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What Type(s) of Support Schemes for Storage in Island Power Systems?

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Working paper series : REFGOV-IFM - 73

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25th April 2010

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Abstract

This paper proposes a support mechanism for energy storage devices for island power systems where intermittent renewable generation is rapidly growing. We base our proposal on the maturity level of storage devices (Chen and al., 2009) and on the linear model for the development of innovations (Foxon et al., 2005). We focus on storage technologies that can be technically developed in island power systems and that achieve the technical needs of these systems. We conclude that the horizon when the power storage shall extend to prevent the development of intermittent renewable generation from being thwarted in these systems, a feed-in tariff with a price varying within the time of day must be put in place. This support scheme will focus particularly on battery technologies. Finally, in order to promote also the European domestic industry, the tariff should be designed to promote the adoption of lithium-ion- and nickel-based technologies.

I. Introduction

The integration of massive photovoltaic and wind power raises problems in some island power systems in Europe because of the intermittency of these Renewable Energy Sources (RES), from 2012-2013 for some systems. For example, in 2013, Réunion Island (France) should occasionally reach the technical limit of intermittent renewable energy representing 30% of instantaneous load. This limit of 30% has been established to ensure reliable operation of the electrical system. Indeed, beyond a certain amount of intermittent renewable power, it is not possible to cut some conventional thermal plants to balance generation and load because it is these conventional thermal power plants that provide the necessary reserve margin to balance instantaneously the power system (Bayem, 2009). Accordingly, when the 30% limit is reached, the system operator for Réunion island, EDF SEI, will cut intermittent RES production surplus to maintain the balance between generation and load. The technical constraint of 30% intermittent RES therefore limits the integration of more renewable energy in Island power systems and make more difficult the achievement of objectives of energy independence and reduction of GHG emissions for these systems.

There are several technologies already available to overcome the constraints of integrating big amounts of RES. Among the most traditional ones, it is possible to develop very flexible conventional thermal power plants such as small oil-fired power stations. But these plants have two major drawbacks. First it makes the power system more dependent on external resources that the isolated island systems have already difficulties to obtain. Second if the integration of more intermittent RES means inserting in parallel flexible thermal power plants, the CO_2 balance of the package could increase rather than reduce CO_2 emissions for the island systems.

Another solution is to rely on the storage of electricity. Storing electricity can take many different forms (water storage, compressed air, heat, electrochemical form, etc.). Electricity storage allows to insert intermittent RES while participating in the global balance between generation and load. Meanwhile, some storage facilities can also flatten the load curve of the system. The baseload power plants that emit relatively less CO_2 are then more called on. And during periods of high consumption, the stored energy is returned to the system. The peakload power plants that relatively emit more CO_2 are then less requested.

All the storage solutions are not applicable to the island power systems due to a lack of technological maturity. And all the storage solutions are not applicable to the island electrical systems more particularly for a question of available space. Some types of electrochemical storage seem to emerge as best solutions under these two criteria and are currently under study in some island power systems in Europe. This storage could be in batteries (lead acid, lithium or sodium-sulphur), flow batteries or fuel cells.

Different technologies of electrochemical energy storage are still in the infancy of industrialization. Even if various battery technologies are operating in some power systems[1], their deployment is still small. This is because their cost is prohibitive, especially compared to the solution of oil power plant (which is already very expensive for island systems).

[1] NGK Insulator Ltd, the Japanese leader of the Sodium-sulphur (NaS) technology, announces 200 megawatts of storage operating worldwide and 450 MW signed for future installations. The market for batteries connected to the power network around 2018 would be only 4 billion dollars (www.pikeresearch.com).

The integration of electrochemical storage in the power system is facing fourfold market failures. 1° The electrochemical storage promotes the development of intermittent RES and reduces CO2 emissions from other power plants by flattening the load duration curve. And the pricing of CO2 does not allow alone to internalize this positive externality (yet?). 2° The scientific and technological efforts associated with R & D and demonstration pilots for the development of these technologies have a public good character. 3° Innovations in the power system such as electrochemical storage face technological entry barriers due to the pre-existence of mature solutions (such as oil power plants) that can provide a similar service. This limits their practical adoption and learning effects which would be associated. 4° A country that would develop an innovative technology as a special electrochemical storage technology has a genuine interest to accelerate the deployment of this technology with a public support to position the related industry sector as an international leader.

The existence of these four market failures raises questions about the form of public support for the development and deployment of electromechanical storage technologies in island power systems. Not only it is necessary to adapt the technological support to these sectors depending on their maturity but also we must consider the relative usefulness of different technologies for island power systems. Is it necessary to have centralized or decentralized storage?[2] Furthermore, it is necessary to adapt the form of support to the peculiarities of island power systems. The deployment would begin quite soon. The public support mechanism should also take into account that the efficiency of energy storage for the power system as a whole depends on the specific times of the day when it withdraws and injects energy and on the location of storage devices. It is then interesting to consider the interest of coupling support for storage with the support already established for RES.

