gas for Europe, the IEO2011 sees natural gas as the second fastest-growing source of power generation after renewables in the outlook for OECD Europe, increasing at an average rate of 1.8 percent per year from 2008 to 2035 (ref 3, page 103). Growth is projected to be more robust than the 1.3 % annual increase in last year's outlook, as prospects for the development of unconventional sources of natural gas in the United States and other parts of the world help to keep world markets well-supplied and global prices relatively low. As a result, natural gas is more competitive in European markets in the *IEO2011* Reference Case than it was in *IEO2010*. In Europe, natural gas prices are indexed to substitute energy prices and move in proportion with other fuels, especially oil-based products and coal. Additionally, there are a limited number of suppliers and many buyers; few players control storage and transport; and therefore costs are currently higher than those in the U.S. (ref. 7).

U.S. natural gas prices have declined significantly as a consequence of technical advances in natural gas extraction from shale, which have opened reserves so extensively that the U.S. has surpassed Russia as the world's largest natural gas supplier (ref. 8). The existence of inexpensive natural gas has lead to a significant growth in the use of gas turbines for electrical energy generation, particularly for peaking power. One characteristic of the U.S. natural gas market that keeps gas prices low is the "gas-on-gas" markets that have volatile prices generally not in "sync" with other energy sources. Additionally, there are a large number of suppliers and buyers and ample storage and transport systems exist (ref. 7).

Electricity Generation from Nuclear: Although the full extent to which European governments might withdraw their support for nuclear power is uncertain, some countries following the Fukishima Daichi reactor incident already have reversed their nuclear policies. The German government has announced plans to close all nuclear reactors in the country by 2022; the Swiss Cabinet has decided to phase out nuclear power by 2034; and the Italian voters, in a countrywide referendum, have rejected plans to build nuclear power plants in Italy.

U.S. nuclear energy capacity is growing. Electricity generation from nuclear power plants grows by 11 % in the *AEO2012* Reference Case accounting for about 18 % of total generation in 2035 (ref. 6)

Transmission Grid: The state of the electrical transmission grids influences the development of renewable energy and the need for energy storage. A robust transmission system is necessary to get newly evolving renewable generation to the consumers and to provide a wider generation area to help mitigate the intermittency of wind and solar generation. The transmission grids are managed by Transmission System Operators (TSOs), which manage grid operations and are main participants in markets for energy, ancillary services, and capacity resources to ensure grid stability and reliability.

In Europe the development of a robust transmission system is progressing. From July 1, 2009 the ENTSOE (European Network of Transmission System Operators for Electricity) has taken over all operational tasks from 6 existing TSOs including the UCTE (Union for the Coordination of Transmission Electricity). The scope of the ENTSOE is shown in Figure 5. The strong growth of renewable electricity sources, especially wind energy and solar PV, has challenged the electricity system in countries such as Spain and Germany. More often, wind turbines in some regions have been switched off – so-called “curtailment” – during periods with high winds, because of oversupply of electricity.

Figure 5: ENTSOE – E network

Maintaining security of supply is of utmost importance in transmission grid operation and planning. For a future grid, where both demand and supply are expected to grow, this can be ensured by increasing transfer capacity in the grid, and by introducing storage and demand- side management (DSM) schemes, which also act to facilitate the use of renewable energy sources (ref. 9). The main cause of non-security of supply is unpredictability of renewable in-feed and consequently bottlenecks in the electricity grid due to oversupply and undersupply in specific regions which is occurring in high voltage and also medium and low voltage lines. Currently renewable electricity surpluses cannot always be transferred to another region with a net demand (i.e. transmission corridors, particularly from Portugal-Spain to France, require significant strengthening). Locally good transmission regions on the Iberian Peninsula support the intermittent renewables there with significant help from hydro pumped storage plants which have been continuously developed, in part because of need and in part due to favorable terrain providing sites for pumped storage plants. Also, good transmission in the

Denmark/German/Austrian/Swiss region combined with favorable terrain in the Alps and other regional geography have supported investments in hydro pumped storage plants to integrate the rapid increase in wind and solar energy generation. Recently in some countries, transmission fees are being imposed on pumped storage operators while pumping, even though the pumped storage plants are providing a stabilizing service for the grid.

In Europe the ENTSOE/UCTE has Primary, Secondary and Tertiary Control schemes in place to operate the generators and commit reserves to maintain grid frequency reliability. These control schemes require certain reserves exist as a percentage of system loads and require reserve commitments in appropriate time frames to maintain grid reliability. Figure 6 shows graphically reserve activation timeframes for Primary, Secondary and Tertiary control reserves (ref. 10).

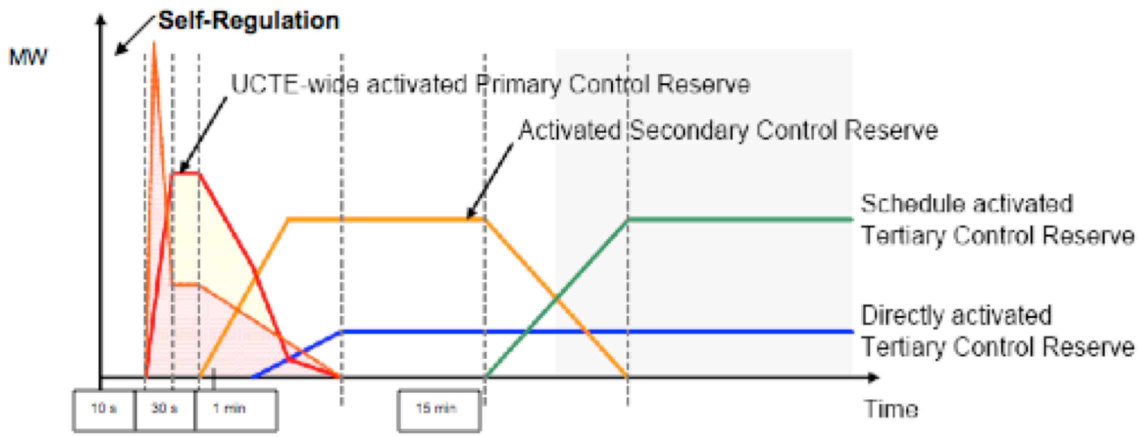

Figure 6: Principal frequency deviation and subsequent activation of reserves

It can be seen in Figure 6 that Primary Reserve commitments are required to be provided in seconds to minute time frames. Some utilities apply thermal power plants for the Primary control and use pump storage plants for the secondary control (ref. 11). This works as long as there is enough installed power from the thermal power plants. When these are decommissioned while wind power is increased, the need for other sources of primary control energy will emerge.

In the U.S., the transmission system has been more regionally focused. There, independent system operators (ISO) and regional transmission organizations (RTO) manage grid operations within their territories and also operate markets, different in each region, through which generation resources are procured (ref. 12). Seven ISOs operate at the present time in the U.S. (Figure 7). ISOs and RTOs are required to implement North American Energy Reliability Corporation (NERC) reliability standards. NERC has a number of regional entities and balancing area authorities within the U.S. and Canada (Figure 8). Transmission systems are marginal in many regions, interconnections between regions are not very robust and as renewable resources grow in response to incentives of the State’s RPS standards regional bottlenecks have increased.

Figure 7: ISO and RTO organizations

Figure 8: NERC regional entities

In the U.S., North American Electric Reliability Corporation (NERC) reliability standards are developed and promulgated by the organization with input from the regional organizations and approved by the U.S. Federal Energy Regulatory Commission (FERC) and the Canadian Provinces (ref. 12). NERC’s Performance Standards ensures that balancing areas (BAs) are able to utilize contingency reserves to balance production and demand and return interconnection frequency within defined limits following a disturbance, require a minimum contribution of the BA to maintaining overall frequency of the interconnection and requires BAs to have sufficient regulating reserves to meet the performance requirement. NERC grid reliability standards have evolved over time and continue to do so. At present, NERC is considering a change of these standards with a new set designed to prevent unwarranted load shedding and to prevent frequency-related cascading collapse of the interconnected grid.

