SEVENTH FRAMEWORK PROGRAMME

THEME 5 - ENERGY

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PARTICIPANT ORGANISATIONS

Participant organisation name	Short name	Country
ALSTOM HYDRO FRANCE	AHF	France
ELECTRICITE DE FRANCE S.A.	EDF	France
ELIA SYSTEM OPERATOR	ELI	Belgium
ALSTOM GRID SAS	AGR	France
IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE	ICL	United Kingdom
KEMA NEDERLAND BV	KEM	Netherlands
ALGOE	ALG	France

1 INTRODUCTION

1.1. Background of the report

The European Union (EU) has decided to take a proactive position concerning the issue of global warming by enacting its 20-20-20 package. This aims at raising the share of the EU energy consumption produced from renewable resources to 20%, reducing by 20% the EU greenhouse gases emissions level of 1990, and improving by 20% the EU's energy efficiency.

New renewables such as solar or wind power have been widely deployed. However one major challenge of new renewable energy consists in it being intermittent while the grid needs to be balanced at any moment. Concretely, this means that the current EU electricity system will need to be more flexible to allow the full utilisation of renewables.

Today, one of the existing solutions to avoid curtailing intermittent renewable generation and that also happens to be available on a large-scale is Pumped Hydro Storage Plants (PSP). PSP are able to store energy when there is a surplus in the energy system and therefore constitute a vitally important part of the new low-carbon electricity system the EU wants to achieve.

However, conventional PSPs can only regulate their power in generation mode, while their operation in pumping mode is typically much less flexible; new technologies are therefore under development to enable greater operational flexibility of PSPs. In that context, the variable speed technology for PSP can bring the additional flexibility in pumping mode as well. This could lead to a better integration of renewables in the electricity system, by serving a dual purpose as the surplus of intermittent renewable energy could be absorbed at any time of the day while at the same time allowing services to be balanced.

In this context, the main goal of eStorage Work Package 1 (WP1) was to demonstrate the technical and economical feasibility of upgrading an existing plant to variable speed, through a concrete realisation.

The plant chosen to perform this demonstration was le Cheylas PSP, a plant located in the French Alps and operated by EDF. Unfortunately, in 2015, as a consequence of the depressed context on electricity markets in Europe, associated to technological developments on variable speed technologies, EDF has taken the decision to suspend to conversion planned in le Cheylas PSP.

1.2. Presentation of le Cheylas power plant

The Arc-Isère hydroelectric facilities were constructed in the seventies and commissioned in 1979. EDF was then granted a 75 year license to operate them. The facilities serve two purposes:

- Electricity generation, using the river Arc inflow conveyed from Longefan to Le Flumet reservoir by a 20 km long tunnel,
- Electricity storage, on a daily cycle, by pumping at night from le Cheylas reservoir into le Flumet.

There is only one powerhouse, equipped with two identical 270 MVA reversible units, each located in a shaft. A water conveyance system common to the 2 units connects the powerhouse to the 2 reservoirs.

Figure 1: Le Cheylas PSP

Unit 1 was dismantled for maintenance in 2010. This allowed verification of all major unit components (spherical valve, pump-turbine, and generator-motor). Their condition is good and only minor operations have been performed on them. They have been put back in service with the original equipment and as a result of this maintenance; unit 1 will continue operating at a fixed rotating speed.

Unit 2 was inspected last in 2010 and found as well in good condition. It could either undergo a similar maintenance operation and continue operating over a long period with the same performance and service levels as unit 1, or be converted to variable speed, to provide additional services.

In 2012, the decision was taken to launch unit 2 conversion variable speed. The interest of this conversion was to offer additional services: future operation would still serve the two purposes above, with additional frequency response services and increased efficiency.

1.3. Objectives of the report

Although the conversion has been stopped in October 2015, 3 years of studies had been performed, and some results have been achieved.

The objective of this report is to present a synthesis of the main achievements during these 3 years of studies, to present the difficulties encountered (some of them had been solved, some were still pending at the moment the decision to stop was taken), and to present the reflexion that has led EDF to the decision to stop the conversion.

More broadly, among this first set of objectives, the objectives pursued in this report are to try to draw lessons from this experience, and define in a most precise way the conditions for success of such a conversion.

2 DETAIL STUDIES OF THE UPGRADE OF AN EXISTING PSP WITH THE DFIM TECHNOLOGY

The conversion of le Cheylas PSP to variable speed with the DFIM technology has been performed up to the detailed studies level. The main results of these studies are described hereafter.

2.1. The conversion to variable speed project: technical aspects and associated risks

As explain earlier, the conversion of le Cheylas PSP to variable speed technology was supposed to be the first realization of such an operation for European industry. The first task considering WP1 of eStorage was then to list every challenge and associated risks in order to tackle them and solve them one by one.

The main risks were listed in the presentation made for eStorage project of the Work Package 1.

Risk ref	Description of the Risk
R1.1	Increase in the size & mass of the Motor- Generator rotor has to fit in the existing civil work and mechanical support structure.
R1.2	Volume availability in the power house (unit shaft line and surface building) to position all additional equipment necessary for variable speed Unit.
R1.3	Fit with new excitation frequencies due to the operation at variable frequency (+/- 7%).
R1.4	Increase in the torque of the Unit above the capacity of the existing shaft.
R1.4a	Increase in the torque of the Unit above the capacity of the existing civil work structure.
R1.5	Hydraulic stability of the Unit throughout the new domain of operation.
R1.6	Inadequate interface between the new equipment and the existing plant: cooling system, control system, shaft coupling
R1.7	Schedule risk: increase in the outage time due to unforeseen problem will have important cost impact.
R1.8	“Surprise” at site during dismantling the existing turbine (additional work)
R1.9	Design risk on Turbine and Generator not to achieve acceptable performance.
R1.10	Non compliance with grid code requirements

Figure 2: Main risks associated to WP1

2.2. Design studies performed

The detailed studies and solutions are described in detail in D1.1 “Plant design and estimated value of unit 2 improvement” delivered to the EC in Oct. 2014 (confidential report).

Globally, they have been successfully conducted by Alstom and validated by EDF, which means than a technical solution had been found for most identified risks.

The main design options validated are the following:

2.2.1. Hydraulic design

In order to take advantage of power regulation in pumping mode, the hydraulic design must allow increased water flow variation. As the original design was not foreseen to operate in such conditions, the hydraulic design had to be re-engineered.

The key design target was to allow a power variation in pump mode of 80 MW under the full head range (i.e. constant power variation close to 30% of the unit’s nominal power, leading to a speed variation of +/- 7%). Both the pump and the turbine design represented an ambitious challenge, at the crossroad between variable speed technology and refurbishment.

Power-Plant	N° Units	Head (m)	Power (MW)	Speed (rpm)	New / refurbishment	Country
Nant de Drance	6	250-390	157	428.6 +/-7%	New	Switzerland
Linthal	4	560-724	250	500 +/-6%	New	Switzerland
Tehri	4	127.5-225	255	230.8 +/-7.5%	New	India
Le Cheylas	1	245-261	250	300 +/-7%	Refurbishment	France

Figure 3: Alstom variable speed hydraulic designs

The pump design is the key part of a variable speed upgrade. When compared to a “classical” pump-turbine refurbishment two new hydraulic challenges constraint the design. The lower pump power limit is set by an instability area where it is not possible to operate (called the humped zone) while the high power limit is defined by cavitation phenomena.

As the complete generator needs to be changed, one can freely choose the rotation speed. The choice of the new reference speed - from a hydraulic point of view - is therefore a balance between cavitation and hump criteria. For design optimization, the decision was made to keep the existing reference speed as the appropriate solution to maximize the pump power variation.

For obvious reasons of cost and planning, it was decided to modify only non embedded parts: the runner and the wicket gates. These components have higher water velocities and they bring the best efficiency / cost trade-off. The choice was made to keep the existing draft tube, stay ring and spiral casing.