As highlighted by He and Zachmann (2009), the literature about electricity storage in power market has mainly focused on the calculation of arbitrage value from energy bought at low price and stored and sold at higher price later. This exercise has been done on several markets (PJM and New York in the USA by Walawalkar and Apt (2008) and by Sioshansi et al. (2008), Nordpool by Lund et al., 2008, Spain by Dufo-Lopez et al. 2009). And several assumptions have been used for the operation of the storage facility (fixed period of arbitrage for Walawalkar and Apt (2008), optimisation of the storage facility over two weeks by Sioshansi et al. (2008), over one year by Lund et al. 2008, use of the real option theory by Muche (2009)). He and Zachmann (2009) open the research field and determine the return on invested capital of different technologies for different market comparing the arbitrage value with the fixed cost of different storage technologies considering their different power ratings. They conclude that for three representative markets in Europe (France, the Netherlands and Scandinavia), no storage facility is profitable despite the benefits they bring to these power systems. To come up with the four market failures we have previously mentioned for the storage facilities, we propose in this paper to implement support mechanisms for some storage technologies that are developing and that are adapted to the need of island power systems.

The paper is organised as follow. First we recall the various forms of public support for the development of clean technologies in the electrical system. We can then link the various stages of the technological and industrial development of new technologies with the adequate support instruments. Second we will identify the services that the storage could provide to island power

[2] For the considered short-run time horizon, it is likely that a unique type of storage will be sufficient to cover the needed of European island power systems. Indeed, the Danish, German and Spanish experiences with wind and PV development shows that the issues linked to intermittency of these energy sources progressively appear with their growing integration.

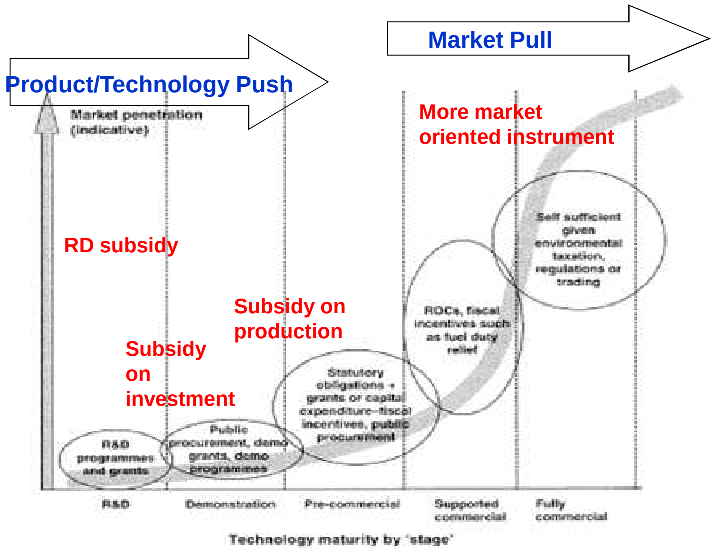
systems to facilitate the integration of intermittent RES. We then establish the electrochemical storage technologies that can deliver these services. In the last section, we will recommend the form of adequate support for these technologies given their technical and economic maturity and their association with the development of intermittent renewable generation for different market designs in particular for the perfect one established by Hiroux and Saguan 2009 and for the market design of the French island power systems.

II. Public support for the development and deployment of renewable innovations

To identify the best suited support scheme to each development stage of an environmental innovation, we refer to the linear model of innovation. This model has 5 stages: 1° invention, 2° the applied R&D phase, 3° the demonstration phase, 4° the pre-commercial diffusion and the 5° the commercial diffusion (Finon, 2009). In this representation, the diffusion of technology follows 3 phases, an initial one with the take-off of technology (stages 1 & 2), a second one with the acceleration of development under the effect of increasing returns from adoption and cost reductions (stages 3 & 4) and a third one with the slowdown of the development developing when approaching the commercial maturity (stages 4 & 5). For an efficient support of technological innovations, the support schemes must be adapted to each of these stages. Figure 1 extracted from Foxon et al. 2005 provides a summary of the tools that can be implemented at each stage of development of innovative technology. We now develop the different stages of innovative technology and their best suited support tools.

The first phase is R&D. It focuses on the development of new scientific and technological knowledge. The public laboratories and the subsidies from government are involved at this stage, possibly under public-private partnerships.

The demonstration phase is characterized by the realisation of few prototype units of increasing size to attain a commercial size. The demonstration phase is marked by the construction of a niche market through large subsidies granted to users to allow innovators to develop manufacturing processes for industrial-size units. This phase is financed by grants for investment, especially when the technologies (for RES) are capital intensive. This phase permits to create a market where small businesses can build up.



Source . Foxon et al., Energy Policy,32 , 2005

Figure 1 The classical pattern for the adequacy between the types of support schemes for RES and the level of maturity

The pre-deployment phase is the stage when the effects of learning by doing and by using are happening and when the production of the technology can move to a higher scale. This period is dominated by the development of industrial expertise and dissemination. It is accompanied by the adjustment of institutional rules to facilitate the diffusion of technology and to create a large scale market for this technology. Bigger players come to the side of small innovators. Without adequate support, the investments by manufacturers as those by users may be particularly risky at this point.