Drivers of Electrical Energy Storage

The variability of consumption, the intermittent nature of wind and solar generation, the emission and wear and tear consequences of varying generation from conventional, mainly thermal electrical generation equipment and concerns of grid stability and reliability are factors which drive interests in use of electrical energy storage for grid voltage and frequency management (ref.13). The governmental, political and social situation related to reduction of green house gas emissions has started and continues to stimulate renewable energy generation, in particular wind and solar electrical energy generation. Wind and solar energy are intermittent in their nature. At times of high wind and bright sun, energy from wind and solar generation must be used when generated, or stored for later use, or curtailed (ref. 14) if in excess of needed energy and the ability of conventional generation to reduce production. At times of low wind, or cloud cover, wind or solar electrical generation is low and additional generation from other (mainly conventional) sources is needed. Time frames from high production to low production can be relatively short (seconds to minutes). Figure 9 illustrates the intermittency of wind and solar installations in Germany (ref. 15). The intermittency of generation illustrated is typical of wind and solar in Europe and the U.S. As the percentage of intermittent electrical generation from wind and solar increases (Table 3), the amount of variation of conventional electrical generation (reserves) needs to increase for grid balance.

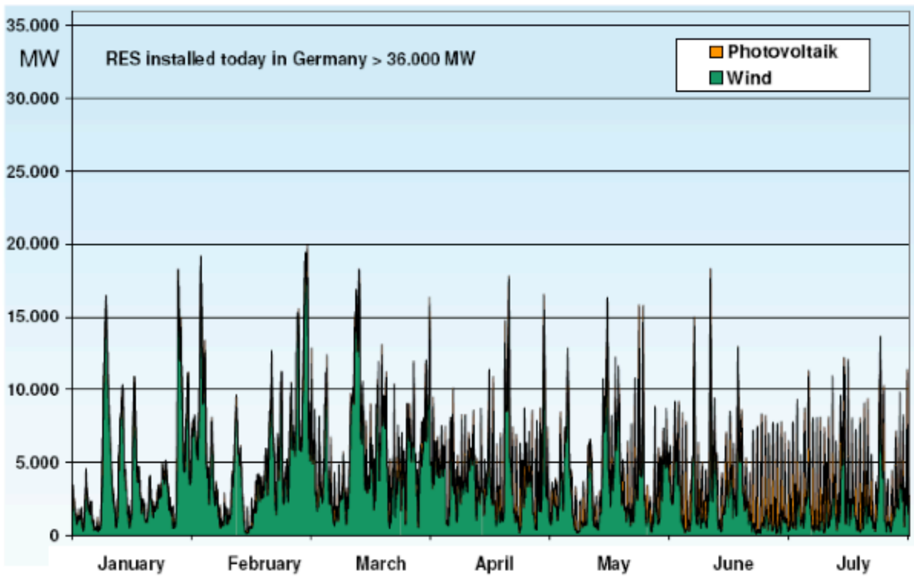

Figure 9: Wind and solar generation in Germany 2010

Nuclear and coal plants are desired to be operated with modest variations in output and are expensive to shut down and restart. Hydro generation therefore has been typically utilized to provide variable generation with water stored in its reservoirs. However hydro flexibility is being reduced by environmental considerations. One example in particular in the U.S. occurred in the Pacific Northwest where Bonneville Power Authority operates the grid. There, significant oversupply of wind energy along with the requirement to operate the hydro projects to minimize fish injuring spill at times of high river flows are leading to direct requirements for wind curtailment or to BPA setting a zero price for hydro energy provided from Federal generation as a means to maintain hydro generation while forcing curtailment of other generation (ref. 16). Hydro generation is also limited in growth and as wind's and solar's percentage of total generation increases less hydropower relative to the total is available.

In the U.S. natural gas generators have been used to provide peaking power and the generation variation needed to balance wind and solar intermittency. They are relatively inexpensive, have short construction times, are cleaner than coal generation and are fairly flexible in their operation. With local gas supply going up in the U.S. and prices going down (ref. 7), combined cycle gas turbine and combustion turbine plants have provided the peaking reserves or electrical energy in times of low wind and solar generation and they can be shut down in times of high wind and solar generation. In Europe, natural gas is not yet plentiful, has carbon emissions, has had restricted and unreliable supplies coming from Russia, does not have a good distribution infrastructure, and has a price structure proportional to oil prices (ref. 7). Therefore, natural gas generators are not nearly as widely used in Europe as in the U.S. as a balance to wind and solar intermittency.

In general, gas turbines and other highly flexible assets are most wanted for their grid stability contribution, but paid for their electrical energy production. Therefore, “flexibility products” need to be developed in new remuneration schemes to make these kinds of generation assets economically attractive.

Energy storage has also been looked at as a means to balance the intermittency of wind and solar generation. In times of excess generation, energy can be stored. In times of low wind or solar generation, energy can be returned to the grid from storage. A wide range of storage solutions has been undergoing development and evaluation (ref. 17). Among the storage solutions, hydro pumped storage plants are a proven and mature technology, which has large energy storage capacities and good turnaround efficiencies. The use of energy storage with hydro pumped storage plants has increased rapidly in Europe to balance the intermittent character of wind and solar generation (Figure 1, Table 1). Under the requests of plant owners there, an advanced generation of pumped storage equipment solutions (Appendix A) has been developed to provide fast acting PS units with varying degrees of flexible operation and improved turnaround efficiency (ref. 18, 19, 20, 21, 22). Advanced conventional single speed reversible units, Varspeed units with variable speed motor generators that provide wider operational operating ranges in the turbine cycle and the capability for regulation in the pump cycle, and Ternary units with a turbine, a motor generator, a torque converter/coupling and a multistage pump on a single shaft offering the most flexible of operations have been applied.

To date, the economics associated with pumped storage plants have been favorable in Europe in the Spain/Portugal region and in the Austria/Germany/Switzerland region. In those regions, the geography (mountains) is suitable. To lower cost of construction and reduce time for necessary approvals, in a number of instances, existing storage reservoirs have been used. Plant owners have been electricity generation companies in Europe. Project economic justification has included revenue streams from energy arbitrage, ancillary service payments (principally regulation) and a portfolio effect where PS plants optimize the operation of a conventional generation portfolio (ref 23). No plants have been built by Independent Power Producers so far. Recent developments of: 1) a transmission fee charged to PS plant operation in Germany and 2) increasing completion from solar generation at mid day will most probably create a more difficult time for justification of PS plants there based on energy arbitrage. In the U.S. while a large number of license applications have been filed by Independent Power Producers, due to unclear economics and financing no new plants are expected to be licensed, built and commissioned before 2020.

Summary

Condensing the above issues results in Table 5. In this table a simplified overview of some of the drivers leading to investments in energy storage in Europe but not in the U.S. are summarized. Some of the significant factors are: Europe has in general much more intermittent generation from wind and solar than the U.S. The use of gas for generation in Europe is not as attractive as in the U.S. The energy arbitrage opportunities due to price spreads for electricity are not as affected by gas generation in Europe as they are and are expected to be in the mid future in the U.S. Storage in Europe is being installed to help firm the intermittent wind and solar generation. Reference 24 provides on look at a European electricity future that gives some hints why storage investments are being made there.

