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Hydro storage reduces electricity costs and keep wind and solar unpolluted

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Abstract. New energy policy is caused by narrow range of operation of Thermal Power Plants, potential risks of Nuclear Power Plants, limited resources of oil, gas and coal, and new trends in ecology. Taking into account that renewable energy, solar and wind power particularly are very dependent on the climate, Hydro Power takes a new role in energy systems. Electricity conversion and storage in periods of lower consumption or available excess production, and electricity production from the stored energy in periods of higher demand or reduced production, are crucial for the maintenance of stable and efficient electrical system. This requirement has especially strengthened nowadays in the world due to the expansion of integration of new wind and solar plants. These renewable sources are characterized with inherent intermittent production both in daily periods and periods of several days, weeks or even months.

A number of technologies might be considered for the electricity conversion and storage, but the only nature and high capacity available technology is based on the pumped-hydro storage plants. This article studies the potential of the pumped storage plants as the effective and economically competitive technology for the storage of wind, solar, run-of-river and other environmentally friendly energies, as well as energy from other conventional thermal plants including nuclear. Nuclear and coal fired plants can change power output to achieve demand but only at the price of extremely high maintenance cost. In addition, natural gas generators contribute to climate change and pollution only slightly less than coal. The pumped storage method is the most common storage system in the electricity sector. It is traditionally dependent on natural conditions, usually making use of rivers or lakes. However, some innovative methods have emerged in recent years, such as the use of the sea as the lower reservoir, or a proposal to use a surface reservoir as the upper reservoir and an underground reservoir as the lower. Analyses indicate that there is a strong economic incentive for further investment in pumped-storage installations when other hydro storages and sites are not available.

Key words: energy system, balancing, pumped hydro storage, renewables, accumulation.

1. Introduction - Why Pumped Storage

Storages and pumped-storages permit electrical grids to be optimized, prevent blackouts and limit price variations. In addition, they mitigate uncertainties, whether in market prices, wind forecast, precipitation, demand, and generators operational troubles; moreover, they maximize operating profit and make it achievable and more certain. Pumped-storages are of paramount importance as the most reliable and most affordable storages of clean renewable energy – wind, solar and run-of-river energy surplus. These plants could substitute up to 50% of nuclear and coal thermo power plants. Pumped storages are the best - easily manageable and most efficient. Yet nuclear and other thermal generators are not stable without easy adjustable stand-by and running reserve to prevent blackouts – again hydroelectric plants are ideal for this purpose.



Wind and solar energy are certainly clean and renewable energy sources; they are the most rapidly growing electricity powers and will be a significant competitor in the near future. Yet to date the variability of wind and the inability of generators to control the energy output has remained a primary problem. For wind and solar to reach its full potential and remain clean, a capable method for clean storing of energy has been inevitable.

The energy consumption from an electrical grid must always be equal to the energy delivered by the electrical generators. If this is not the case, the frequency and voltage will fluctuate with severe disturbances of the supply/load balance and the system could collapse. The electric transmission system interconnects the distribution systems providing multiple redundant alternate generators and routes for power to flow when failures occur (whether due to weather or equipment). Generators cover demand, but the transmission system has a key role in connecting distributed sources and consumers. If generation, demand and transmission are not in balance, the equipment will shut down in an attempt to protect the system. If the imbalance is severe, blackouts will occur [1, 2, 29].

Pumped-storage has excellent maneuverability in operation. A hydro plant is possible to start up from zero power to full power within several minutes [5, 28]. Grid system operators usually hold pumped-storage stations in such an operational mode, so that pumped-storage will be ready to cover any peaks of electricity demand associated with peak hours, or even during breaks in popular TV programs. Yet, it is possible to improve stability by operating the unit spinning-in-air either as a pump or turbine. In these reserve modes, pumped-storage units use less than 1% of their rated power, but by operating water valves so that they can switch to pump or generate mode in less than 10 seconds. These modes are also synchronous compensators for improving the power factor reducing transmission line losses, which could be even much more than losses in the units spinning in air. The pumped-storage plant can rock the power-output broadly within several seconds; such plants may operate as partial-load-reserve machines. Furthermore, pumped-storage plant works as a reserve power generator to manage any unexpected demand or generation-loss fluctuation. Operation of pumped-storage plants are often completely automated, and automatically respond to frequency fluctuations. As a result of all these benefits, we can conclude that pumped-storage contributes to overall grid power quality and improved system reliability.