Two approaches are possible to support innovative technology at this stage. Either an investment subsidy is directly granted for the users of the technology. Or the investors are paid a production subsidy through a feed-in tariff that guarantees the revenue of their new equipments during a large part of their lifetime (commonly 15 to 20 years). The choice between investment subsidy and production subsidy at this stage depends on the characteristics of cost of innovative technology, the financial size of adopters, the level of maturity of technology and the regulatory opportunism.

- The investment subsidy is adapted for the early pre-commercial deployment when the cost structure of technology is dominated by upfront capital costs. It can take different forms: direct subsidies, loan subsidies, tax credits, etc. The investment subsidy has three defects in the process of prematurity. First, this support is exposed to the political risk of a stop-and-go policy because this support is directly paid by the State. Second, the investment subsidy does not encourage users to seek the equipment with the best performance, which does not contribute to a rapid selection of the most reliable manufacturers. Third, it does not incentivize either to the maintenance of equipment and can lead to stop the equipment from the first major challenge when it is already depreciated.

- The production subsidy becomes a more efficient tool at the stage of pre-commercial maturity because it is based on the production performance of installed units. It therefore prompts the search for good performance because the investor receives a payment for the lifetime of the RES investment directly linked to its production. It also encourages the operator to perform needed maintenance to maintain the performance of the facility. The grant is provided on each device over a period sufficiently long to allow for a normal return on investment. It gradually evolves with the reduction of costs by learning effects and fades thereafter.

The penultimate phase of technological maturity is the last stage when technology is supported. In this last phase of support, the innovative technologies are more exposed to market risk through the support mechanisms. It is thus possible to introduce quota systems (such as green certificates). But the quota systems induce many risks and offer limited visibility to investors regarding the returns on their investment. Instead, the mechanisms of environmental premium (or feed-in premium) that varies with the market prices so as to ensure a minimum purchase price offer greater certainty for investors while exposing technological innovations to market risk in a measured manner. Besides, fading out the level of the environmental premium is a way to integrate progressively the technology as a full market-friendly one.

III. Energy storage and fatal renewable energy on island power systems

Energy storage participates in the compensation of the technical effects of intermittent generation on the operation of power system. In order to assess the benefits of energy storage, we can look at the impact of intermittent renewable generation on the different modules of tasks which constitute the electricity system first considering there is no storage and then considering that storage is introduced. After studying all the storage technologies, we can clearly make out those suited to the issues of island power systems.

A. Impact of intermittent RES on the island power systems and the need for energy storage

In the absence of adapted storage devices, the integration of intermittent renewable energy has three major impacts on the electrical system.

First the inclusion of intermittent generation reduces the quality of the power signal (with the presence of harmonics and variations of the voltage amplitude). This is due to the stochastic variations of these energy sources and to the technology used to produce electricity from these energy sources.

Second the introduction of intermittent renewable energy increases the need for balancing in real time and reserve capacity to maintain frequency close to 50 Hz. This is due to the stochastic variations and the low predictability of these energies to the operational horizons of power system from seconds ahead to day-ahead (Hiroux, 2007). For example, in one hour, Reunion island may lose no more (but still) 45% of its photovoltaic production (ARER, 2008).

At last, beyond a certain volume of intermittent generation, it may be necessary to disconnect sometimes a share of this production to ensure the balance between generation and load, or to manage network congestion (Bayem, 2009).

The low flexibility of thermal power units does not allow for sufficient change in their production level to balance generation and load in a reliable way with a massive amount of intermittent generation. The instantaneous mismatch between production and consumption is well known for wind generation (Maupas, 2008). It is also true for PV production, although to a lesser extent. This is illustrated in the following chart which shows that PV production (represented by the sum of the following areas, the yellow one, the shaded green and yellow one and the shaded red and yellow one) consistently exceeds consumption (red line) during the daytime while it is absent during the evening peak.