Issue	USA	Europe
Carbon	No carbon trading	Carbon trading
Social Choices	Pro renewables	More Pro renewables than U.S.
Governmental Policies	State RPS stimulus; uncertain tax incentives; feed in tariffs	Strong EU and country stimulus (NREAP); economic incentives; feed in tariffs
Feed in Tariff Policy	Sometimes; uncertain timeframes	Yes; generally strong and for a relatively certain period of time
Intermittent Generation (Wind and Solar) Penetration	2010 2.3%: 2020 3.6%	2010 6.6%: 2020 16%
Natural Gas Supply	Abundant and low cost	Growing but reliability of supply concerns; price currently pegged to oil
Transmission	Regional and in need of strengthening; NERC U.S. wide requirements; industry fragmented w/o common voice; over 140 control areas	EU wide; country regulations; more centralized planning and strengthening now
Curtailment Policy	Beginning in some regions (BPA), ERCOT	Exists and expected to increase
Markets	Some active markets for medium and longer term energy; evolving with new payment streams including capacity payments; markets don't exist everywhere	Active markets for short and medium term energy; still country based, but in process of unification; addressing "flexibility" by new market products still missing.
Return on Investment	Uncertain	Energy arbitrage, Ancillary Services payments, Portfolio effects reward investment
Plant Investors	Principally Independent Power Producers (IPP)	Principally Generation Utilities

Table 5: Overview of some Drivers for Energy Storage in Europe compared to U.S.

Conclusion

In Europe, particularly in the Iberian Peninsula (Spain/Portugal) and in the region Germany/Austria/Switzerland, pump storage plants are being built to supply energy storage (Figure 1) (ref. 19, 20, 21) and stabilize the energy system with increasing intermittent in-feed from renewable sources. The increase in installed capacity of pumped storage plants is being justified by builders based on the PS plant need for integrating intermittent renewables reliably into the transmission grid, and by revenue streams coming from 1) energy arbitrage, 2) ancillary services such as those for regulation and reserves, and 3) savings in operational costs of thermal generation sources in the portfolio (ref. 23). The increasing availability of lower cost natural gas in Europe has so far not played a significant role in reducing energy arbitrage earning opportunities, possibly because of not so long ago political restrictions of natural gas supply from Russia, a significant supply source, and possibly because of the pricing structure of gas relative to oil and coal (ref. 7). Wind and solar generation growth is outpacing energy generation from gas at the moment. While environmental concerns exist related to new PS plant construction, the presence of existing reservoirs in many cases and the expansion of existing hydropower schemes and sites to include additional pumped storage capacities have taken place in many situations which mitigate the cost for obtaining approval for those installations and for the construction of new PS at those reservoirs. An important revenue stream for PS in some countries is the reserve market for both Primary and Secondary reserve. This is of interest as the TSO is responsible and pays for these services. At the same time in some countries, the TSO is charging pump turbine service providers a fee for use of the transmission lines during pumping - this fee has made the arbitrage earnings margin less rewarding for PS operators but this development is still under discussion as it may slow down the general development of a cleaner generation portfolio.

In the U.S., while existing plants are being modernized and in some cases uprated to add PS capacity within the existing units, new pump storage plants are not being built and no new units are being added at existing reservoirs at the moment. The penetration of renewables in the U.S. is in most areas lagging 10 years behind Europe. The intermittency of renewables is in most cases being handled by existing hydropower plants, existing pumped storage schemes, and by natural gas generation assets. Governmental licenses for building a plant require a significant investment due in part to environmental concerns associated with the siting and construction. The lack of a long term financing mechanism hinders investment. And the increasing abundance of low cost natural gas is limiting the peak energy pricing, one component of energy arbitrage earnings. In certain regions (New York ISO), with limited peak energy pricing due to low cost generation from natural gas and yet similar pricing at night due to demand with little wind and solar in the system, even existing PS plants have difficulty earning sufficient revenues to cover O&M expenses. The result is seen in Figure 1 where the U.S. increase in PS capacity is minimal in comparison to Europe. In the Pacific Northwest region of the U.S. (BPAT) wind generation and environmental issues limiting hydro generation flexibility are working to produce near zero prices for hydro generation when demand is low and wind generation is high and thereby economically encourage curtailment of wind generation. This situation lowers the nighttime price of energy which if it occurs over a long enough time may provide sufficient price spreads for energy arbitrage opportunities to incentivize PS building in the region despite natural gas generation limiting the peak price during times of high energy demand.

In should be noted that this comparison represents a snapshot of a period in time. The energy generation and supply business in Europe and the U.S. is a dynamic one that is influenced by politics, incentives, supply and demand, weather experiences, and the overall state of the economy. Therefore the factors that influence costs and economic returns of pumped storage equipment will continue to change as time progresses.

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Appendix A

An Overview of Advanced Pump Storage Equipment Technologies

Introduction

The history of pumped storage development started about 120 years ago. The first use of pumped storage occurred in the 1890s in Italy and Switzerland. In 1907 the first storage set in Germany was commissioned. In these early days the typical pumped storage plant consisted of two sets of equipment, a motor driving a pump with a separate turbine in the plant turning a generator. Later on, the sets where combined into a ternary unit which consisted of a motor generator, a pump and a turbine, all connected on one shaft. In the 1930's reversible pumped storage units were developed. These reversible units could operate as both turbine-generators in one rotational direction and in the reverse rotational direction as electric motor driven pumps. The first use of pumped-storage units in the United States was in 1930 by the Connecticut Electric and Power Company, using a large reservoir located near New Milford, Connecticut, pumping water from the Houstatonic River to the storage reservoir 230 feet above. Another technological milestone was set with the development and delivery of the first large reversible pump turbine in 1937 for the Pedreira project in Brazil.

Pumped storage units were originally designed to shift excess energy generation from thermal plants available during the night to peaking power generation during the times of heavy use during the day (Figure 1). With the advent of Nuclear

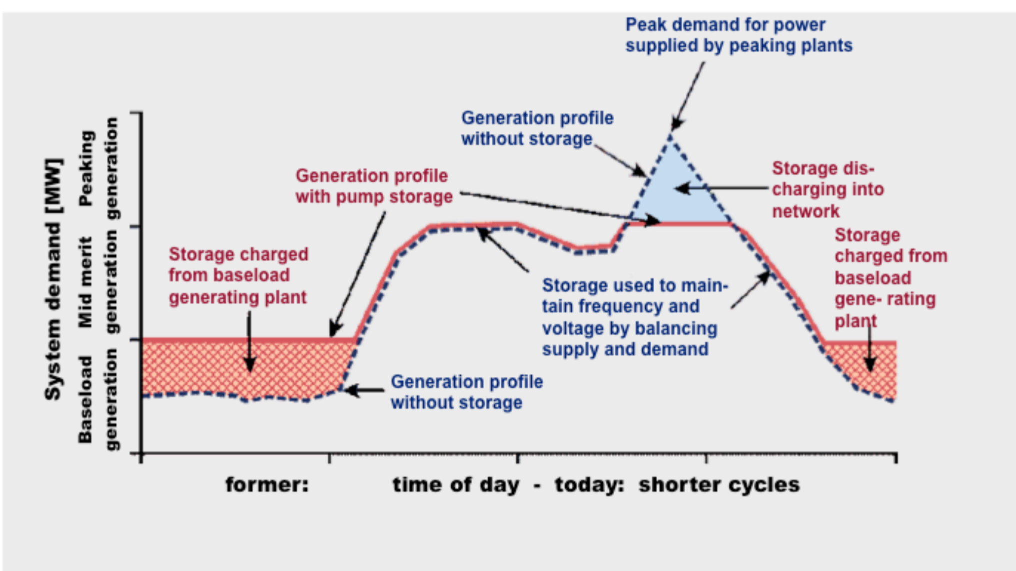


Figure 1: Pump Storage use in night to day energy shifting.

power generation, a surge in pump storage plant building took place in the time period beginning in the 1960's and continued through the 1970's. Most plants built were designed for Grid Power Control Energy Management service and had operational times for start up, change over and so forth in the order of 10 minutes or more (Figure 2). They were designed for the typical operation of only several