Pumped-storage is an opportunity that has been frequently overlooked at a substantial cost to be paid by either the environment or the economy [4, 25]. The key advantage of this enticing opportunity is to achieve an efficient, reliable and stable power system and set the stage for exploiting the advantages offered by renewable. The electricity market should support the complementary nature of pumped-storage and wind. Besides, nuclear coal fleet cannot support market demand and contingencies, or only at very high price; complementary pumping power plants balance base loads just as well [15, 26, 27]. It must be emphasized that natural gas energy contributes to climate change only slightly less than coal. Natural gas and other thermal stations supporting wind further increases pollution.

Conventional storage hydropower plants can accumulate energy and release it when the grid needs it. It is quite common for hydropower plants to be used only at times when energy demand is greatest. They are very good for this purpose, because they can start and stop quickly, and it is at a "small" cost [15, 25]. To do this reliably requires considerable upper reservoir and imparts no corresponding ability to absorb excesses in wind, solar and based load from the grid as pumped-storage systems do. This feature is vital to nuclear and coal generation plants as well because they can only change their load very slowly and/or at extremely high costs and energy dissipation heating and polluting, but pumped-storage plants can be used to absorb their output at night.

Variable speed hydraulic machines operate all the time at the best efficiency and highly reduced vibrations, decrease operating and maintenance cost for even 50% or more if appropriately managed by experts. The total efficiency of a cycle is increased; electrical energy pumped into the storage at off peak hours, generates into the grid up to 85% as expensive peak energy. But such energy sources require a large capital investment. Design, construction and operation of hydroelectric projects require a great many details to be accurate and must be well-conceived and executed. The design has to be carefully coordinated to achieve safe and economical operation, and to ensure social, technological, and environmental success.

Hydrogen as a fuel cannot be cheap and an economical storage of electricity. The efficiency of the transformation cycle (electricity surplus – hydrogen – electricity peak energy) is at the level of less than 40%, frequently even less than 30% (the so-called thermodynamic bottleneck). Hydrogen is the important candidate for replacing gasoline. Various institutions are studying technologies for generating hydrogen in large-scale amount as the clean vehicle fuel.

Hydraulic transient design analyses of pump storage and conventional hydro power plants are pointed out in this paper.

2. Wind, Nuclear, Fossil and Solar Power

Wind is a clean and renewable energy source; it is one of the most rapidly growing sources of electricity and may be a significant competitor in the near future. So far the variability of wind and the inability to control the amount of energy generated, has remained a primary problem. There are also times when the wind turbines deliver excess energy that cannot be supported by demand on the grid. Alternatively, there are times of low wind or an absence of wind, when no energy is being produced **Error! Reference source not found..**

For wind to reach its full potential, a capable method of storing wind energy is required. Nuclear and coal fired plants could change power output to demand, but at extremely high maintenance costs and dissipation of energy as heat. In addition, it takes time to adjust to the grid. Oil and gas fired generators require 15 to 20 minutes to start if they are off-line, and when they are on-line synchronized to the grid as speed-no-load or spinning reserve the response is fast (immediately manually or automatically), but they are emitting greenhouse gases and [have](#) other environment effects.

Clean hydro storages as balancing mechanisms for wind energy have been one of the best and cleanest environmentally friendly solutions.