An additional constraint was that the turbine must still match the existing transients' performances, particularly considering the operation of unit 1 which will not be upgraded, led to a further challenge. Despite these constraints, an efficiency increase of up to 5,2% in turbine mode an 0,8% in pump mode has been reached and validated through the performed model test.

2.2.2. Electrical design

The installation of a new double fed induction motor-generator (DFIM) inside an existing pit requires special attention to existing limitations such as structural design, interfaces to the auxiliaries, as well as the crane capacity to handle the increased rotor dimensions and weight. The integration of a new frequency converter has a direct impact on space requirements, the cooling system and power supply and is therefore one of the key elements to be checked in the early stage of the project.

The voltage source inverter using IGBT or IGCT is preferred to the cyclo-converter because it enables rapid response to the grid. In addition, as the VSI requires no reactive power for the commutation of its power electronic devices, the volume of the electrical machine is smaller. This is a key point when upgrading a power plant and fitting the new components into the existing civil works. In addition, there is no sub-harmonics injection that could generate sub-synchronous resonances. The DFIM technology is used by Alstom in all its variable speed pumped-storage projects (see figure 3). The DFIM design has been adopted because it is the best trade-off regarding the given constraints.

The DFIM uses the exchange between the wound rotor and the frequency converter to provide the speed variation, per figure 4. As a consequence, the stator needs to be oversized in sub-synchronous mode, due to the additional power transiting from the rotor to the stator, which could lead to power limitation due to the given civil works.

Keeping the existing stator could have been considered if the reactive power supply could have been reduced. The reactive power is partially provided by the frequency converter. However, in such a case, the stator winding needs to be compatible with the rotor winding. Due to a requirement for a factor power decrease from 0.91 to 0.85 in generating mode, the replacement of the existing stator was compulsory.

Another constraint on the DFIM design was to fit the stator and rotor within the motor-generator pit. The pit dimension was a factor limiting the DFIM's maximum output, especially as the rating of the stator is bigger than its synchronous counterpart for the same power at the main transformer.

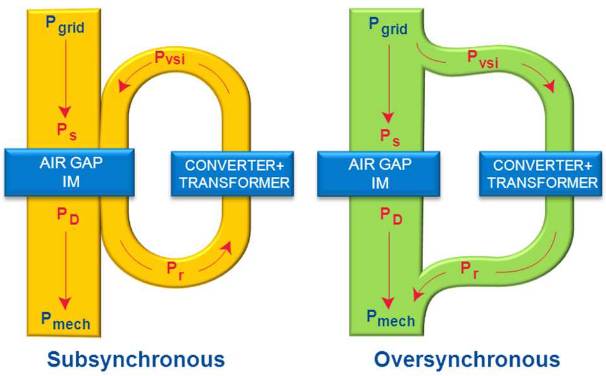

Figure 4: Rotor/converter exchange

The DFIM wound rotor is 23% heavier and has more volume than a salient pole synchronous rotor which impacts the shaft line behaviour. Due to the cylindrical rotor and to the bigger volume, the weight is greater, as the utilization factor is lower than for a synchronous machine. A comparison of the weight can be found in figure 5. As it can be seen in this table, the cylindrical rotor impacts the weight increase as much as the lower utilization factor.

	DFIM	Synchronous Machine with same volume as DFIM	Synchronous Machine “optimized” for the same power output as the DFIM
Rotor weight [t]	440	390 – 400	360

Figure 5: Rotor weight comparison.

Beyond the generator motor, the whole unit electrical equipment had to be reengineered: several parts of equipment may be reused while others have to be replaced, of course new ones must fit in the powerhouse premises. For example, synchronous rotor excitation devices must be dismantled while stator MV gears could be reused.

Most of the new equipment that has to be installed in the powerhouse is for the DFIM rotor feeding. The equipment includes:

- Heavy duty power tapping on the MV side of the unit’s power transformer
- Short circuit current limiting reactors
- MV breaker
- Special VSI transformer
- Harmonic filters
- VSI
- Segregated Phase Bus ducts from VSI to rotor ring cubicle
- Rotor over current and over voltage protection cubicle
- Non-conventional current transformers and voltage transformers for rotor current and voltage measurement at very low frequency

It has to be noted that the largest pieces of equipment required for rotor excitation (VSI transformer and VSI) represent roughly 150 m² of ground space which might be difficult to find in some underground power stations. Hence, large pieces of equipment such as the tapping transformer or VSI module will be placed outside of the power station.

On the stator side, more traditional pieces of equipment need to be placed:

- Isolated Phase Bus ducts (part of which may be reused from existing synchronous unit);
- Starting/braking short circuit breaker used for the DFIM launching in motor mode and for the re-generative braking sequence;
- Generator Circuit Breaker (GCB;
- Phase reversal disconnectors: it may be re-used or replaced depending upon its condition, ageing and rating.

Last but not least, the unit power transformer shall be replaced in order to accommodate a higher MVA rating. This replacement provides an opportunity to increase stator voltage and optimize DFIM design.

Some important features of the synchronous unit must also be undertaken by the variable speed unit such as black start operation or isolated network feeding or line charging capacity. Black start operation without tapping energy for rotor excitation is obtained thanks to a low power feeder that energizes the VSI enough to create voltage on the stator side and from there build up stator voltage. Isolated network or line charging capacity is not more a challenge than with a synchronous unit.

2.2.3. Mechanical design

Considering that the hydraulic studies demonstrated that there is no benefit to modify the rated speed and considering that the unit maximum power at rated speed had not been substantially modified, the unit shaft line and bearing were merely affected by the turbine upgrading. For example, the calculation of the maximum over speed and of the new runner hydraulic loads did not show any significant change compared with the existing pump-turbine.

On the contrary, the motor generator upgrade impacted the machine shaft line and bearing a lot, through several key parameters, such as: the possible increase of radial bearing span related to the increase of the rotor volume, the massive increase of the rotor weight. The most critical feature for the shaft line is the natural bending frequency. The difficulty is overcome by the re-arrangement of the unit layout. For example, the lower generator/motor radial bearing was shifted above the thrust bearing at the nearest position the rotor.

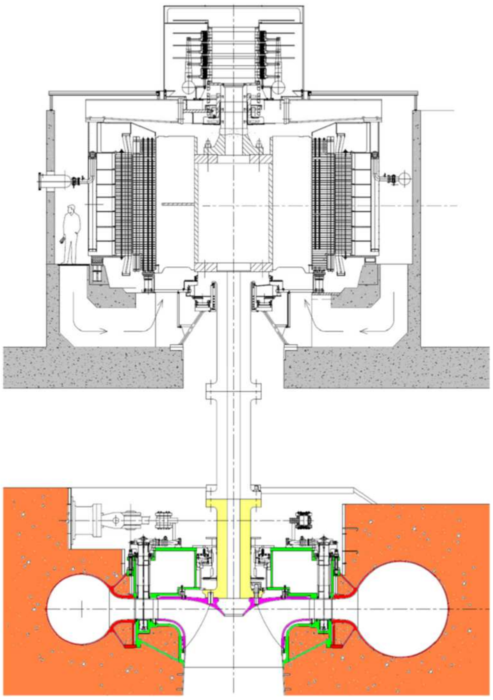

Figure 6: Planned unit layout

The thrust bearing needs to be redesigned too, with a higher capacity to support the supplement of unit axial load which comes mainly from the DFIM rotor. Calculations by finite element showed that the thrust bearing should better be put on the turbine top cover. In that case, the implantation of the thrust bearing supporting cone onto the pump-turbine top cover is not too difficult since the top cover and the distributor will be replaced with new ones. Actually, replacing these two turbine components was better than refurbishment for two main reasons. First is reduced machine outage time. Second was the possibility to modify the top cover arrangement to avoid a higher frequency excitation range coming from the variable speed.

2.3. Impacts of the DFIM solution on le Cheylas existing power plant

Beyond the studies performed concerning the design of the new unit, some other studies have been conducted concerning the consequences on the existing plant of the chosen solution.