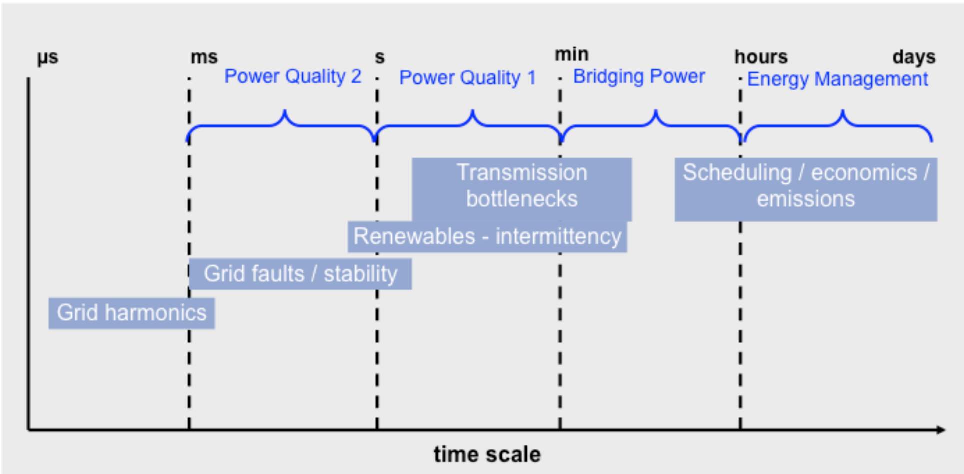


Figure 2: Grid power control issue and energy management timeframes.

starts and stops per day. Using technologies of the day, turnaround efficiencies of those plants were typically in the 70-75% range. The development of these kinds of machines with respect to large powers started in the 70s, and peaked with the Units at Bath County, still the largest pumped storage plant in the world.

In the 1990's driven by the anticipation of wind and solar power generation growth (Figure 3), interest in more flexible pump storage plants began in Europe.

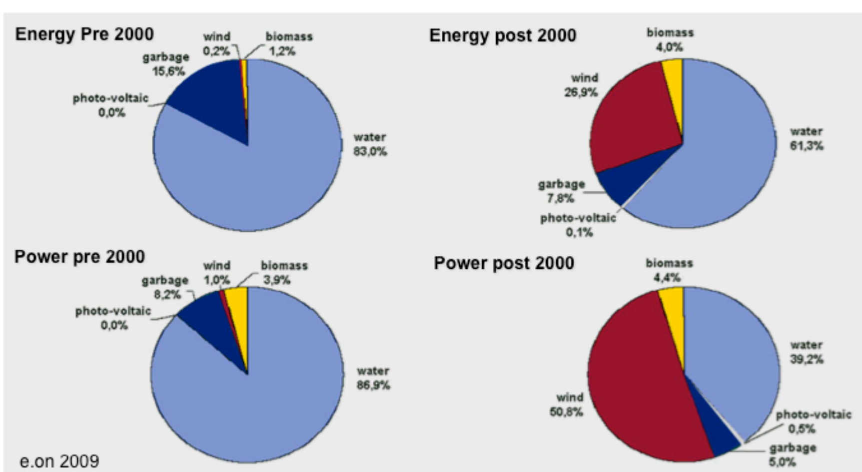


Figure 3: Change in renewable energy generation in Germany

The intermittency and variability of the renewable energy generation and the need for more responsive pump storage plants stimulated future owners of such plants to work with equipment designers to develop designs with a) wider load ranges in the turbine cycle of operation, b) enhanced design robustness to support many more stops and starts per day, c) faster start up and mode of operation changeover times, and d) the ability for regulation during pump operation. Out of the requirements for operation, a new family of Advanced Pump Storage units and plants were and continue to be developed which provide higher turnaround efficiencies, and more robust and flexible equipment.

Pumped Storage Equipment Overview

Pumped storage equipment can be classified into several types: separate pump and turbine units, reversible units; and ternary units. The pumped storage equipment described above can be used for various head and power ranges as shown in Figure 4.

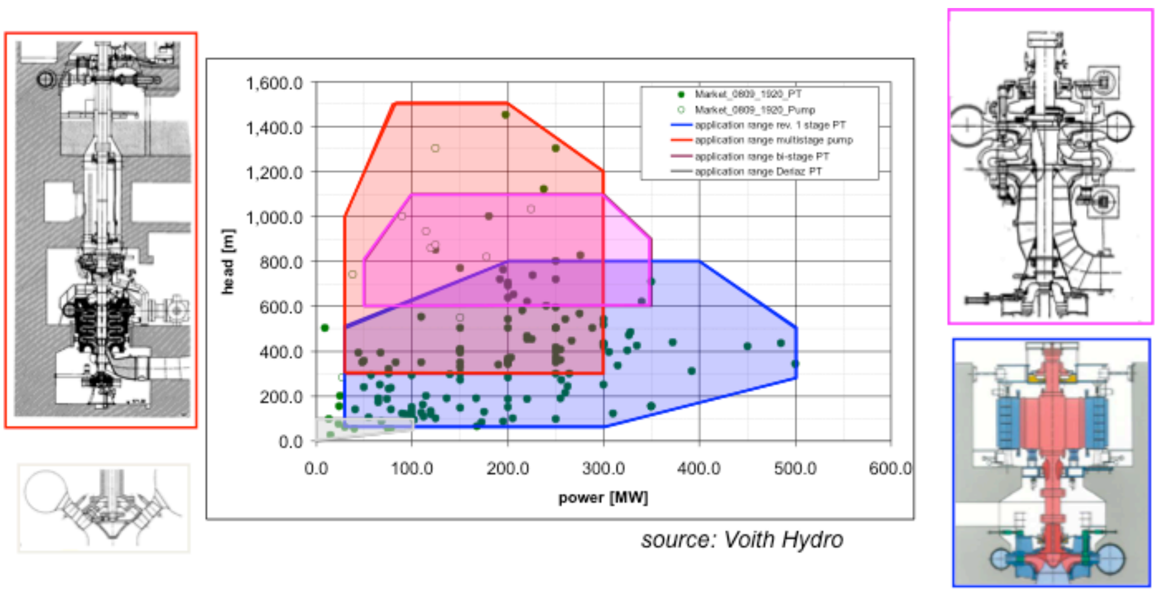


Figure 4: Head and power ranges of modern advanced pump storage equipment.

Reversible Pump Turbine units can be found in several configurations: 1) fixed speed single stage reversible; 2) fixed speed multi stage reversible; 3) variable speed single stage reversible; 4) fixed speed Ternary units with separate pump and turbine on a single shaft; 5) fixed speed adjustable blade Deriaz units; and 6) fixed speed axial units. Single stage synchronous fixed speed reversible units can be operated in either pump or turbine mode depending on direction of rotation. Multistage reversible units exist which increase the head of application. Power control in the turbine direction of operation occurs usually through opening and closing of wicket gates. With fixed speed motor-generators, power in the pump direction of rotation is not controllable. Reversible units can also be operated with variable speed motor-generators and then are called variable speed pumped turbines. The use of variable speed allows for a wider operational range of turbine power and for a typically 30% variation in power regulation in the pump cycle of operation. A special class of reversible pump turbines usable at low head has been in use that were developed with adjustable position turbine blades in the rotating turbine/impeller. These so called Deriaz pump turbines operate at fixed speed. They can be operated at various power levels when pumping as a consequence of the adjustable blade position. Modern advanced technology pump storage plants are operating which have turnaround plant cycle efficiencies up to 82%

Ternary pump turbine units have a separate motor-generator, turbine and pump on a single shaft and are operated in a single rotational direction. Ternary units can have turbines that are either impulse or Francis type, and pump sets on Ternary units are often multi stage. Advanced ternary units also can have a hydraulic torque converter coupling connecting the pump to the shaft system for fast startup of the pump.

Not shown on this figure are special infrequently used pumped storage equipment applications such as reversible axial flow bulb pump turbines and reversible Kaplan style pump turbines which have been used at low heads and powers for special applications. Separate synchronous speed pumps and turbines have also applied at some plants to provide energy storage service.