Natural gas generators contribute to climate change only slightly less than coal (**Error! Reference source not found.**). Therefore, a mixture of wind power with hydroelectric and pumped-storage is a key strategy to ensure an important and stable source of clean renewable electricity (**Error! Reference source not found.**). Hydro storages and pumped storages play a central part in the operation of the electricity system. They are the electricity grid's stabilizers, helping to ensure that the electricity supply is both regular and steady [4, 15, 28]. They could be ready to step in at any moment to generate the extra power that electricity grid may need to carry out its business and other activities.

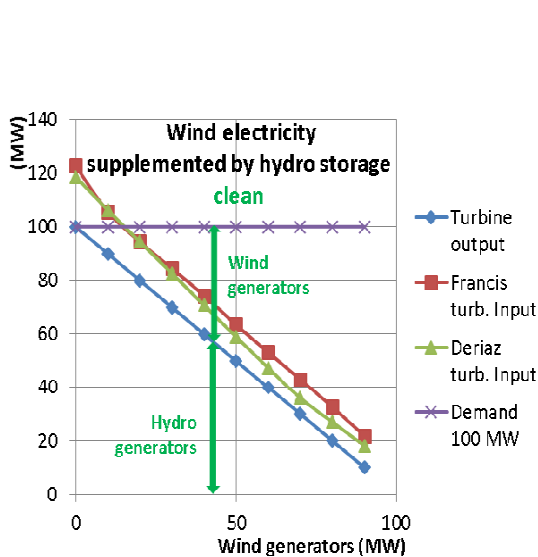


Figure 1 Wind and hydro only clean electricity

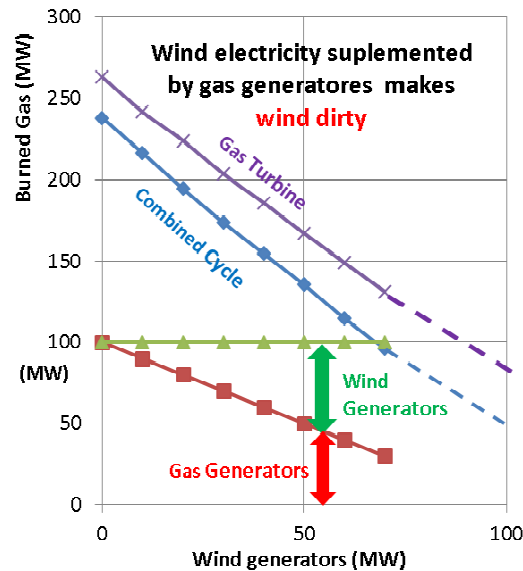


Figure 2 Wind and natural gas pollution

Assertions based on analysis of long term measured data of wind Power analyses in the United Kingdom in 2008 to 2010 [28], include:

- Average output from wind was 24 – 27%
- At the four highest peak demand periods wind output was low, at respectively 4.7%, 5.5%, 2.6% and 2.5% of capacity
- Capacity below 20% occurred more than half the time
Capacity below 2.5% occurred for one day in twelve days.

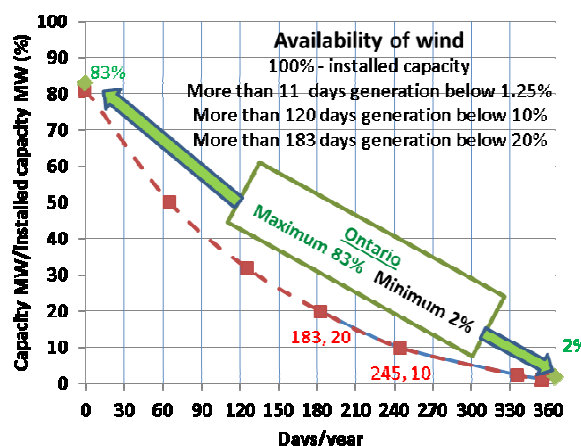


Figure 3 Availability of wind in UK (2008 to 2010 and Ontario (IESO <http://www.ieso.ca/>))

Analysis of wind in Ontario shows similar characteristics, available never more than 83% and never less than 2% - Figure 3.