As already discussed in the former paragraph, the insertion of the new machine in an existing plant is not so easy, because the new constrains associated to the machine had not been integrated during the initial conception of the plant. The main associated constrains can be divided in two categories:

- Constrains that will have an impact on the design of the new group because plant adaptations are not possible;
- Constrains from the new machine, imposing modifications on the existing plant.

Concerning the first category, the issues have been mainly discussed in the former paragraph. The main concern is about space availability. Among others, the dimensions of the existing pit cannot be modified, which impacted DFIM design. New space requirements (power plant of Le Cheylas is a very compact structure) had also to be taken into account when studying the installation of every new auxiliaries needed (generator circuit breaker, switch...)

Concerning the needed modifications on the existing plant, the issues were the following:

2.3.1. Handling issues

For an asynchronous machine, there is a three phase rotor. Alstom studies have determined a new mass for this rotor of 386t (compared to the 300 t of the existing synchronous rotor). As a consequence, the existing crane and frame of the plant are not dimensioned to handle the new rotor.

Several options to tackle this issue were investigated:

- Replacement of the existing powerhouse’s crane : increasing the load capacity of the travelling crane accordingly to the new weight of the rotor, with a re-enforcement of the crane supporting metallic structure;
- Assembling directly the rotor inside the motor generator pit, and in this case, the rotor remains life-confined in the pit. The rotor repair works will take place inside the motor generator pit, after removing the stator;
- Use of a specific lifting equipment dedicated to the cylindrical rotor and installed when required above the motor generator pit.

The first solution has been excluded; the reinforcement of metallic structures, and of the civil foundations of the plant, and the replacement of the travelling crane, are too expensive, and lead to too many impacts and constraints on the powerhouse.

The second solution comprises lots of risks during the building of the rotor because of the lack of place, and to set the verticality of the machine.

Finally, the third solution represents the best economic and technical option among the three alternatives and had been chosen. Several adaptations have been done in order to reach an acceptable solution:

- the current powerhouse crane will not be modified, and will be able to handle the new stator thanks to an optimization of its weights,
- the rotor maintenance works take place inside the motor generator pit, after removing the stator with the current travelling crane,
- the rotor is removed from the motor generator pit with the specific lifting equipment only in exceptional cases of important fault or short-circuit,
- the columns which carry the temporary driving way of the specific lifting equipment must be installed on the central area between the 2 units of Le Cheylas. The Static Frequency Converter (SFC) of the current unit, which launches the units in pumping mode, takes about one third of the space of this central area, so the replacement of the SFC was planned to be anticipated (this equipment is obsolete), the new one being installed outside the powerhouse, in order to facilitate the installation of the specific lifting equipment. Studies show that it is possible to put the variable speed rotor in the pit with the presence of the SFC, but with an inacceptable increase of risks considering handling operations on the rotor.

In this scheme, the handling operation was not carried out directly by EDF but by a lifting contractor, commissioned for that operation. This option can only be interesting if it doesn’t occur to often and raises the question of the availability of the lifting contractor (impact on outage duration in case of forced outage). As the machine installed by Alstom had to be a prototype, this was a new risk carried out by the project. Nevertheless, in order to minimize the associated risk, it was planned to introduce in the contract with the lifting contractor a 5 years period of intervention in case of non-anticipated need to handle the rotor. This provision characterized by a delay to provide the handling equipment was not a zero cost.

Moreover, in order to limit the need for the specific handling equipment, it had been decided between EDF and Alstom in September 2014, at the moment the equipment purchase was launched, that current maintenance operations should be performed in the pit.

2.3.2. Civil work

As the supporting civil structures of the existing plant are reused, every stator support had to be checked against the loads and the torque created by the DFIM. Several studies have been executed: frequency analysis, verification of the support stiffness of the unit bearing on the civil structure, calculation of the shaft line verticality, verification of the current reinforced concrete in the new machine configuration and the corresponding forces.

- Improvement of thrust bearing:

  After detailed check by Civil Work team, it appeared that the quality of the concrete is very low (compared to what was anticipated). A lot of small cracks can reduce the rigidity of the concrete by a factor of 4. It is mainly critical for the intermediate concrete beam which supports the thrust bearing. The support of axial force by concrete beam below the thrust bearing cannot be saved and it was then necessary to select a new shaft line design.

  Based on other power plant arrangements, the mechanical team had selected a solution using a cone to put on the turbine head cover to support the axial force, which has a lot of technical advantages:

- The axial effort is transmitted to the new turbine head cover which can be designed to support the full force with a good safety margin.
- The lower DFIM bearing is independent of the thrust bearing. It is then possible to install it closer to the DFIM rotor which increases the rigidity of the shaft line.

- Civil work reinforcement in the pit:

Concerning the pit, the studies performed show that concrete blocks which support the bracket must be reinforced by anchoring metallic plates. Additionally, stator embedded supports need to be adapted, and the concrete slab near the bracket of the lower bearing of the DFIM needs reinforcements to absorb forces especially during short circuit sequences.

As a consequence, the outage duration for the conversion, which was initially planned during 10 months, was expected to be increased to 14 months. The nature of the civil works to be performed did not allow any co-activity with Alstom team because of dust and water emissions near the turbine area (hydro demolition of existing civil work and reconstruction of the pivot slab)

- Existing powerhouse

A modification of the front of the powerhouse was needed, in order to bring the new rotor once built inside the powerhouse in one piece.

- Building dedicated to rotor erection

Considering the organization of works in le Cheylas, it was initially planned to build the rotor and stator inside the powerhouse. After detailed analyses, this solution did not appear realistic due to the space requirements, inducing additional risks on the planning and on safety for workers (unit 1 still in operation during that period). As a consequence, it had been decided to manufacture the stator in the powerhouse and to build a new building dedicated to the manufacture of the rotor (that would be used for the storage of the existing conventional motor-generator after the implementation of the project)

At the moment EDF decided to stop the conversion, studies, terms of reference and authorization process were launched:

- the terms of reference for the new building were issued;
- EDF asked and received the authorization to build this new building (building permit was delivered);
- the procurement process for the building was in progress.

The construction of the building, supposed to start in September 2015, though had to be postponed. The specification of the slab of the building were more demanding than anticipated in matter of tolerances and led to review the requirements for the building. The selection process for the suppliers was stopped in order to find new solutions. The construction was finally postponed due to the necessary complementary studies to answer to the new specifications.

2.3.3. Other aspects

- Cooling system

Upgrading the machine with variable speed also has an important impact on the powerhouse cooling system. Increase in thrust loads, converter losses and slip ring filtration and the cooling system need to be reconsidered, both for the sizing and for the routing of the water cooling system. Special attention needed to be paid to the water velocity in the existing embedded pipes. For example, rather than increasing the cooling water flow to take away the additional heat, other alternatives can be found such as looking for other possible sources of cold water / fresh air, increasing the capacity of heat exchangers designed to transfer more heat with the same water flow.

- Mechanical constrains :

New mechanical constraints had to be evaluated, including critical speed of the shaft line, and the strength on all bolted rotor VV holding the rotor windings. The number of bolted elements in the winding overhang support system is a specificity and considered as a higher technical risk compared to conventional salient pole machines.

- Compliance with French grid code

The Grid code has been developed for synchronous machine but the new revision of code includes asynchronous machine with mainly 2 constraints:

- Harmonics rejection on the Grid;
- Capacities to support a voltage drop without major disturbance.

2.4. Synthesis on risks after studies

The detailed design studies described above have been validated by EDF. This validation means that an acceptable technical solution has been found for every identified risk (except of course one risk related to the work phase, that cannot be addressed during the design studies).