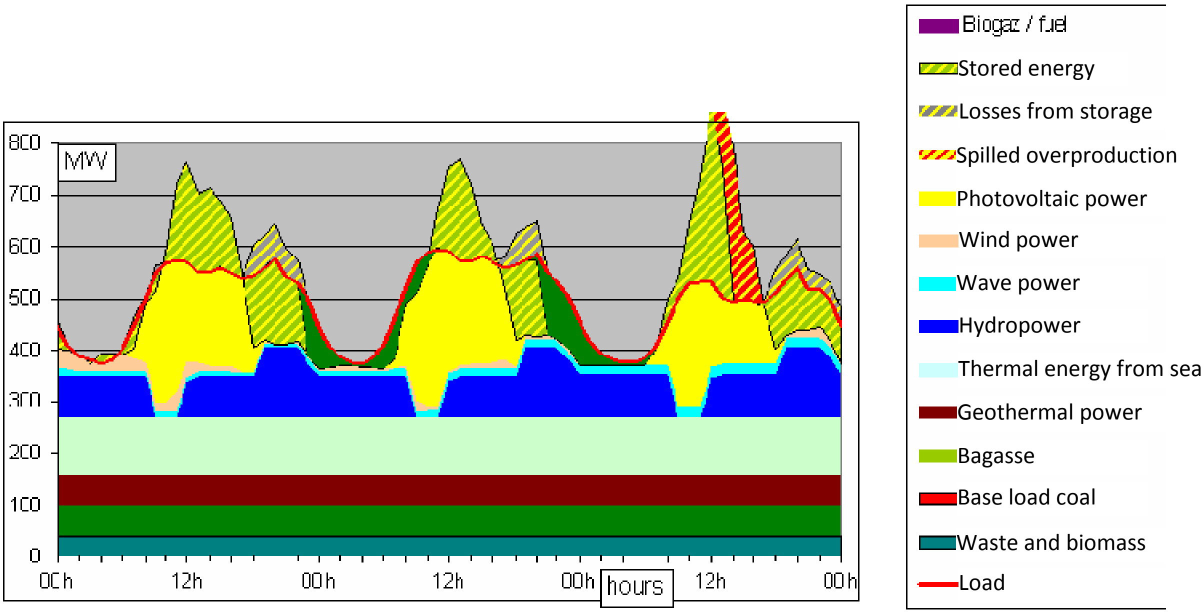


Figure 2 Example de of power generation for 3 days in Reunion Island for 2050

Intermittent renewable generation in island power system is generally very localised. For instance, PV production is concentrated in Reunion Island in the North and South of the island, where the resource is most abundant. The wind farms will similarly be concentrated under the prevailing winds (South East of the island here).

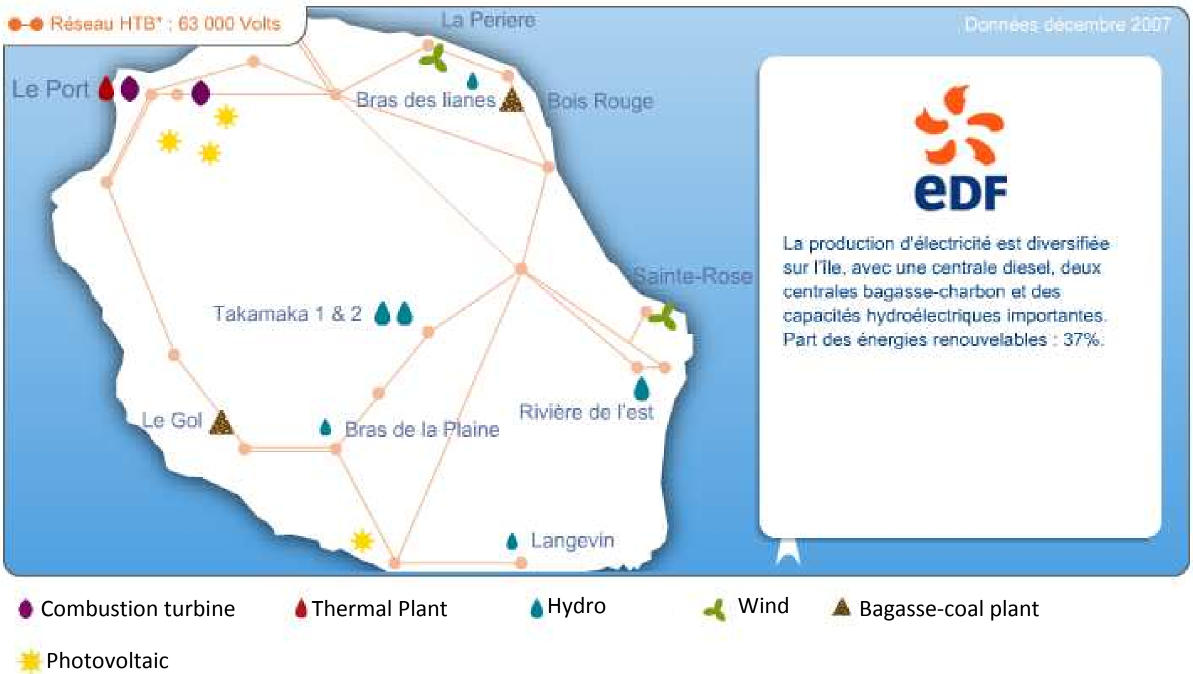


Figure 3 Power network of Reunion Island. The installed photovoltaic capacity was 1.3 MW in the South and 1.75 MW in the North in 2007. Source : sei.edf.fr

Another important constraint to consider is that the grid has a limited capacity. It may then be needed to limit the installed capacity of these intermittent renewable generation units. This limitation is reached efficiently only when it is required to spill a certain volume of those energy sources. Indeed, by increasing the installed capacity of these generation units, the volume of spilled energy of course increases but the rest of produced energy also increases.