There is a need for long-term storage facilities to cope with longer periods of windless or low-wind conditions. A calm lasting ten days is not unusual in Germany. Indeed, in October and November, 2011, the country experienced a protracted high pressure blocking weather pattern for 44 consecutive days, causing a spectacular breakdown in wind

generated power. During 27 days in November, of all the 27,215 MW of wind power capacity installed in Germany at that time, the wind turbines were able to only provide the following [7]:

- 30% of their potential electric power for just 2 days,
- 15% for 4 days,
- 7 – 8% for 5 days,
- 4 – 5% for 2 days,
- 2-2,5% for 11 days.

The extremely low share of wind in electricity power in November 2011 is shown in Fig. 4.

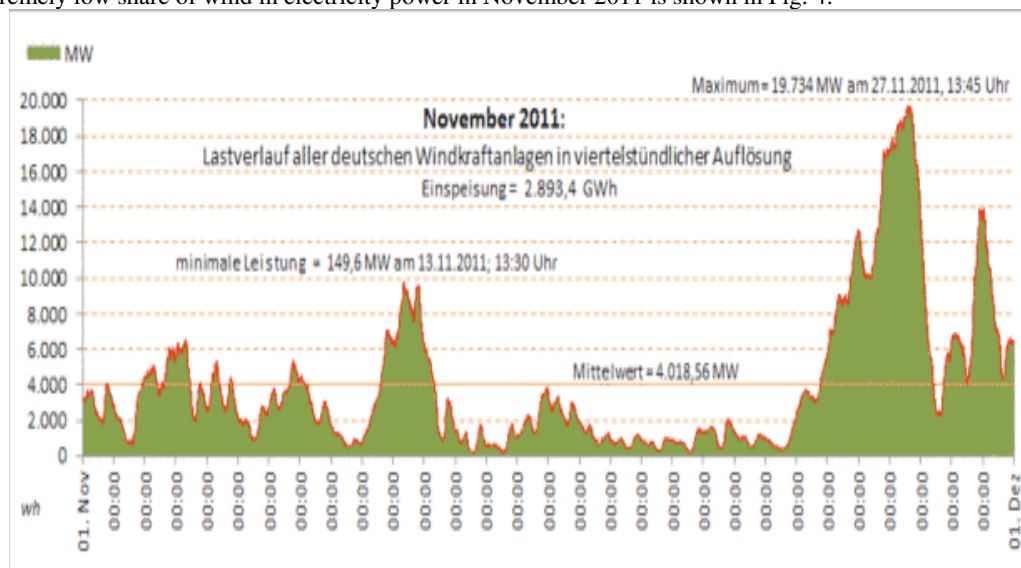


Fig. 4 Conventional power generation and wind power during November 2011.

Therefore, wind and solar power plants should not be listed as available capacities even when installed or online. For instance, in 2010 Ontario had an installed capacity 35,183 MW of which 33,481 MW was available. By 2030 it is expected to have 40,900 MW installed but only available 30,200 MW (

Figure 5) [12]. Increasing the capacity of wind and solar electricity should be carefully analyzed or will increase the instability, price and pollution; analyses indicate that there is a strong economic reason for pumped-storage installations. According to the research pumped-storage plant could be paid off even in four (4) to seven (7) years [3]. Amount of energy that can be stored by pumped-storage, divided by the amount of energy required to build it is 21 times better than best batteries and 110 times better than lead-acid batteries [21]. Other electrical and electro-chemical storages are still under development or too expensive and cannot yet compete the hydro storages [19].