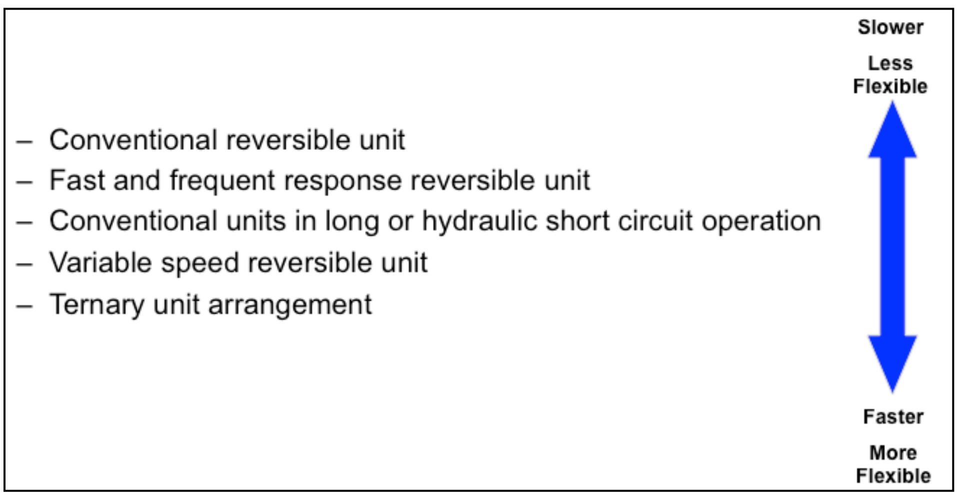


Figure 5: Relative grid service capability of advanced pumped storage units.

Pumped storage equipment can also be characterized based on their regulation responsiveness to grid needs (Figure 5). Pump Turbine waterways including penstocks, surge chambers and discharge tunnels need to be designed in accordance to the speed of response desired from the plant. Modern conventional reversible pump storage units are typically at the slower and less flexible range. Advanced conventional reversible units have been built for very fast and frequent start up, mode change and fast ramping operation. Multiple units in the same plant or in nearby plants can be operated together in a so called asynchronous balanced (hydraulic short circuit) mode to provide increased flexibility from the plant to support grid needs (i.e. a unit operating in the pump mode while an adjacent unit operates in the turbine mode to provide fast and flexible absorption of power from the plant should it make economic sense based on ancillary service payments). Variable speed Pump Turbine units provide yet more flexible responsiveness to grid needs in many cases. They can operate at lower power % of rated than conventional reversible machines and can provide power regulation when operating in the pump mode. For applications providing very fast and flexible operation Ternary Pump Turbine units are at the most flexible and fastest response range. Figure 6 shows typical power range of operation of Advanced Pumped Storage units. Figure 7 shows typical mode changeover times from/to full load pump or full load turbine operation and startup times to full load achievable from advanced pumped turbines operating today. Figure 8 shows timescales in which the advanced pumped storage units operate to provide grid services in Europe today.

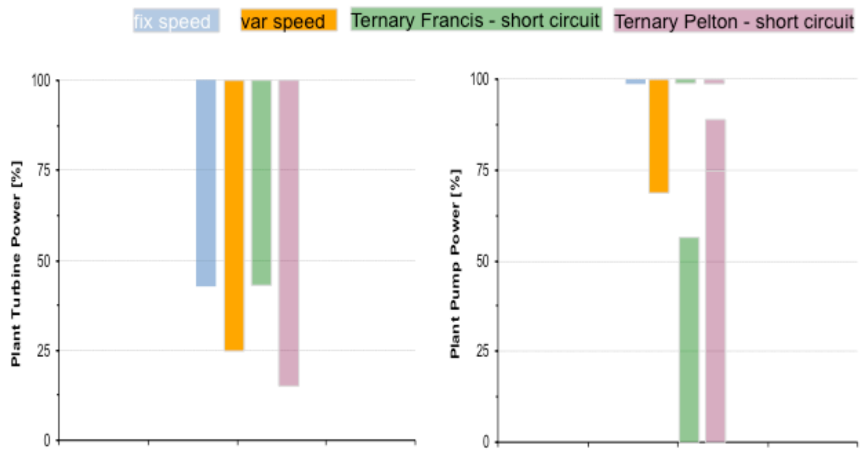
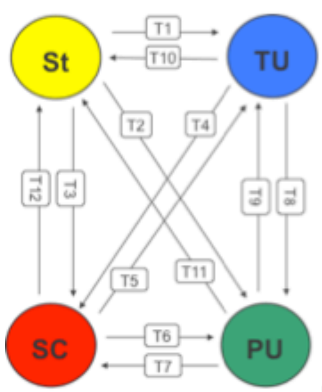


Figure 6: Plant regulation range for various types of advanced PS schemes.



T	Pump Turbine Mode change		time [seconds] A	B	C	D	E
1	Standstill	TU-Mode	90	75	90	90	65
2	Standstill	PU-Mode	340	160	230	85	80
5	SC-Mode	TU-Mode	70	20	60	40	20
6	SC-Mode	PU-Mode	70	50	70	30	25
8	TU-Mode	PU-Mode	420	240	470	45	25
9	PU-Mode	TU-Mode	190	90	280	60	25

Reversible PT
A – advanced conventional (2012)
B – extra fast response conventional
C – VarSpeed, DFIM
Ternary set
D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine
E – same as E but vertical with Pelton Turbine

Figure 7: Mode change times for various operating advanced PS concepts.

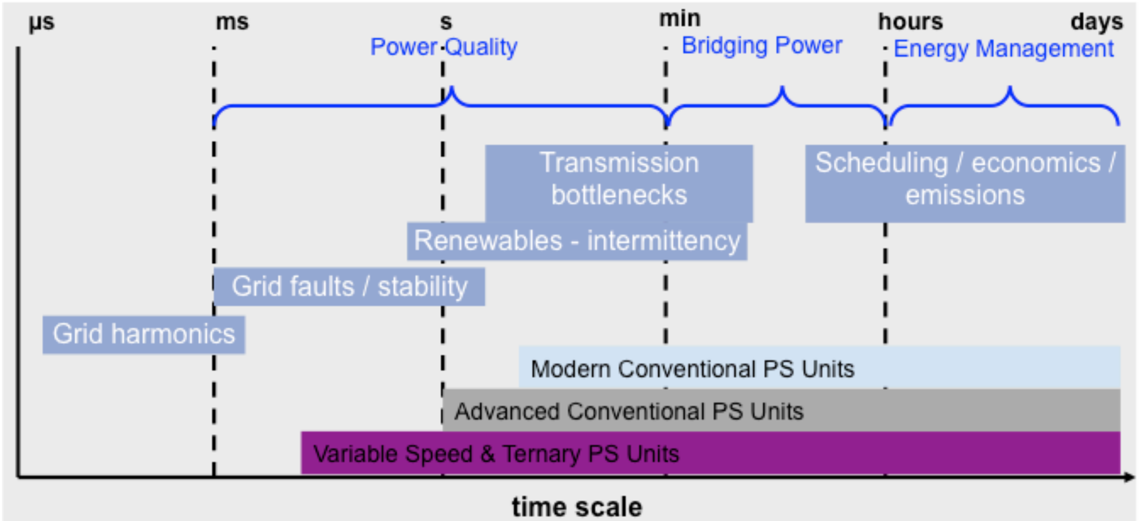


Figure 8: Timeframes for modern advanced PS unit regulation.

The following sections provide some details on modern pump turbines configurations in use today.

Modern Conventional Single Stage Synchronous Speed Reversible Pump Turbine

The modern conventional single stage synchronous speed reversible pump turbine (Figure 9) has been developed for operating heads up to 800 meters and to be capable of supporting fast mode change and load ramping service with frequent starts and stops during the day. Minimum loads for continuous operation in the turbine cycle are typically in the range of 40-45% of full load power, an improvement over the higher minimum loads of those conventional pump turbines designed in the time period 1960-80. Depending on the operating head and how they are designed, turnaround cycle efficiency of units can be as high as 82%. As a consequence of improved design and manufacturing technologies and materials, operational maintenance of modern pump turbine units is reduced even though the duty cycle is more intense. In the pump mode, pump power absorbed is only dependent on head, and at a fixed head there is no power regulation capability.