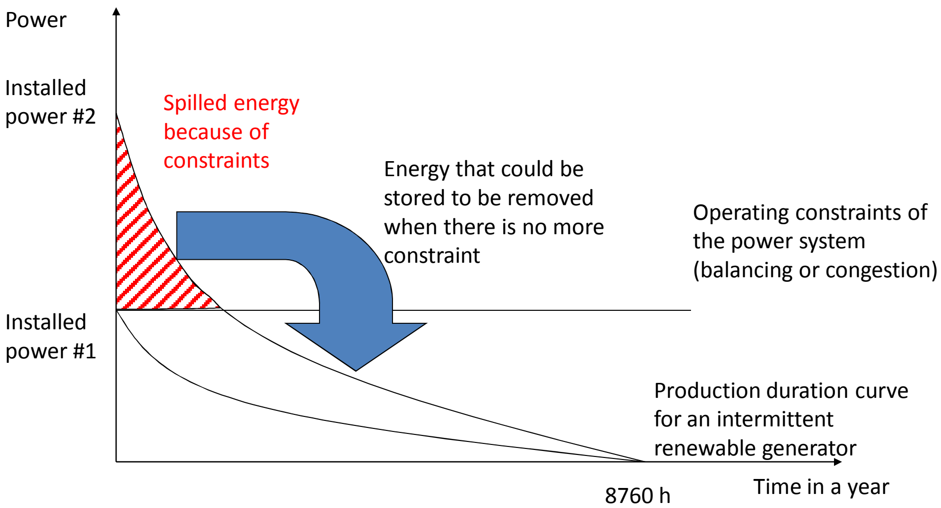


Figure 4 Illustration of the impact of storage on the operation of intermittent generator

Some storage technologies enable to offset significantly the three above mentioned effects. Some of them also induce a collateral beneficial effect for the whole power system.

1° The power electronics required for the integration of electrochemical batteries can control and improve the quality of the power signal despite the stochastic variations of intermittent production.

2° Some storage technologies exhibit temporal dynamics that allow them to participate actively in balancing generation and load either providing power reserves or balancing.

3° Some technologies provide storage capacities in adequacy with the needs of some island power systems. For instance, in Reunion Island, the need for storing intermittent energy is primarily a daily storage (ARER, 2008). The presence of storage required for the integration of more intermittent renewable generation once installed can also allow to flatten the load curve and thus to reduce the need to run peakload generation units that emit important CO_2 emissions.

4° A storage device can flatten the production duration curve of intermittent generators. This can limit the amount of spilled renewable energy otherwise needed to avoid congestion on the network where the generator is connected. Put simply, the storage device can be positioned close to either the producers, the consumers or in the core of the power grid. The closer the storage devices will be to the sources of disturbances, the less these disturbances will interfere with the whole system operation. Moreover, locating storage devices in the core of the grid has the disadvantage of generating significant transit flows on the network while other locations can smooth the network usage. It is interesting to abound local intermittent sources to limit the use of storage and play on the economies of scale for electrochemical technologies. The placement of storage close to the intermittent generation is still the most appropriate one for the island power system (Delille et al., 2009). The storage technologies that are rather medium size and decentralized are more suited to this need.[3]

B. Resolving the problems associated with intermittent energy with the different storage technologies

Chen et al. 2009 propose a technical and economic analysis of all technologies of energy storage. We rely on this analysis to evaluate the storage devices that are the best suited one to meet the challenges raised by intermittent energy in island power systems. Chen et al. 2009 compare the storage technologies using the following characteristics:

- Energy density,
- Power density,
- Storage duration,
- Range of nominal power of installations,
- Self-discharge per day,
- Capital cost,
- Technical efficiency over a charge-discharge cycle,
- Lifetime,
- Maximum number of cycles,
- Discharge time,

[3] The conclusion may be a little bit different for the continental power system because the best location for storage devices should then be at the substation between the low voltage and medium voltage networks (Delille et al., 2009).

- Effect on environment,
- Maturity of technology.[4]

To make easier the reading of this analysis, we placed each technology in a range that corresponds to each of the previous characteristics. For each characteristic, we defined these ranges in the appendix. We can see from the table next page that no storage technology does all indicators green.

We nevertheless observe that the Pump Hydro Storage (PHS) devices are those with the greatest benefits. Thus, they appropriately respond to all the desired requests in an island power system.[5] The PHS technology is mature that has been widely implemented in power systems for a long time and that is already used for balancing island power systems. The PHS technology will thus have an important role to play for the island power systems developing intermittent renewable generation. But the integration of intermittent renewable energy sources requires the creation of more hydroelectric dams. And the big water reservoirs associated with this technique raise substantial environmental problems. In addition, the local topography does not always allow the creation of new volumes of PHS.

The Compressed Air Energy Storage (CAES) is a developed technology that has not yet reached commercial maturity. It also requires considerable air volume amounts for implementation[6], which is not compatible with the geographical constraints of island power systems.

[4] As mentioned in the appendix, the maturity of the different technologies is evaluated with 5 stages corresponding to the 5 stages of development from the liner model of innovation.

[5] For the most classical type of PHS, these storage devices cannot deal alone for problems of harmonics. However, it is possible to complete these installations in a relatively inexpensive manner to solve this problem. Besides, a new type of PHS with variable speed includes power electronics and so can deal with the problem of power quality.

[6] On continent, this is not necessarily a problem because the CAES can be done underground using natural sealed cavities.