The table hereafter details risk by risk the situation after design studies:

Risk ref	Description of the Risk	Situation after detailed studies
R1.1	Increase in the size & mass of the rotor has to fit in the existing civil work and mechanical support structure.	A suitable solution has been found to handle the different elements. Considering existing structure, the shaft line has been rearranged in order to limit the stress on existing concrete. Civil work reinforcements in the pit are nevertheless necessary, increasing the cost and outage duration, but without technical difficulties
R1.2	Volume availability in the power house (unit shaft and surface building) to position all additional equipment necessary for variable speed Unit.	Risk under control after detailed studies. The new VSI will be outside the existing plant and a building needs to be erected to build the rotor (cost impact)
R1.3	Fit with new excitation frequencies due to the operation at variable frequency (+/- 7%).	Risk addressed through head cover design and under control after studies
R1.4	Increase in the torque of the Unit above the capacity of the existing shaft.	The new runner has been modeled and its design has been validated: the associated risks are under control.
R1.4a	Increase in the torque of the Unit above the capacity of the existing civil work structure.	
R1.5	Hydraulic stability of the Unit throughout the new domain of operation.	Risk under control after mechanical studies
R1.6	Inadequate interface between the new equipment and the existing plant : cooling system, control system, shaft coupling	New cooling system studied
R1.7	Schedule risk: increase in the outage time due to unforeseen problem will have important cost impact.	This risk occurred: outage time would have increased because of civil work reinforcement needed.
R1.8	“Surprise” at site during dismantling the existing turbine (additional work)	The existing turbine has finally not been dismantled. This risks remains after detailed design studies
R1.9	Design risk on Turbine and Generator not to achieve acceptable performance.	The modelling of the turbine performed by Alstom have validated the performances of the new turbine
R1.10	Non compliance with grid code requirements	Risk under control after design studies

2.5. Alstom REX on DFIM technology

Due to the limited experience in the industry, the development of large high speed double fed induction machines for hydro applications requires significant efforts in design, manufacturing, assembly and testing of the rotor components. Between October 2011 and March 2014 a real scale prototype, corresponding to the motor-generator of the project Linthal 2015 in Switzerland was assembled in the factory of Alstom in Birr, Switzerland. The main objectives of this investment were design validation and testing of the entire supply chain as well as the definition of assembly procedures and the training of the site team. In June 2014 the assembly of the first rotor started at the site. During first installation of the rotor lessons learnt from the assembly of the large scale mock-up were implemented. Nevertheless several improvements on tools and procedures have been identified and continuously adapted to the conditions at site.

The wet commissioning of the first unit in the Linthal 2015 PSP started in July 2015. First synchronization was done in December 2015, trial operation started in May 2016. The commissioning represents a key milestone of the project execution and development of the variable speed units. During wet commissioning and trial operation of the first units in the Linthal 2015 PSP special measurements were performed in order to validate the operational reliability of the motor-generator components. The measurements of the open- and short circuit characteristic have provided a first important feedback to the electrical design of the motor-generator. The measured curves are in line with calculation and confirm the calculated characteristics.

During wet commissioning and trial operation the most important ventilation parameters, such as air volume flow and main temperatures, were tracked in order to prove a safe and stable operation. In a second stage, detailed measurements of air flow and pressure were done to prove all relevant parameters about the cooling of the motor-generator. In order to access potential hot-spots on the rotating parts, a high resolution pyrometer has been developed which enables temperature measurements on the winding overhang covering the complete rotor circumference. The heat run confirmed that the machine and all subsystems were capable of continuous and stable duty at the nominal operation point within the guaranteed temperature rise of the main components such as the stator and rotor winding.

For the Linthal 2015 project the requirements from the Swiss Grid Code are implemented and controlled by the variable speed controller. Compliance of the new developed control and rotor protection has finally been successfully tested with dedicated tests involving the grid operator in Switzerland.

Due to the complexity of the variable speed machines, the overall duration for the commissioning is significantly longer compared to conventional units. On the one hand much more operation points have to be tested, on the other hand the optimization of the flexibility e.g. mode change needs adjustment of many parameters particularly on the AC excitation system.

The verification of the operational reliability of all individual components as well as their interaction in any operation condition will remain a key priority for Alstom. Hence visual inspections and electrical tests will be performed after several months of operation. Data from operation as well as the results after warranty inspection will finally be used to optimize the future maintenance strategy of the machines.

The optimization of Pump-Turbine, Motor-Generator and converter requires an in-depth understanding of the entire system and innovation on all major components. The experience gained during development, manufacturing, installation and commissioning is systematically used to develop and execute new, flexible pumped storage units using latest technologies.

3 PRELIMINARY INVESTIGATIONS OF AN ALTERNATIVE SOLUTION: THE FULL FED TECHNOLOGY

3.1. Recent evolution on variable speed technology

There are two technologies for varying the speed:

- Replacing the synchronous motor-generator by a double fed induction machine (DFIM) connected to a reduced power supply frequency converter on the rotor. This is the solution that had been chosen for le Cheylas, and its implementation issues have been discussed in the former paragraph;

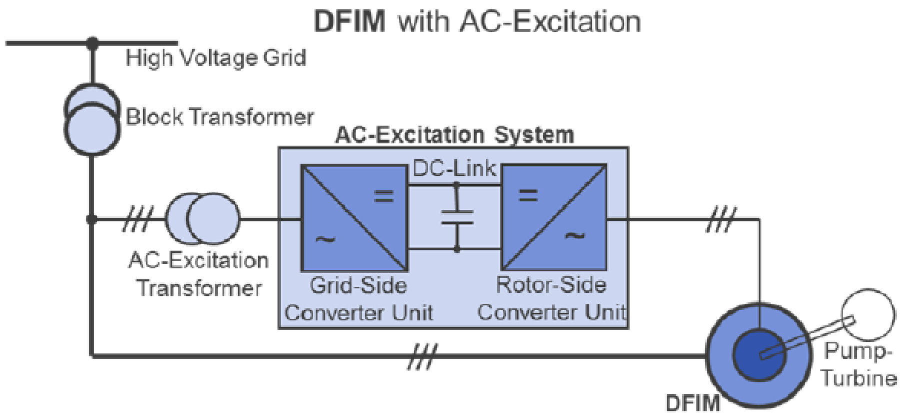

Figure 7: Asynchronous variable speed with DFIM technology

- Keeping a synchronous motor-generator connected to a full power supply frequency converter (fully fed motor-generator). The main characteristics of this solution are the following: conventional (synchronous) motor-Generator; and converters (VSI) on stator, designed for full power and large speed variations.

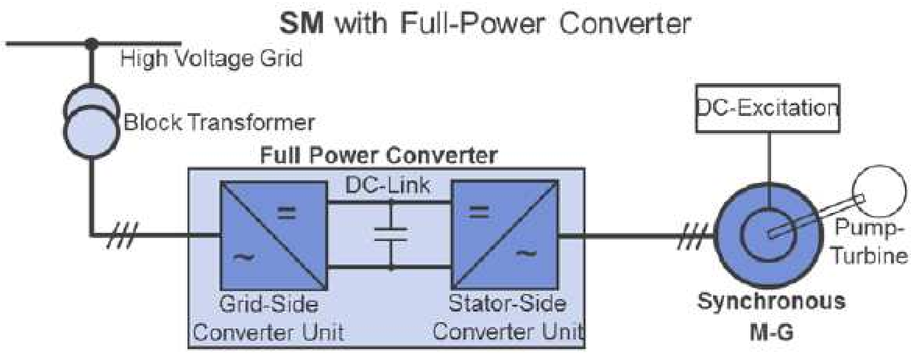

Figure 8: Synchronous variable speed solution with full power converter

The first option is most suitable for low outputs (<100 MW per unit in 2012 when the decision to launch the project was taken) but it also requires an excitation system. For higher outputs, the cost of the frequency converter was at that time prohibitive. Even if prices have decreased since then, in 2016, this solution is still more expensive than the DFIM one. In addition, the space requirements means that its installation within existing civil works may in some configuration (especially for PSP in caverns) not be possible.

For the le Cheylas conversion, the main advantage considered at the moment the decision was taken is that it requires low-power converters that use only a small fraction of the total output. This means less power loss in the converters, lower global price and a much smaller footprint for the power electronics while delivering the most benefit variable speed can offer. On the contrary, pump power variations are limited by the stability and cavitation characteristics of the pump and not by the frequency range of the power converter. Concerning le Cheylas conversion the pump operating is about 80MW power variation for a plus or a minus 7% frequency range variation, as said before.