3. Hydroelectric Storage Plants

Conventional hydroelectric stations have management restrictions on the operation of the stored water depending on precipitation and water level variations. However, they can respond quickly to demand variations and other grid irregularities. Conventional storage hydropower plants can accumulate energy and release it when demand for is high. It is quite common for hydropower plants to be used only at times when energy demand is greatest. They are very good for this purpose, because they can start and stop quickly at a small cost. To do this reliably, a considerable upper reservoir is necessary.

Conventional hydropower plants have no ability to absorb wind, solar and base load surplus from the grid like pumped-storage can. This feature is also vital to nuclear generation plants because nuclear plants can only change their load slowly and pumped-storage plants can be used to absorb their output at night. The maintenance costs of certain types of gas fired power stations increase sharply if they are forced to reduce their load at night, and so they benefit from the storage plant attached to the grid. Even oil and coal-fired stations can be operated closer to their optimum efficiency reducing gaseous emissions if the supply system includes pumped storage plant [25].

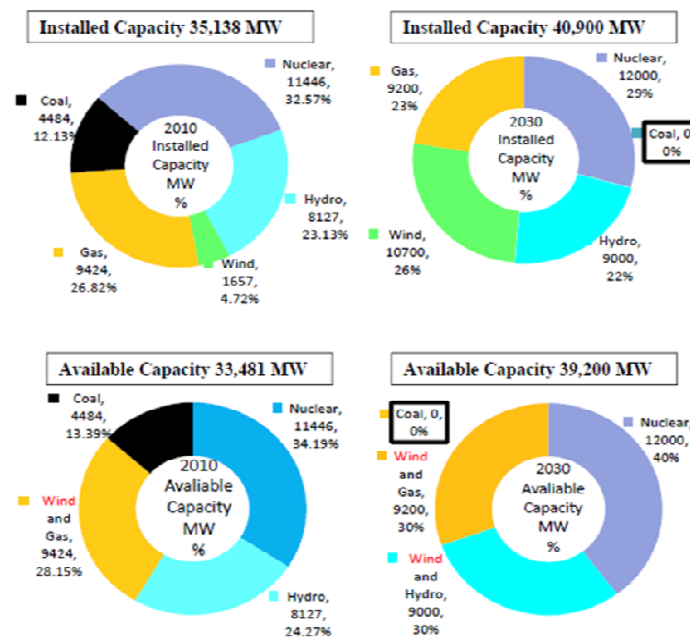


Figure 5 Projected installed and available capacities in 2010 and 2030¹

For pumped hydroelectric energy storage two water reservoirs at different heights are used. In charging mode, the water is pumped from the lower to the upper reservoir. In discharging mode, the water flows from the upper into the lower reservoir, driving the reversible turbines and producing electricity. This is the most common storage system in the electricity sector. It is traditionally dependent on natural conditions, usually making use of rivers or lakes. However, some innovative methods have emerged in recent years, such as use of the sea as the lower reservoir (Japan) or a proposal to use a surface reservoir as the upper reservoir and an underground reservoir, possibly below the other, as the lower reservoir [3]. It is a mature technology, widely deployed worldwide, with a high durability. The efficiency of older systems can be increased by retrofitting some of their components, in particular the runner. Drawbacks might be the location limitations, long lead times, environmental issues, and the high initial costs. "Dinorwig" (UK) with 1800 MW is the largest facility of this type in Europe, with a black start capability. "Bajina Basta" (Serbia) is the first single stage pumped-storage power plant constructed in Europe, see Fig. 6. Characteristics of different available technologies for electricity conversion and storage are presented in Table 1 [3].