Table 1 Evaluation of the different storage technologies

	Energy density (Wh/Kg)	Power density (W/Kg)	Storage duration	Nominal power	Self-discharge / day	Capital cost (€/KW)*	Efficicency of a charge cycle (%)	Lifetime (years)	Number of cycles	Discharge time	Effect environment	Technological maturity
Pump Hydro Storage	Very weak	Sans objet	Very long	Very High	Very weak	High	Medium	Very high	Very high	Very high	Negative	Mature
CAES	Medium	Sans objet	Very long	High	Weak	Medium	Medium	High	Very high	Very high	Negative	Developped +
Batteries												
Lead-Acid	Medium	High	Long	Medium	Weak	Weak	Medium	Medium	Medium	Medium	Negative	Mature
NiCd	High	High	Long	Medium	Weak	Medium	Medium	High	High	Medium	Negative	Developped +
NaS	High	High	Short	Medium	High	High	Medium	Medium	High	Medium	Important	Developped +
ZEBRA	High	High	Short	Weak	High	Weak	Medium	Medium	High	Medium	Important	Developped +
Li-ion	High	High	Long	Weak	Weak	High	High	Medium	High	High	Important	Developped +
Fuel cell												
Generic fuel cell	Very High	Very High	Very long	Medium	Very weak	High	Weak	Medium	Medium	High	Important	Developing +
Metal Air	Very High	Weak	Very long	Very weak	Very weak	Weak	Weak	Medium	Weak	High	Weak	Developing -
Flow Battery												
VRB	Weak	Medium	Very long	Medium	Weak	Medium	Medium	Medium	High	Medium	Important	Developped -
ZnBr	Medium	High	Very long	Medium	Weak	High	Medium	Medium	High	Medium	Important	Developped -
PSB	Weak	High	Very long	Medium	Weak	High	Medium	Medium	High	Medium	Important	Developped -
Others												
SMES	Very weak	Very High	Medium	Medium	High	Weak	High	High	Very high	Very short	Important	Developped -
Flying wheel	Weak	Very High	Very Short	Weak	Very high	Weak	High	Medium	Very high	Short	None	Developped +
Supercapacities	Very weak	Very High	Short	Very weak	Very high	Weak	Medium	Very high	Very high	Very short	Weak	Developped +

The electrochemical storage devices, that is to say the batteries, flow batteries and fuel cells technologies are the best suited technologies to the need of island power systems with growing integration of intermittent renewable energy. The power electronics required for the insertion of these DC facilities on the AC island power systems solves the problems of power quality. Their temporal dynamics is relevant to their participation in the system balancing. Moreover, the storage duration of these technologies is around a day or two and is so aligned with the need of island power system. At last, the energy and power densities of batteries are adapted to space constraints in the island power systems. This offers a great flexibility in the location of electrochemical storage, which facilitates the resolution of congestion through such means. The major default of all the electrochemical storage technologies is cost. At the same time, Baker (2008) explains that the existing electrochemical technologies can see substantial technological improvements in 30 to 40 years. By improving various components of the battery (electrodes, current collectors, membranes, electrolytes, packaging cells, etc.) it is possible to increase the energy density of batteries 10 to 20%, increasing their lifetime (in years and number of cycles) and of course reduce their manufacturing costs. Nevertheless, these different electrochemical storage technologies clearly have not the same potential development in island power systems.

The different battery technologies have not the same benefits. The lead-acid batteries have a medium lifetime that is poorly compatible with the operation of a storage device for several years. Despite an advanced technological maturity, the environmental and health impact of lead represents a major flaw for these batteries. Although the Nickel-Cadmium (Ni-Cd) batteries have more interesting technical features in terms of robustness over time, they have a similar environmental and health problem because of the presence of cadmium. The last three types of batteries (NaS, ZEBRA and Li-ion) have a smaller impact on the environment (because of the low presence of heavy metals). Moreover, their stage of development is close to commercial maturity. Their robustness over time is also relatively good. The ZEBRA battery is distinguished by a low cost. The Li-ion battery has the advantage of having a better efficiency on the duration of a charge-discharge cycle. The Lithium-ion technology with a size of few kWs could be installed in homes to ease self-consumption when they have a photovoltaic system.[7] The Lithium-ion can also reach the size of hundreds of kWs. The NaS battery is rated suitable for larger installations of a few megawatts.

The storage with fuel cells has a major drawback due to its low efficiency. In addition, the fuel cells technologies are still in development phase and thus suffer a crippling problem of maturity for a rapid deployment.

The flow batteries have a low energy density. The size of these facilities would reduce the number of options for their location. And such technologies are still at a stage of development too far from the commercial level for an easy and robust deployment.

The last storage technologies (SMES for Superconducting Magnetic Energy Storage, Flywheel and supercapacity) are mainly storage for power (for energy to be stored and removed very quickly) that would not solve the problem of balancing generation and load of power system on the horizon of a whole day.

[7] This battery technology is planned to be used for electric vehicles. Thus, subject to adequate communication infrastructures, the batteries of these vehicles might be involved in balancing the system provided they are connected to the network.

The table below summarises the benefits provided by the different storage technologies to the power system.

Table 2 Adequacy of storage technologies to the needs of power system from growing integration of intermittent renewable generation

		Technologies					
		PHS	CAES	Fuel cells	Batteries	Flow batteries	Others (SMES, flywheel, supercapacity)
Power system needs with growing integration of intermittent renewable generation	Power quality from power electronics	New → Yes Old → No	No	Yes	Yes	Yes	Yes
	Balancing	Yes	Yes	Yes	Yes	Yes	For reserves only
	At least daily storage duration	Yes	Yes	Yes	Yes	Yes	Yes
	Location flexibility	No	No	Yes	Yes	Partly	Yes

To conclude, our analysis of support mechanisms for storage devices on island power systems highly focuses on the electrochemical storage devices (fuel cells, batteries and flow batteries).