Finally, the DFIM technology was the one used by Alstom in all its variable speed pumped-storage projects.

The DFIM design has thus been adopted because it was at that time the best trade-off regarding the given constraints.

Since 2012, synchronous technologies have made great progress, opening the way towards high power applications. Due to the progress in power electronics, synchronous technologies have indeed improved very quickly:

- Recent communications from power converter manufacturers show the availability of 500MW system in the near future, which would fit the European Pump Storage market;
- 98.8% achievable yield, targeting 99% or more, while, 2 years earlier, equipment manufacturers were offering no more than 97%;
- Lower risk of stator bars insulation ageing due to overvoltage (less severe voltage edge), as well as lower equipment cost because of lower harmonics filtering needs, thanks to multilevel inverters.
- Cost of the converter: approximately 110 k€ / MVA. The dimensioning of the converter must be provided for 115% of the power of the synchronous machine (synchronous machine must operate at power factor equal to 1 because it is not connected to the network, the VSI provides the reactive voltage)
- The size of the converters : about 10m3 / MVA
- Risk of aging by overvoltage: these risks are low thanks to multilevel converters.
- Harmonics: with multilevel inverters, the THD is acceptable without filter. There is no need to oversize the 400kV transformer iron losses
- Pump start: no need to use a dewatering of the P/T runner, the time to start pump is the same as in turbine.
- The dewatering circuit could be removed because the converter can act as a static converter. The converter has indeed enough capacity to start the turbine even in water. The associated devices (pump, air compressor and associated circuits) to dewater it are not needed anymore.
- Available torque motor at zero speed: 30 to 60% of the nominal torque, the torque value guarantees which enable starting in motor mode in all conditions
- Electric braking with energy recovery is possible without any wear of equipments
- Inertia effect can be recovered by injecting a part of the kinetic energy of the rotor to the network via the converter
- The converter stator isolated the machine to the network, the risk of false coupling does not exist

- The speed variation range can go from 0 to 100% and implies better performance hydraulic in turbine and pump mode
- The HTA system is simpler without GCB breaker, without short-circuiting and stator phase inverter
- Providers of these VSI are: ABB, Siemens, GE. Note, however, that depending on the evolution of the turbine yields on the operating range, it can be interesting to bypass the converter, so as to further increase the overall efficiency. In this case, there must be a GCB and the synchronous machine must itself meet the requirements of reactive voltage (power factor...) and must have the required MD² (case of Swan Lake project).

Moreover, the solution made of a variable speed machine with a converter in the stator reduces the level of technological risks:

- Much simpler technology, which does not require changing the generator unit. As a consequence, the level of risk for the maintenance of the system should be lower.
- In absolute value, the maintenance costs would probably be lower since most of the parts would be identical to existing technologies, because neither the plant's structure nor the unit's mechanics would need to be modified:
- Installation work would be simplified and scheduling risks reduced as the installation of the power converter could be performed while keeping the plant in operation;
- Unit could be operated as a fixed speed one by bypassing the converter in case of failure of the new components.

Most recent converters are now achieving good yield with power levels similar to Le Cheylas.

The major drawback of this synchronous technology is the size of the power converter subsystem, which prevent adopting this technology for locations with very limited available space. Le Cheylas site doesn't show such constraints since all main power devices and transformers are installed outside the powerhouse. There is therefore no real volume limitation to position the power converter.

Nevertheless, at the present time, the synchronous technology is still more expensive than the one that was envisaged in the eStorage project.

3.2. Comparison of the asynchronous vs synchronous technology for Le Cheylas site

EDF conducted preliminary investigations on the possibility to upgrade le Cheylas PSP with the full fed technology. The results of these investigations are described in the following paragraphs.

3.2.1. Necessary works/ works avoided for a synchronous solution (compared to the asynchronous solution)

In the case EDF had decided to implement a synchronous variable speed solution at le Cheylas, the consistency of the works to perform would have widely differed.

Some would have been the same, some would have been avoided, and on the contrary, for certain aspects, new works would have been necessary.

The aim of the following paragraph is to detail the similarities and differences of the two solutions (of course, as the synchronous solution has not been studied, the elements presented there are only very preliminary ones)

For the synchronous solution, there is no need to replace the stator neither the rotor. This conversion consists mainly in installing a convertor, more voluminous that the one envisaged in the asynchronous solution, and to connect it to the stator. As the consequence, the work associated for such a conversion would be the following:

- Procurement, installation and connection of the VSI. Considering the same maximum capacity in pumping mode as for the conversion project developed (280 MW), and considering that the power of the convertor has to represent 115% of the maximum pumping capacity, the capacity of the convertor should be of 320 MVA. The estimated size for such a convertor is 3000 m^2;
- Construction of new building associated to the new convertor, but smaller than the one envisaged to build the rotor in the DFIM solution;
- Installation of a new cooling system for this convertor, because it releases more calories, as it transits the whole power of the synchronous machine (calorific capacity about 3 MW);
- Replacement of the runner, because it needs to be compatible with speed variations (as the one designed for asynchronous variable speed);
- Refurbishment of the intermediate shaft, the pivot shaft and the bearing structures rather than replacement,
- Recalculation of the upper cover of the variable speed machine and repositioning of the bearing to its original position,
- Revisit of the distributor or optimization of the existing one,
- Design of a new intermediate bearing, relocated to its original position,
- Design of a new pivot shaft relocating it to its original position,
- Recalculation of hydraulic transients, due to the lower inertia of the reused rotor
- Recalculation of the shaft line to ensure that there is no impact on the civil work,
- Maintenance of existing rotor and stator, as performed in 2010 for Unit 1;
- SCADA modifications still needed, but a more standard solution can be considered, compared to the one envisaged for asynchronous solution;
- as for asynchronous solution, the existing transformer has to be replaced because the maximum output is not the same as the existing one;
- Discussion to be conducted with RTE for grid connection.

The avoided works are of importance because the unit remains synchronous. The most important avoided works would be the following:

- The existing motor generator is not replaced but only maintained;

- No VSI needed for the rotor;
- No civil work reinforcement needed in the pit, if the shaft line calculation really remains unchanged (it should be the case, but the studies have not been performed)
- No special handling needed, the existing crane capacity remain sufficient;
- No rotor building (but a smaller building to install the convertor)
- No modification of the existing powerhouse
- No busbars
- No HTA modifications
- No replacement of intermediary and thrust bearing shaft;
- Possible suppression of the auxiliaries linked to the condenser mode;
- No specific tools for G2 maintenance

3.2.2. Impacts on delays and outage

Considering the phasing of the work and the associated outage periods, the impact of the implementation of a synchronous variable speed solution are the following

Work period: as the civil work reinforcement are no more necessary, the additional 4 months outage period dedicated to civil works are useless. The outage duration could then be reduced to 10 months, which would offer the possibility to optimize the placement of the outage throughout the year to minimize the production losses. Moreover, as this solution requires less displacement of heavy and voluminous pieces (rotor and stator), implying the implementation of special handling equipments and the temporary occupation of some space inside the plant, it could be possible that the outage duration could be shorter than 10 months

Commissioning period: as there are fewer auxiliaries as in the asynchronous solution, and as the rotor and the stator are not replaced, no tests are needed on theses equipment, which could lead to a shorter commissioning period (potential duration shortening estimated between 1 and 2 weeks)

3.2.3. Risk analysis

Compared to the asynchronous solution, the risks analysis (in this very preliminary phase of study) is the following:

Technical risks:

- In case the convertor connected to the stator does not properly operate, it would be possible to disconnect it from the stator and operate back as today (if a by-pass has been implemented)

- In turbine mode, with a restricted operating range (limited to 0,7 Pmax), deteriorated efficiency (more than 1 % less), and more vibrations (but a priori acceptable),
- In pumping mode, under the conditions to have a connection between the FSC of Unit 1 and varspeed unit 2, and to have kept the dewatering auxiliaries.