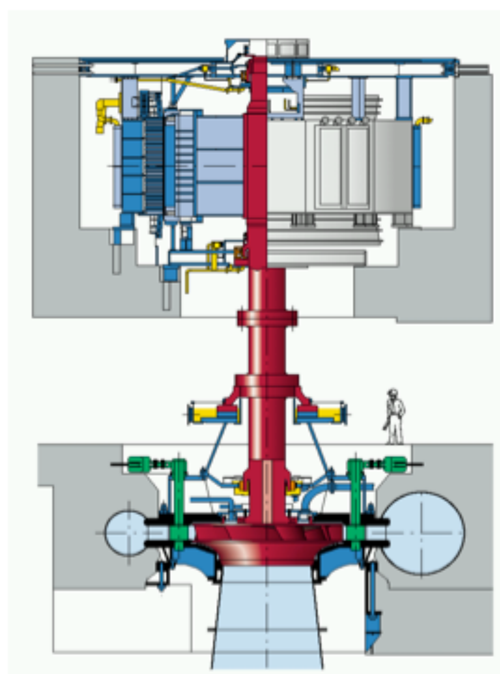


Figure 9: Reversible PS unit.

Modern Two Stage Synchronous Speed Reversible Pump Turbine

Modern designs of two stage reversible pump turbines (Figure 10) have been developed for operating heads of 600 to 1100 meters. The modern units have power regulation in the turbine cycle utilizing wicket gate control in both stages. For sites with higher heads, the designs offer increased operational efficiencies in the pump and turbine cycles of operation and less submergence below tailwater compared to single stage pump turbine units. In the pump mode, pump power absorbed is only dependent on head, and at a given head there is no power regulation capability.

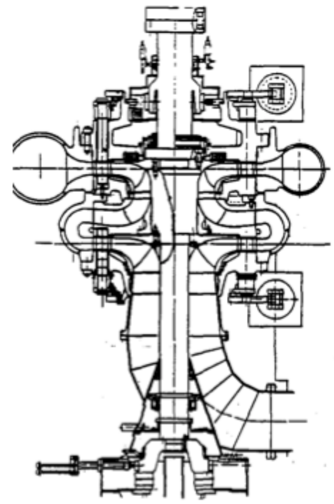


Figure 10: Two stage reversible PS unit

Modern Single Stage Variable Speed Reversible Pump Turbine

The development of adjustable/variable speed motor-generators has led to the single stage variable speed reversible pump turbine (Figure 11). The variable speed design utilizes solid-state electronic frequency converter technology. The frequency converter has some efficiency losses, but allows the operating efficiency of the pump turbine unit to increase (both turbine and pump cycle of operation). Through the use of speed adjustability, in turbine operation a lower speed can be chosen than in pump operation which allows an increase in hydraulic machine operational efficiency in the turbine cycle of operation compared to fixed speed pump turbines.

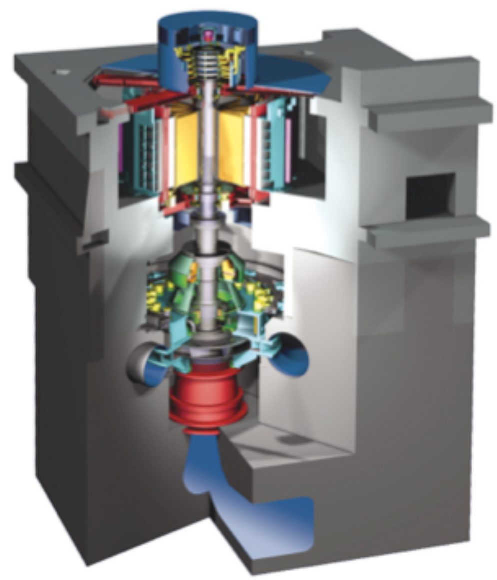


Figure 11: Variable speed PS

At best efficiency at a given head, the increase is about the same as the decrease in efficiency related to the frequency converter creating the variable speed. However at the turbine part load operation, operational efficiency can be significantly improved, and additionally the turbine can operate at lower loads due to reduced vibration. This produces the wider operating range of the variable speed pump turbine in the turbine cycle (Figure 12), which helps plant owners in using the design for power regulation to support grid needs. In the pump cycle of operation, changing the operating speed with power changing by approximately by the speed change cubed can vary the operating power absorbed by the pump. A 3% change in speed can be associated with a 9% change in power absorbed. The speed change can be made until hydraulic cavitation limits, hydraulic

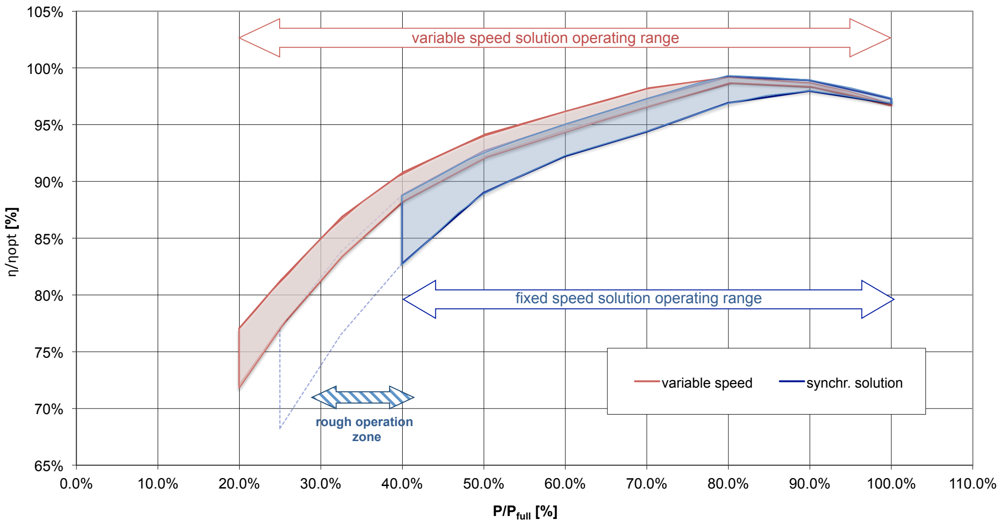


Figure 12: Comparison of turbine cycle range of operation of a fixed speed pump turbine to a variable speed pump turbine (DFIM, including converter losses).

stability of operation limits or generator temperature limits restrict operation. Typically a power variation at a given head can be approximately 30% (Figure 13). As in the turbine cycle, the use of a variable speed pump turbine expands the grid services provided by variable speed pump turbines compared to fixed speed pump turbines. An additional advantage of variable speed reversible pump turbines is that they can be used for plants which have higher difference between maximum and minimum head than would occur for a fixed speed reversible pump turbine.