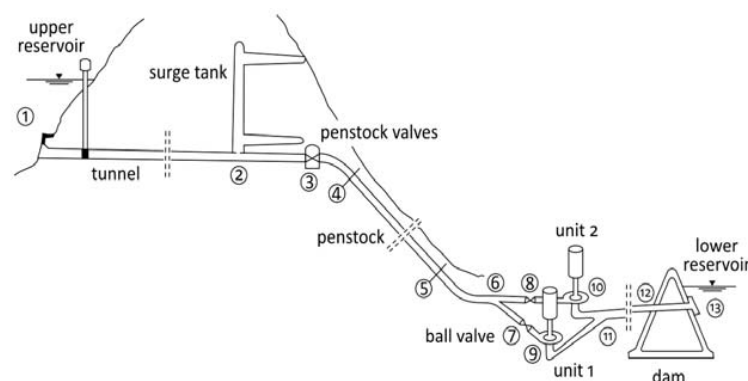


Figure 6 Pumped-Storage Power Station "Bajina Basta", Serbia (2X300 MW)

Furthermore, pumped storage plants deliver ancillary services to the grid; such as standby and reserve duties, black-start, frequency control, and flexible reactive loading. Pumped-storage could also be used to provide replacement power to mitigate market response. Production and consumption could be optimized in the following ways:

¹(Conservation excluded). New hydro storages are the clean solution; other storages and thermal gas and oil plants turns clean wind and solar energy into dirty pollutants.

improved efficiency, cost reduction, greenhouse gas and pollution reduction, blackout prevention, black start capability², increases in profit and enhanced consumer price protection.

4. Blackouts and Troubles

Pumped-storage plants can provide grid stability during contingencies and prevent blackouts. The cost of the North America 2003 blackout has exceeded \$10 billions and caused 11 deaths [1]. A comprehensive approach to the optimization of the electrical system enables the realization of two significant goals: first, in obtaining essentially free spinning reserve, and secondly, simultaneously achieving the most economical generation. If the grid is not optimized, we leave our economy vulnerable - each blackout may cost billions of dollars. Any trouble announces itself in time. It is important to recognize it on time, in advance. Vibrations of the unit (bearings, turbine head cover and generator) and shaft oscillations are very important and must be analyzed and considered on-line all the time. When measured vibrations are close to the limits, operation is only permitted under careful monitoring and supervision; if the limit is exceeded, an incident should be expected; the units must be repaired to prevent an accident [11]. Energy production costs are dependent mostly on vibration intensity and related exposure rate, which is increasing continuously in time.

Table 1 Electrical energy storage technologies and their characteristics

	Power rating (MW)	Discharge duration (h)	Efficiency %	Durability (years)	Durability (cycles)	Capital cost (\$/kW)	Capital cost (\$/kWh)	Techno level (1 to 5)	Availability
Hydroelectric energy storage	100-5000	10-100	70-87	40-100	12000-30000+	600-2000	5-100	5	95%+
Compressed air energy storage	1-400	2-100	40-80	20-100	30000+	400-800	2-50	5	65-96%
Lead-acid chemical batteries	0.001-50	h	70-92	5-15 (~10)	500-1200	300-600	200-400	5	99,997 %
Ni-Cd chemical batteries	0-46	s-h	60-70	5-20	1000-2500	500-1500	800-1500	4	99%+
Li-ion chemical batteries	0.1-50	0.1-5	85-90	5-20	1000-10000	1200-4000	600-2500	4	97+
Na-S chemical batteries	0.05-34	5-8	75-90	15	2000-5000	1000-3000	300-500	4	Up to 99,98%
Metal-air batteries	0.02-10	3-4	40-60	-	100-300	100-250	10-60	1	N/A
Fuel cells	0.000001-50	s-24+	20-70	5-15	1000-10000	10000+	6000-20000	2	90%
Thermal energy storage	0.1-300	1-24+	30-60	10-40	2000-14600	200-300	3-60	3-4	90%

Exposure rate as a correlation between the real time (real measured vibrations) and reference time of operation (reference vibrations) is the most important characteristic of the unit. It is essentially statistical in nature. Some standards, guidelines and technical papers consider vibrations and correlate them to the exposure rate. The on-line measured data compared to the data measured several hundred hours ago are changing in time. They are highly influenced by real time of operation and exposure rate, and operating point. Vibrations (amplitudes and corresponding frequencies) and other machine characteristics have a strong influence on numerical values of exposure rate. Statistics are based on the data from technical literature and should be and could be improved for any generator analyzing files of measured and logged records, which will then improve numerical on-line measured and calculated values [11].