- On the contrary, with the DFIM design, no step backyard is possible, unless considering a very long outage period.

- Exciting system is complex for the DFIM, the reuse of an synchronous machine mitigate the risk of failure of the system
- In the case the converter is connected to the stator, the handling of the whole equipment can be operated with the existing travelling crane. One of the risks of the DFIM solution is to require too often the use of the special handling equipment to carry the rotor out of the pit (not a zero risk considering the prototype effect)
- Several risks associated with the synchronous solution have also to be considered: efficiency, space availability in the powerhouse of le Cheylas, cooling system…

Risks during the work period:

In this option there are only two main work places: the works associated to the runner are located in the centre of the powerhouse, and the works associated to the implementation of the convertor occur outside the plant. There are neither works associated to the rotor nor to the stator.

Risks associated with delay issues:

As for the asynchronous solution, the critical pathway of the synchronous solution is associated to the runner issues. Nevertheless, as the project is less complex, and presents fewer interfaces, we can imagine that the project presents a less risky profile.

Risks during operating period:

If the new machine is a synchronous one, maintenance operations needed are similar to the one of exiting Unit1.

On the contrary, concerning the DFIM machine, Alstom has presently no experience on the maintenance of the machine, and some issues were still pending at the time EDF decided to stop the conversion, which eventually could results in increased risks - financial, technical or even on safety. For instance the lifetime expectation of the slip ring brushes might be a concern. The slip ring feeding the current in the rotors are very specific to variable speed units in term of current and voltage. This might require a higher rate of change than in fixed speed units which would have impact on the unit availability. Moreover the general bearing arrangement of the unit linked to the increase of weight and length of the rotor will bring accessibility issues making maintenance operation more difficult. The very specific SCADA (adapted to asynchronous machine) might also be an issue, as it would have been the only one of that technology operated by EDF.

4 ECONOMIC ANALYSIS IN A DEPRECIATED ENERGY MARKET AND EDF DECISION

EDF had three options when launching the upgrade of “Le Cheylas – Unit 2”:

- perform the minimal maintenance on existing equipments and continue operating with the same performance and service level as today (this is the choice that had been made for unit 1 in 2010);
- replace the turbine only and carry out maintenance on the existing generator so as to benefit from increased yield of the new runner shape;
- launch the variable speed conversion project, more costly and risky, but potentially providing more benefits because of the flexibility offered in pumping mode, and gain experience on this new technology.

The first option had not been selected in 2011 since anticipated electricity prices, at that time, made it profitable to increase yield and, consequently, the amount of power generated. Among the 2 remaining options, the conversion project, means the most innovative one, has been chosen. The business plan established in the framework of D1.1, therefore considered the additional costs relative to the classical solution together with the additional benefits arising from the use of this new technology.

The main assumptions of the business plan established for the launch of the project are described in the paragraph below.

4.1. Economic analysis perform at the launch of the project

Concerning the economic benefits of the conversion, two different aspects have been analyzed.

First one is directly linked with energy generation: as a consequence of the turbine efficiency increase, the annual energy production as well as the cycle opportunities will be increased. These two elements will lead to additional value on energy markets.

The second element to be estimated is the additional flexibility led by the possibility to control the load in pumping mode, allowing offering some ancillary services during off peak periods. Although present market rules doesn’t allow to value properly these new services, it was anticipated to be of increasing value for the years coming, in line with the development of intermittent renewable in Europe.

4.1.1. Enhancing the power generation and the cycle opportunities

As stated above, with the new runner design, global efficiency in turbining mode would increase by 5,2 % and in pumping mode by 0,8 % compared to the former unit.

As far as power generation is concerned, these better efficiencies will lead to two effects:

- Enhanced generation through inflows, because every cubic meter will generate 5.2 % more power than before. Considering that there are two units in le Cheylas, and that the design flow is far more important than the intercepted flow, unit 2 will be preferentially used compared to unit 1.
- Enhanced generation because of an increase of the cycle opportunities. Considering the new performances of unit 2, the new storage efficiency has been estimated to 82 %, while it is 78 %

with the unit presently operating. As a consequence, the spread on market prices needed to make the pumping profitable is lower, which will lead to greater opportunities of cycling.

To determine the impact of increased efficiency of G2 unit, the operation of le Cheylas has been modeled (on the basis of historical inflows) considering its present and future configuration. As anticipated, although in the present situation, the two units (presenting the same characteristics) are used similarly, around 80 % of water inflows are turbined through the modified unit 2. In this new configuration, unit 1 is now dedicated to peak periods. This leads to an additional generation of 45 GWh/year, corresponding to an 8% increase of gravitary generation.

Considering the cycling aspects, the annual duration of pumping is not a physical value (as gravitary generation which is based on available inflows), but is a result of optimization: The number of cycling opportunities varies of course of the spread between peak and off peak market prices and its distribution throughout the year. As a consequence, it is not possible to determine once and for all the additional generation allowed by these additional pumping opportunities. Optimizations have then be realized under different market conditions, and have proven an increased in cycle opportunities between 5 and 10 %.

4.1.2. Offering additional flexibility

The second important aspect of this conversion is the possibility offered by the variable speed technology to vary the power absorbed in pumping mode, which is not possible with fixed speed technology. This new functionality will then allow offering ancillary services (primary, secondary and tertiary frequency reserve) in pumping mode, corresponding to periods of low demand or of high intermittent renewable generation.

Le Cheylas PSP, in its present configuration, is already able to provide flexibility in turbine mode, and the upgrade of unit 2 will not modify this characteristic. In pumping mode, the upgrade will allow to offer +/- 40 MW of frequency control, in periods where the need for flexibility is the more needed. In order to assess the economic value to these new services, the operation of le Cheylas PSP has been modeled considering the possibility (or not) to offer primary and secondary frequency reserve. In France, ancillary services are remunerated today through bilateral contracts between the generator and the TSO (RTE), at a value that does not represent the actual costs of desoptimisation.

Therefore, the assessment took place in operational and historical conditions. In order to have different yearly situations, it has been decided to simulate 3 historical years (2010 to 2012). The mathematical optimization framework running daily is then configured to retrieve the value of the new variable speed turbine. The tool used is Apogée, an internal EDF operational tool enabling to daily fix the optimal generation schedule for all EDF units in France. In this study both units of le Cheylas has been modeled: unit 1 with its present characteristics and unit 2 with its present (identical to unit 1) and future characteristics.