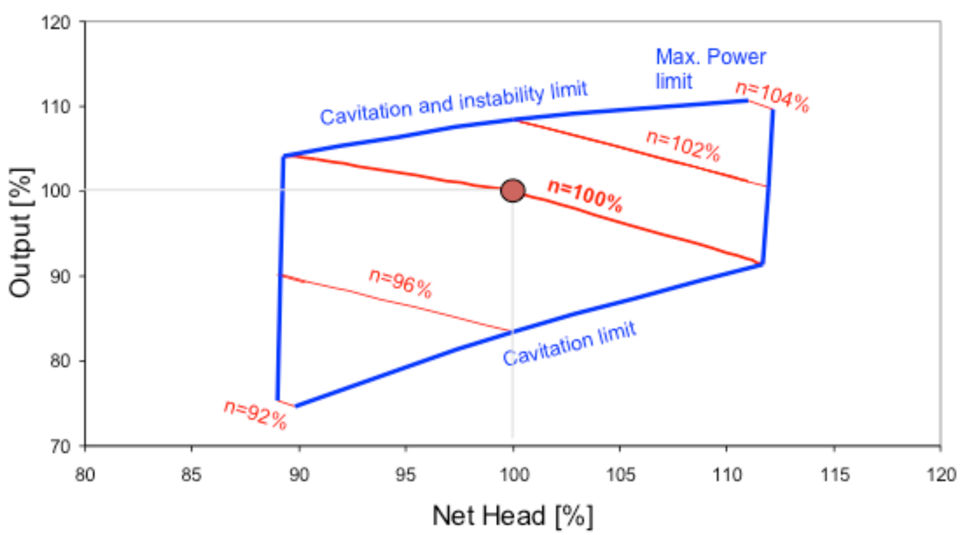


Figure 13: Effect of variable speed as % of rated speed on pump power absorbed.

Two types of variable speed motor-generators are being applied today (Figure 14), one for lower power pump turbine applications and the other for higher power applications. Both use electronic solid-state frequency converter technology. The Synchronous Machine Full Inverter (SMFI) uses a synchronous style generator design with the converter providing conversion from the grid frequency to the operational frequency of the generator. The stator is fed with the variable frequency excitation. This variable speed synchronous generator design has the frequency converter deal with the full power of the input/output of the motor-generator. Due to limitations of the solid-state component capacities, the full converter SMFI style of design is economically limited in power (Figure 15). Because the converter deals with the full power of the electrical machine, the losses in the SMFI converter are higher as a percent of the full power of the motor-generator. The design however has a wider electrical speed variation potential. Additionally no special equipment is needed for starting the pump, and the design also allows for direct transitions between pump and turbine operation and for starting of the pump in water.

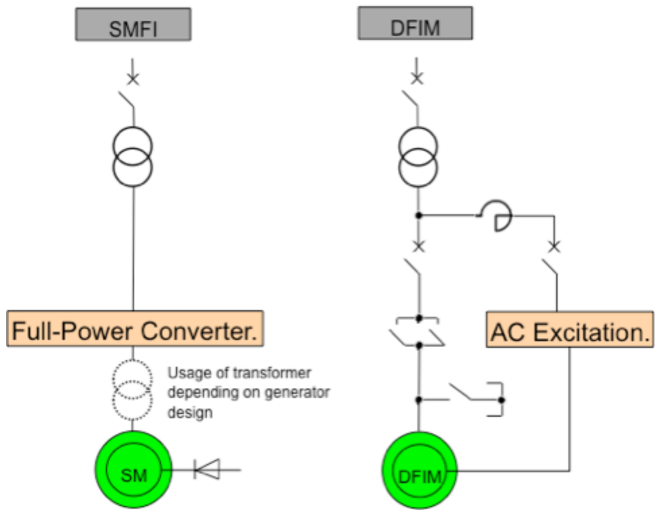


Figure 14: Variable speed motor - generator methodologies

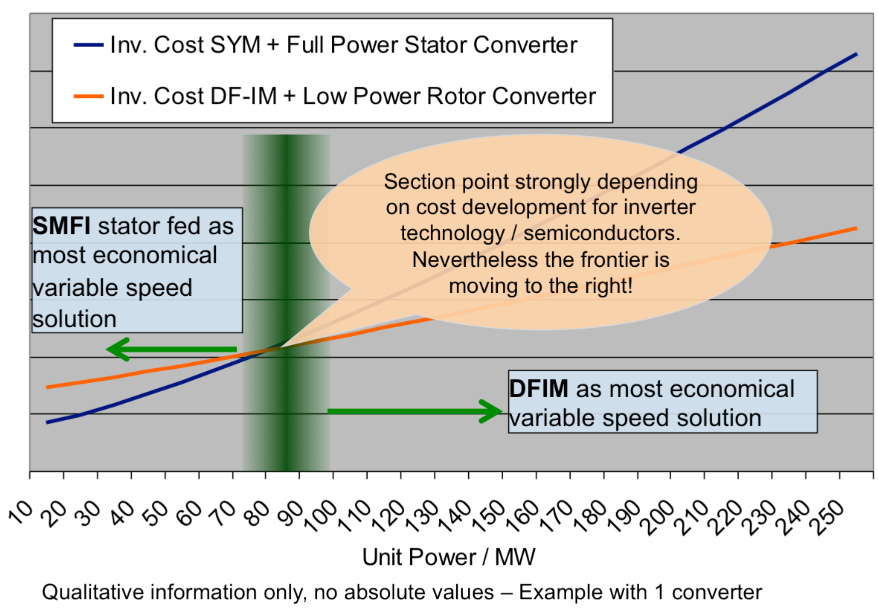


Figure 15: Power ranges of application of SMFI and DFIM applications.

The second type of variable speed uses a special motor-generator design (Double Fed Induction Machine – DFIM) with converter-fed rotor circuit for the electric motor generator including a special wound motor-generator rotor design and slip rings on top of the rotor (Figure 16). The solid-state electronic frequency converter technology is used to inject a high amperage variable frequency current into the rotor. With the DFIM design the frequency converter deals with only a percentage of the machine power resulting in lower costs and lower losses for conversion equipment. Frequency variations are chosen which typically allow around 10% variation in speed that matches the needs/restrictions of the hydraulic machine. For the DFIM motor-generator a higher powerhouse is needed to accommodate the slip ring assembly (Figure 17). Both SMFI and DFIM technologies require considerable space in the powerhouse to locate the converter-inverter equipment. Modern DFIM designs utilize Voltage Source Inverter (VSI) technology. These modern designs can use the VSI equipment for startup of the pump in air without any additional equipment.