IV. What forms of support for storage?

The electrochemical storage devices are developed from a technical perspective but have not yet reached the commercial maturity that would allow development beyond a support mechanism. For the efficient development of all these technologies, it is therefore necessary to adapt the support to the level of maturity of these technologies. At the same time, the gains offered by the storage of electricity are maximum if the facilities inject and withdraw electricity at the best moment and if the storage facilities are appropriately located on the grid. Such efficient management of storage is easily permitted in a refined market design. However, all electrical systems do not necessarily have such a market design. This is especially true for the island power systems in Europe.

Therefore, we will first establish the support mechanisms to implement in a perfect market design. Then we study how these support mechanisms must be adapted with a market design whose features are moving away from the ideal case.

A. A support mechanism for storage with a textbook market design

Hiroux and Saguan (2009) address the same question as in this paper but for the case of the large-scale integration of wind power in Europe. So we will rely on their work to recall the design of a perfect market and to propose support mechanisms for the electrochemical storage in this ideal framework.

Hiroux and Saguan (2009) show that it is possible to support wind generation while exposing it to the market price in order to have this technology integrated in a market-friendly and efficient way. More specifically, the integration of wind energy is all the more effective (in terms of social surplus for the electrical system) that it is in a perfect market design. The table 3 below recalls all the main options for designing an electricity market design.

Other things equal, a perfect market design would be as follow. It would be centralized with a gate closure close to real time. The daily intraday and real-time prices would vary with the location of the electrical nodes. A single price would be used for the settlement of real time imbalances[8]. And the network access fees would be zonal. The producer or storer receives all the market signals that effectively incentivise him to respect its contractual position in real time, to be constrained on or off when the system needs it and to locate efficiently.

Hiroux and Saguan then show that a feed-in premium that complete a classical market revenue (from selling energy and ancillary services) presents a good compromise between exposure to signals from markets and the need for a minimum of financial certainty needed for a massive integration of wind power. Of course, some features of the perfect market design lead to an increased risk for market players and in particular for clean technologies. Of course, this may discourage the adoption of these last technologies. But it is possible to increase the level of the support mechanism to compensate for this increased risk. Thus, technologies or investors who behave best with respect to these risks will be rewarded. Furthermore, a feed-in premium that completes the market signals is a solution that facilitates the future end of support mechanism, gradually reducing the level of this premium.

Table 3 Extract from the table "Market design, market signals related risks" (Hiroux and Saguan, 2009)

	Potential market signals	Potential integration costs reductions	Market design options		Accuracy of market signals*	Risk induced by market signals*
Day-ahead and intra day markets	Temporal differentiation of electricity	Balancing and reliability costs	Degree of centralization	Decentralized	0	0
				Centralized	+	-
			Gate closure	Far real-time	0	0
				Close real-time	+	-
Balancing market	Value of electricity at delivery/ Value of flexibility	Balancing and reliability costs	Imbalance price	Dual price	0	0
				single price	+	+
Congestions (and losses) pricing	Locational/ temporal differentiation	Congestion and reinforcement costs	Zonal aggregation	Redispatching	0	0
				Zonal	+	+
				Nodal	++	++
Connection and network tariffs	Locational/ temporal differentiation and cost recovery	Congestion and reinforcement costs	Connection and network tariff	Shallow	0	0
				Deep	+	++
				Zonal tariff	++	+

Applying a similar rational to the electrochemical storage has different implications depending on the maturity of technologies. Fuel cells are still in the stage of technical development. As a result, this

[8] It is the real-time physical positions with respect to the contractual positions resulting from the market outcomes.

technology should primarily benefit from public subsidies to increase its level of R & D. For the case of hydrogen fuel cell, a niche market can begin to develop. The exposure of this technology to market signals at this stage of maturity is of no interest.

The flow battery technologies are in the early phase of pre-commercial development. The support that best suits their level of maturity is an investment grant. At the same time, exposing the technology to market revenue can now allow to integrate the needs of the system in the architecture of this storage device. It is then possible to see the investment subsidy as a hedging contract with guaranteed income for the investor. As a consequence, the investor would be initially paid by the market (or the system operator for ancillary services) for all the services provided to the system. This revenue offers all the more rapid inflow of cash that the investor effectively participates in the market. And the government grant would complement this income to reach the specified level of revenue in the contract subsidy.

The battery technologies are at the end of the pre-commercial development phase. They are indeed the most suitable technologies to solve problems by the middle of the decade in some European island systems. The sodium-sulfur (NaS) technology is perfectly suited to the needs in terms of power for large installations (several megawatts). The Li-ion technology is perfectly suited to the needs in terms of power for small installations, a photovoltaic installation at home for example. The most appropriate support for this level of maturity is a production subsidy. Exposing the battery technologies to the market revenue can allow to integrate from now on the needs of the system in the architecture of the storage devices. It would thus be wise to use a feed-in premium that completes the market revenue when the storage facility injects energy in the system[9]. At the same time, these facilities are still scarce. So the regulator has very little information on the cost of these facilities. Because of this asymmetry of information, it would be efficient for a first phase of support for batteries to use a tender where participants propose a floor for revenue. The feed-in premium would then be calculated based on this floor and the market price level in the considered system.