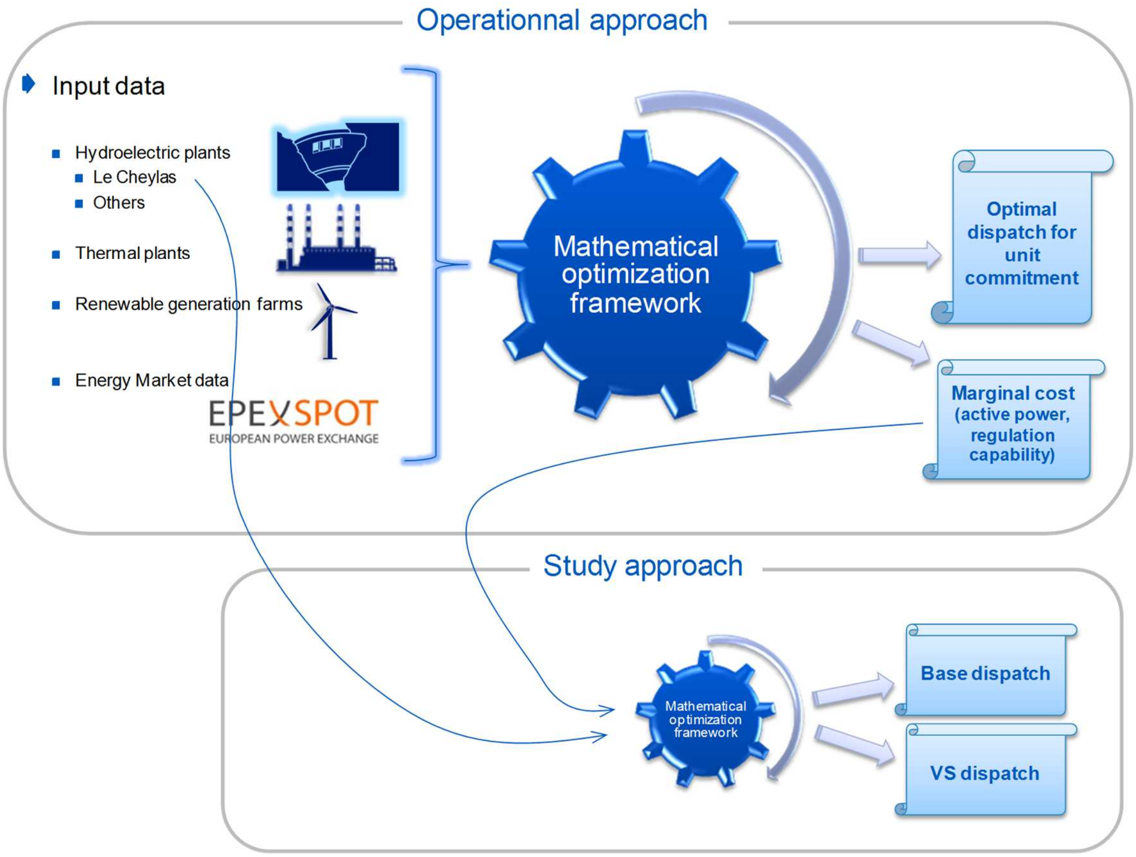

Figure 9: Methodological approach to assess le Cheylas operation and value

The main results concerning frequency control supply were the following:

- Le Cheylas supplies much more frequency control: sum of primary and secondary reserves represents an increase of +57%;
- Logically, this increase comes from unit 2 pumping periods;
- But it is also coming from the new generation periods: the more energy is pumped, the more energy is then generated. Frequency control is supplied when generating this additional energy;
- Unit 2 is almost always supplying frequency control while pumping, and unit 2 is much more used than Unit 1 for pumping.

The current price that uses RTE in France to compensate the power generators delivering capacity for frequency control is around 17 €/h.MW. RTE organizes the secondary frequency control through mandatory bilateral contracts with producers that must reserve an asked volume for every half an hour.

Considering this fixed price, the annual value of additional flexibility is the following:

	Additional primary frequency reserve (h.GW)	Additional secondary frequency reserve (h.GW)	Annual profit based on present remuneration
	h.GW	h.GW	M€/year
2010	47	72	2.1
2011	43	66	2.0
2012	32	49	1.5
Average	41	62	1.9

Figure 10: Economic assessment of ancillary services considering present RTE remuneration

At the time this study was performed, this value was foreseen to increase in the future, as a combination of two impacts: the increasing need for regulation in pumping periods, and the necessity of market design to evolve so as to value these services as their true value.

As a conclusion, it was already stated at that time that, considering the costs associated to this conversion, and even with the funding of European Commission, the operation was not profitable under French existing market conditions.

Nevertheless because of its commitment for research & innovation, EDF decided to launch the main procurements for “Le Cheylas” G2 conversion in 2014, because, this conversion could be considered as part of the solution for the integration of intermittent generation in the European power mix, provided that the market design allows for appropriate revenues for the services provided.

Unfortunately, since then, EU power market conditions have continuously and significantly changed, leading to less and less favorable conditions for investment.

4.2. A power market in Europe deeply depressed

Power prices have profoundly dropped since 2011

If we consider the last few years, the power prices on French markets were about 50 €/MWh in 2010 - 2011. With an average value around 35 €/MWh in 2014 - 2015, spot prices have dropped by approximately 25%.

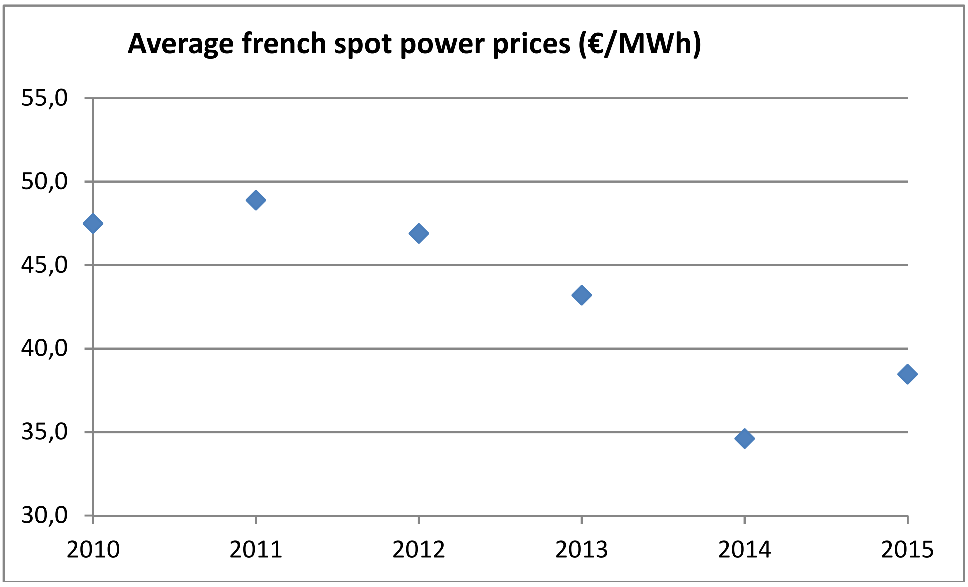

Figure 11: historical French spot power prices

Moreover, this decreasing trend is more accurate for the coming years. The forward prices are even lower, and the decrease of market prices have been accelerated since end of 2015 to reach a value of 26 €/MWh for years 2017 – 2018 and 2019 last spring.

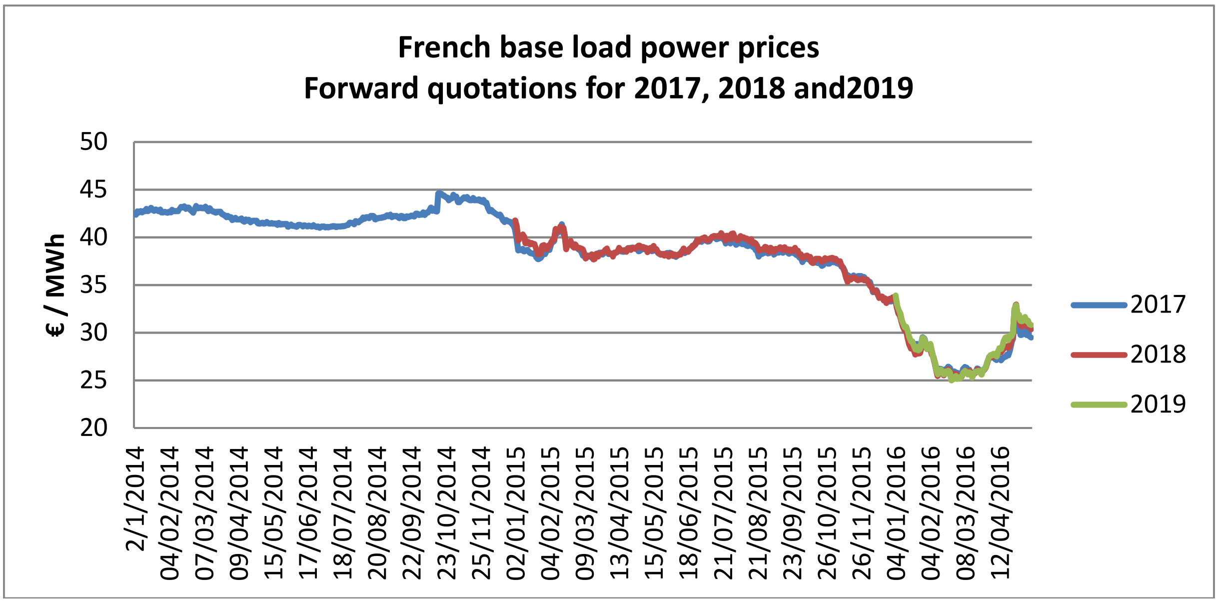

Figure 12: French base load power prices as a function of the quoting date

Beyond baseload prices, a second fundamental element to determine the revenues of a PSP is the peak – off peak ratio. The graph presented here below presents the evolution of the price difference between peak and off peak periods (spread) since 2001. It has decreased from 1.7 (peak price = 1.7 x off-peak price) to close to 1.2, i.e. a 30% decrease. Because of the losses of the pump / turbine cycle and the costs for grid access, pump-turbine cycles are only profitable when the spread (on a daily basis) is greater than 1.33 (1.25 for an 80% yield).