²Black Start is the process of restarting a generator to recover from a shutdown of the transmission system without external electric power.

5. Financing

Analyses indicate that there is a strong economic reason for pumped-storage installations when other hydro storages and sites are not available. Uncertainties regarding market rules are one of the reasons for lack of investment. However, many countries (including Switzerland, Germany, Austria and China) have already invested in pumped storages due to the predictable upgrade benefits. Key factors that influence the economics is capital cost reduction, legal constraints, and efficiency. Analysis based on the US market price data (Figure 7) shows the results that large high-head underground pumped-storage plant could be paid off in 7 to 10 years with average revenue (\$300,000 /MWyear) or even in 5 years if arbitrage, and regulation revenue is maximized (\$600,000 /MWyear). Surface plants at suitable locations can be paid off even in four to six years [3].

Some electrical grids operate effectively without storage. However, cost-effective storage of electrical energy could assist making the grid more efficient and reliable. We have to optimize the system to deliver cheaper electricity and increase generators' profit. The benefits could have reduced the number of peak generators (expensive/polluting peaking plants), the number of thermal (nuclear, coal, oil and gas fuelled) plants, and the strain on transmission and distribution networks. The environmental impact of pumped-storage stations is less than that of conventional hydropower stations since the required water storage is much smaller. The typical design life is 100 years; the environmental impact of construction and operation is very low as well [21]. In addition, they could also provide ancillary to important services such as frequency control, voltage support, and operating reserves, thereby enhancing grid stability and reliability, even reducing transmission losses (improving the power factor).

All rotating machines have natural flywheels. To control speed rise and conduit pressure rise hydraulic machines' flywheels are artificially increased. Optimizing rotating masses by turbinizing and pumping hydro facilities frequency regulation can offer one of the highest revenue for storage [3].

Analyses show considerable achievement with regulation revenue 83%, energy arbitrage 12%, and capacity revenue 3% [3]. Market rules have significant influence and change these percentages.

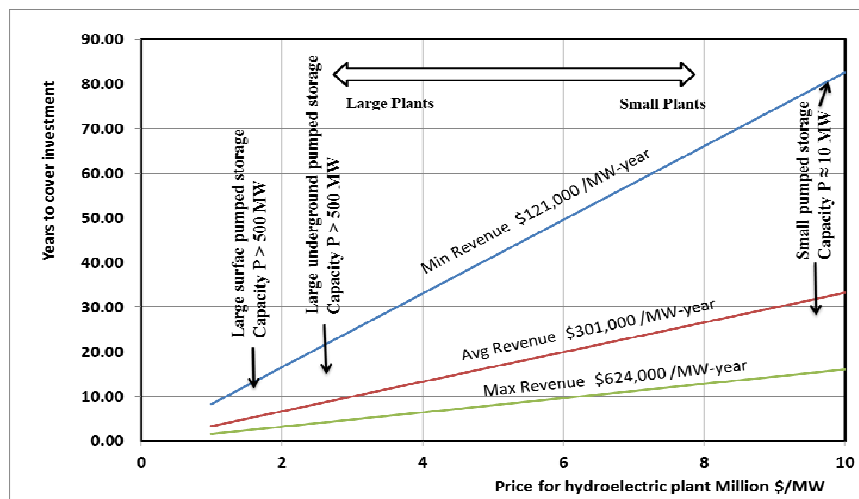


Figure 7: Number of years to operate to cover investment.³

6. Fifty Percent (50%) of Hydro Systems Have Accidents and Troubles

Hydropower knowledge and experience has acquired a very high degree of maturity, but this knowledge and experience has also been lost, being hidden in few companies and even fewer experts usually not transferring technology to young new coming staff. Fascinating fluid mechanics and applied mathematics know-how applied in fascinating electric plants and technology over centuries unfortunately teach us that more than 50% of these monuments of humanity have troubles in operation. There are very few accidents published, therefore “lessons have never been learned.” The same accidents have been repeated and will likely happen again. An organized system, not solely schooling, is the right method for the modern transfer of centuries old experience. As human lives are short, only a properly organized transfer of knowledge and experience could support further progress based on high technology.