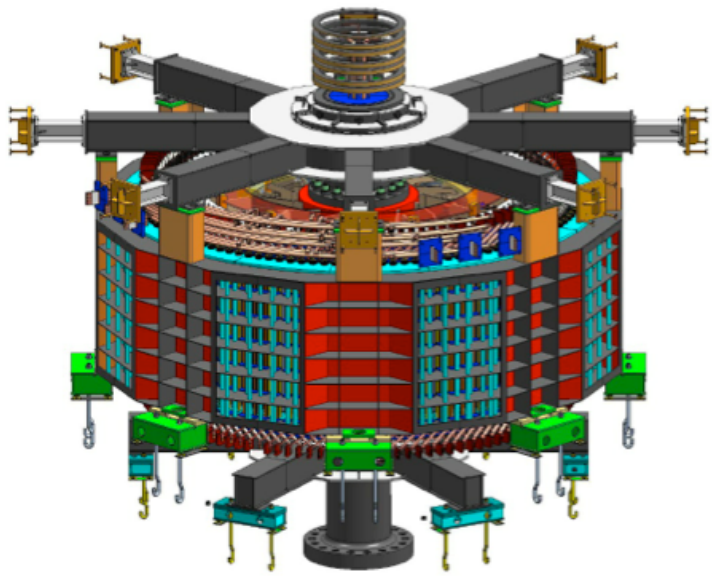


Figure 16: Variable speed motor-generator

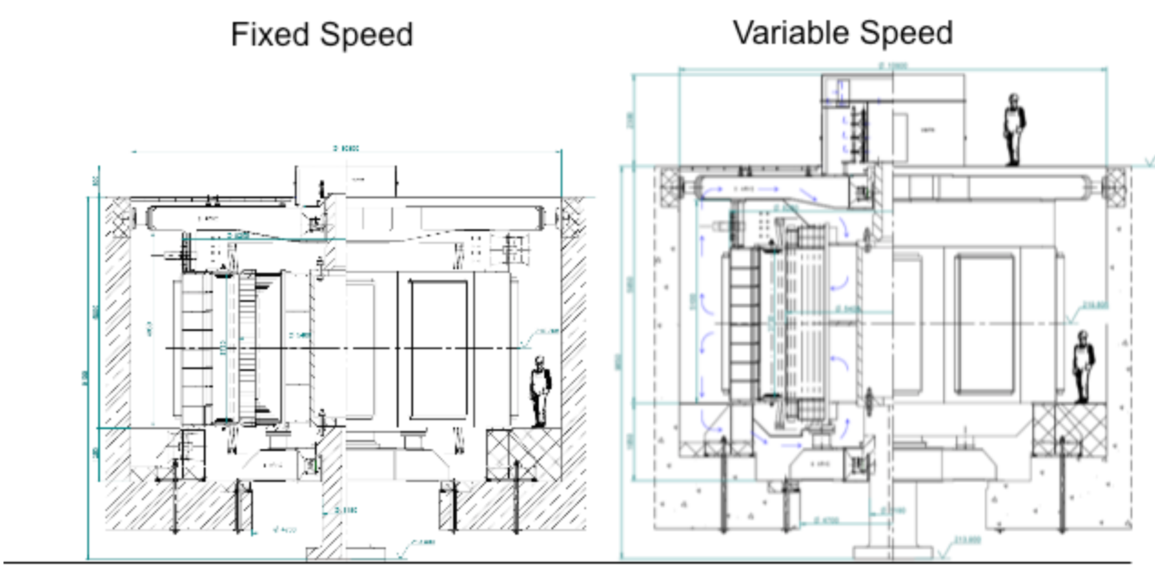


Figure 17: Comparison of large fixed speed MG and Variable speed MG.

Modern Advanced Ternary Pump Turbine

Modern Ternary pump turbine machines feature a motor/generator, a turbine that could be a Francis style turbine (Figure 18) or an Impulse turbine (Figure 19), a coupling, and a multistage pump.

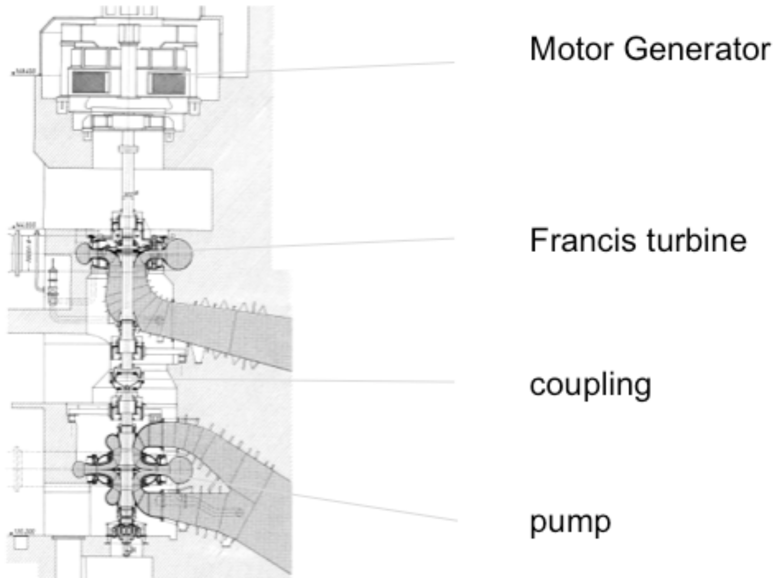


Figure 18: Ternary Francis Pump Turbine

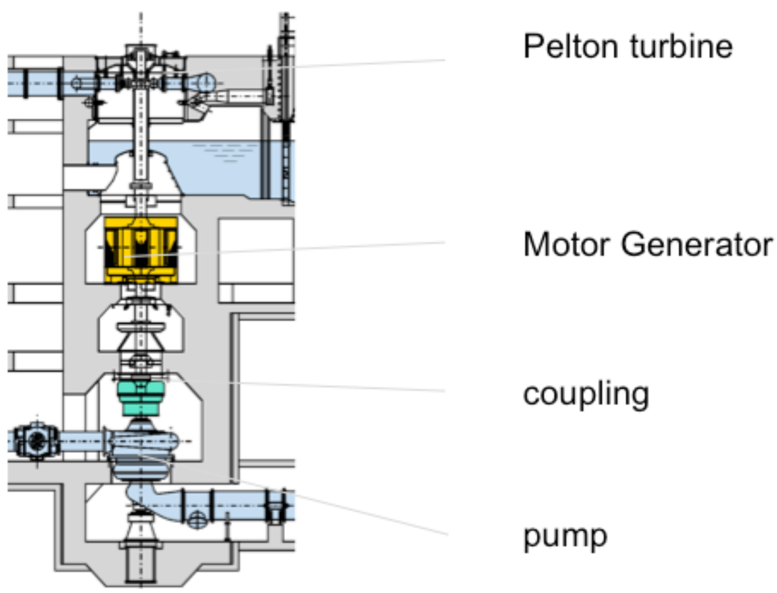


Figure 19: Ternary Impulse (Pelton) Pump Turbine

All equipment is on one shaft line and rotates in the same direction. Compared to reversible machines, no time consuming changes in rotational direction are necessary.

For high flexibility in operation the coupling can be a hydraulic torque converter with a no slip gear coupling. The hydraulic torque converter has adjustable vanes allowing its use for starting and stopping of the water filled storage pump. For startup the hydraulic torque converter is filled with water that can then be emptied dynamically after synchronization and gear coupling engagement and then it rotates in air. It's variable speed and dynamic water fill feature allows for transmission of initially high acceleration torque allowing for fast startup of the pump without sudden load surges to the grid. As the hydraulic torque converter is a variable speed device, the water filled pump starts and rotates up to speed providing load as it starts. Within 10 seconds after start of rotation about 60% of the pump power is already on the grid. The no slip gear coupling is engaged when the unit is near synchronous speed to maximize efficiency of power transmission during steady state operation of the pump. The hydraulic torque converter is also used to smoothly decouple/recouple the pump from the rotating system while the turbine is in operation allowing for transition of the Unit from power absorption to power production and back.

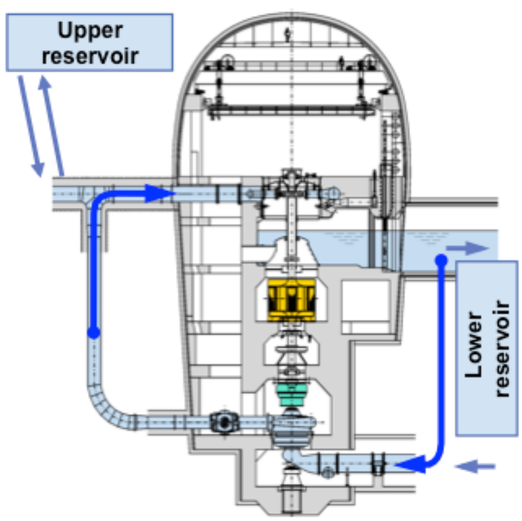


Figure 20: Ternary PT with possibility to operate in hydraulic short circuit.

The Ternary unit can be configured to provide hydraulic short circuit operation (Figure 20) allowing it to operate as a turbine, as a pump or as both a pump and turbine at the same time in a hydraulic short circuit mode. In the hydraulic short circuit mode, the turbine utilizes some of the water produced by the pump to generate power that offsets power used by the pump. This allows the unit to provide a wide range of adjustable power absorption to the grid with the unit operating principally in the pump cycle (Figure 6). Additionally the flexibility and speed of mode change make this configuration very responsive to grid needs. (Figure 7) The Ternary machines recently commissioned at Kops II in Austria represent such a machine (Figure 20). In recent experience there, the operators at Kops II report mode changes as frequent as 500 per month with monthly operation in turbine mode 200-500 hours, in pump mode 10 to 50 hours, in synchronous condense mode about 10 and in hydraulic short circuit operation from 150 to 400 hours, all with the unit experiencing only 20 to 30 start/stops per year. The Ternary configurations provides the most flexible arrangements of the pump storage machine and the fastest changes to operational state should these be needed to support grid needs.