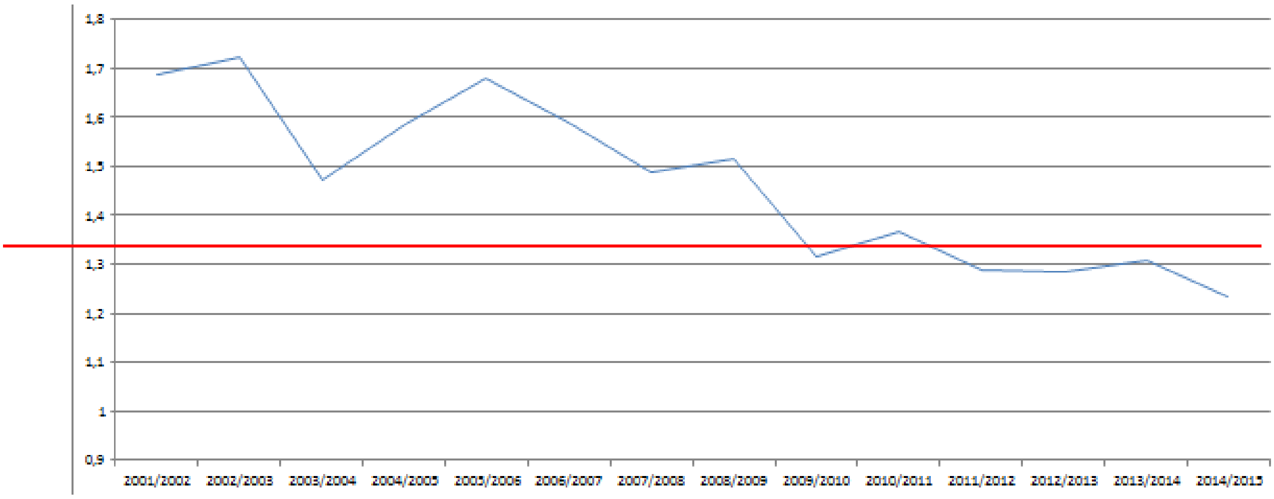

Figure 13: Ratio Peak/off-Peak – [30 June year 200N – 1st July year 200N+1] between 2001 and 2015

Because of the decrease of the spread, the PSP use decreases, as shown in the following table presenting the energy consumption through pumping per year for the "Le Cheylas" site.

2010	2011	2012	2013	2014	2015
435,0 GWh	369,7 GWh	416,0 GWh	394,7 GWh	331,4 GWh	341,2 GWh

Figure 14: Historical consumption by pumping of le Cheylas PSP

Disregarding 2011 - renovation of unit 1 caused a high level of unavailability - pumped energy at "Le Cheylas" plant has decreased continuously. In other terms, the use of the plant has decreased 25%, because of the evolution of power markets, which reduces the possibility to have profitable pumping operations.

As a consequence, between 2012 and 2015, the benefits arising from sales of energy produced in le Cheylas PSP has dropped by 30 %, with no perspectives of change for the next three years.

This situation is not specific to le Cheylas PSP. More broadly, between 2011 and 2015, the benefits arising from sales of energy produced by Pump Storage Plants in Europe have significantly dropped with no perspective of change for coming years.

This has translated into a difficult situation for PSP projects in Europe. As a consequence, most of the PSP projects under development in Europe have been postponed since 2011.

The second element of value for le Cheylas conversion was associated to flexibility and to the possibility to offer ancillary services in pumping mode. Unfortunately, since frequency regulation can only be offered when the unit is in operation, the above mentioned reduction in pumping duration directly causes a reduction of the possibilities of supplying frequency reserve services and therefore an additional reduction of revenues. The later have decreased by more than 25% over the last 5 years.

Concerning ancillary services, there is a second element reducing the operation in pumping mode. In the study carried out for D1.1 and described above, we considered the possibility of Le Cheylas plant turbining (using unit 1) and pumping (Unit 2) simultaneously so as to increase the adjustment possibilities. However, it appeared through the studies carried out in 2015 that operating the turbine and the pump simultaneously would cause damage and head loss, resulting in an unacceptable yield and costs, reducing even further the profitability. This operating mode is thus not envisaged anymore.

4.3. Market prospective beyond medium term

The presented analysis conducted by EDF to assess the revenues, is based on historical data as well as on prospective scenarios. Being one of the largest European Power Producers, EDF has developed several prospective scenarios in order to assess the potential evolution of European electricity markets. These scenarios are based on hypothesis regarding electricity demand, fossil fuel and CO2 prices, regulation issues, renewable development... The use of these prospective scenarios confirmed the conclusion mentioned above regarding the non-profitability of the upgrade

Planned evolutions of European regulation concerning ancillary services and balancing issues have been integrated in the economic analysis. In particular, cross border FCR (Frequency Containment Reserve) and FRR (Frequency Restoration Reserve) exchanges have been taken into account. The potential French participation to the existing European FCR auction[1] will not change significantly the value associated to "le Cheylas" conversion.

Lastly, a longer-term possible evolution on regulation concerning cross border FRR exchanges has not been integrated. As not required in the future European network code for Electricity Balancing services, this evolution is more uncertain. Anyway, it would not generate any significant additional value for the project.

5 LESSONS FROM LE CHEYLAS EXPERIENCE

The studies performed during the 3 first years of eStorage project regarding le Cheylas conversion to variable speed tend to prove that this conversion is technically feasible, with performances in line with the one anticipated.

As the conversion has not been implemented, it is however not possible to have feedback on the work period or on the operating results.

Nevertheless the developments and commissioning of recent projects such as the Linthal 2015 PSP provide valuable feedback for the variable speed technology. The first synchronization of the first unit in the Linthal 2015 PSP was done in December 2015, trial operation started in May 2016. The commissioning represents a key milestone of the project execution and Alstom's development of the variable speed units. In order to validate the characteristic of the machines, all relevant parameters such temperatures, vibrations in different operation conditions were measured. Compliance of the new developed control and rotor protection has been tested with dedicated tests involving the grid operator.

Depressed economic conditions present for several years in European power market is today a barrier for investment for every asset exposed to market prices. The situation is even worse for PSP, because they are not net generators, but have to optimize generation and consumption in an increasingly flat market.

In those conditions, and until the context evolves favourably, the only possible configuration to envisage a conversion would be a situation with an existing PSP whose turbine and motor generator are reaching the

[1] « FCR cooperation », common auction between Germany, Switzerland, Austria and the Netherlands.

end of their technical life and require a refurbishment on a short term (without prejudging the technical solution to be implemented)

Considering le Cheylas, the plant is presently still operating, generating renewable electricity delivered on the grid. A maintenance operation has however to be defined and planned in the coming years, in order to maintain the unit in safe and efficient conditions. Considering the ongoing diagnosis on the different elements of the unit, this maintenance operation is foreseen for 2020 at the latest.

Decisions on the maintenance operation content will be made in due time, accounting for market conditions and associated forecast at that time, as well as on the progress made on variable speed technologies.