The design and construction of the (hydro) electric power station is a complex task, requiring a high level of expertise and experience. Finance, feasibility and environmental studies usually require broad planning, design and construction schedules. This is compensated by long service life and low operating costs. Hydropower plants hydro storages and pumped storages are “fuel is free⁴” compensating unstable fossil fuel prices in general continuously increasing and one-day sources may be depleted. If barriers of a legal and administrative nature stand in the way of

³Number of years to operate to cover investment. For different revenue and various investments.

⁴ Pumps fill storages at off peak hours when grid has surplus of energy. There are periods when thermal plants pay not to be off grid; negative electricity price. In this case, pumped-storage plants can make money even while pumping!

economic analyses, the potential of this cheap renewable energy will be postponed. However, the feasible prospective can also go beyond the economic potential, if construction can be afforded by the Governments.

The construction of hydroelectric plants is not possible without some environmental impact. For example, this impact might be in the form of ecological changes of animal and plant species. Moreover, changes in the thermal regime, energy, which is registered in large lakes, changes in the local climate, increasing the lowest temperature and decreasing the highest temperature.

7. Standards, Guidelines and Recommendations Are In Need of Revision

At the time of the design of the “Bajina Basta” pumped-storage plant (Figure 6), some of the recommendations and standards could have not been applied and the vital parameters of safety and safe operation have been based on experience and knowledge of designers and equipment suppliers. Due to the limited space only one example is mentioned here. The minimum absolute pressure in the draft tube of 0.5 bar does not fit the complex flow conditions at the exit of the runner, and new previously unpublished procedure applied.

The Guidelines in hydropower design have not yet been changed and updated! In the meantime many unpublished and some published accidents occurred [17]. Some technical areas have lost valuable experience and knowledge that has accrued in more than 100 years. Poorly coordinated transfer of practical and theoretical experience appears to be the root cause of this loss. The consequences are an unstable market and investment climate, accidents, inefficiency and troubleshooting (of the same problems) which have all shown up regularly in recent years and will continue in the future if appropriate steps are not taken. The organized multidisciplinary transfer of experience is a major task that needs to be undertaken by nonpartisan organizations. It is urgent that decisions be made. There is a clear need to plan, finance and implement some long-term initiatives [8].

8. Conclusions

Pumped-storage is not only a potentially significant environmentally clean load that may help compensate the need to limit wind power output, but also a balancer of supply and demand of electricity in many distribution grids. Energy storages could make the system and market more efficient and reliable. Pumped storages could substitute up to 50% of nuclear and coal generating plants. They are easily manageable and are 75 - 85% efficient across the energy storage cycle. A rushed study might incorrectly conclude, for that reason, that these plants have been harmful to the environment due to the energy dissipation resulting in gaseous emissions (GHG). A more detailed analysis discloses this is not the case. It may be that a reduction in emissions, that results in pumped-storage displacing the older plant from the day-time peaks, absorbing clean wind, solar, run-of-river spills, nuclear energy at night, and replacing part-loaded, inefficient plants from standby and reserve duties. The exact situation depends on the supply mix, stability, and other features of the grid system in question.

Fascinating plants and technologies, though applied now over more than a century, continue to face challenges. Indeed, experience teaches us that more than 50% of these monuments to human ingenuity experience considerable troubles in operation. A more systematic and complete commitment to the organized transfer of knowledge and experience could form the foundation for further progress toward the crucial need for human energy in a challenging world.

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