The table below summarises the support mechanism to associate to each electrochemical storage device in a perfect market design.

Table 4 Support schemes for electrochemical storage devices in a perfect market design

Technologies	Technological maturity	Support scheme ➔ associated to the support scheme of intermittent renewable generation
Fuel cells	Developing +	R&D grant
Flow batteries	Developed -	Investment grant as a hedging contract that completes market revenues
Batteries	Developed +	Feed-in premium with floor that completes market revenues Obtained from tender in a first phase

[9] The storer would pay the market price to withdraw energy from the system and to store it.

B. Support for storage in real market designs: the case of French island power system

The study of support for storage technologies in a system with a perfect market design provides a reference for the study of support in any market design. We rely on this preliminary study to propose now a support for storage in European island power systems focusing on the case of France. We make this choice because the market design for the French island power system is very different from the perfect market design[10] and it is well documented and information is easily available. First, we describe the market design of these power systems. Then, we propose a support mechanism adapted to this design.

The market design of the French island power systems is very different from the perfect market design.[11] EDF is the vertically integrated utility for these systems. EDF operates a significant part of the power plants on these systems and it also operates transmission and distribution of electricity. Third party access to these networks is regulated. The connection tariff is a deep cost[12] one for low voltage network[13], an average deep cost[14] one for medium voltage (for facilities for up to 12 MW) and deep cost for installations in high voltage[15]. In addition, a network access fee applies to producers (mainly for the management and billing in medium voltage and also for the injection in high voltage) but also for consumers. No forward market or centralized real-time is established in these islands. Producers other than EDF being connected in island power systems are usually renewable energy producers benefiting from a feed-in tariff.

The market design of the French island power systems raises problems for the integration of storage facilities. The lack of power market in particular prevents from benefiting from the gains offered by the storage for the entire system. Indeed, a significant proportion of revenue from storage comes from the possibility of intertemporal trade-offs (withdraw energy from the system at a time and store this energy to remove and inject it in the system later). However, these tradeoffs can be made only while referring to market price signals. Moreover, considering the absence of market, no short run locational signal can be provided.[16] This problem is partly solved when EDF SEI publishes the accommodation capacity of the island network substations. However, storage facilities face a major problem in the French island power systems (and more widely in Metropolitan France), they must pay the network access fee both as producers and as consumers. This measure is known to impact significantly the profitability of the storage facilities in France (He & Zachmann, 2009). It is important to note that in the absence of precise locational signals in the design of the French island power

[10] We must take into account the cost of the change in market design to assess the absolute distance between the current market design and the perfect market design.

[11] Source: sei.edf.fr

[12] With a deep cost tariff, the full costs of all new infrastructures required for changes in network utilization (whatever reason: a local increase in consumption, a new connection, increased generating capacity of an existing power plant) will be directly imputed to the network users responsible for this change in network use.

[13] The voltage on the low voltage network is less than 1 kV. The voltage of medium voltage network is between 1 and 50 kV and the voltage of high voltage network is between 50 and 130 kV.

[14] For connection in medium voltage, a price reduction (*taux de réfaction tarifaire*) is applied. This rate reduction is 40%. When the generator connects to the network, it then pays only 40% of deep cost.

[15] These connection rules are implemented in Metropolitan France for this voltage level. The rule applied in Metropolitan France is the shallow cost tariff. But considering that there is only one high voltage level (63 kV) in the French island power networks, it is in fact a deep cost tariff that is applied.

[16] The deep cost access fee does not provide locational signal because no signal is publicly available. The generator must ask to connect to know the connection cost.

system, it appears easier to associate systematically the support for a storage device to the intermittent renewable generation.[17]

Given the considered market design here, the support mechanisms previously proposed with a perfect market design are modified as follow.

The support for fuel cells is related to R & D grants and the establishment of a niche market. So it is not affected by considerations of market design in the island power systems.

For the flow batteries, in the absence of market prices, the investment subsidy for the appropriate level of maturity of this technology is applied in its simplest form. To incentivise the investor to use efficiently this storage device, it is possible to link this investment subsidy with the performance of the facility. This principle was applied to subsidy the photovoltaic sector in California (Finon, 2009). In the case of storage, we can define several time ranges (late night, day and early night for instance) and the performance of the storage facility would be calculated based on the periods mainly used to store and remove energy. Such a mechanism would push the storage device to store more late night (when the conventional thermal power plants are reluctant to drop their production below the technical limits) and day (in bright sunlight) to remove energy at peak time in early night. This mechanism does not allow to reach the optimal use of storage but it allows to approach it with a support mechanism the simplest as possible.

Without market prices and given their precommercial level of maturity, the battery technologies should be supported with a feed-in tariff. Nevertheless, to ensure energy is stored and removed rather efficiently, these rates should be differentiated in time as we previously described for the flow batteries. Remember also that these facilities are still scarce. The regulator has very little information on the cost of these facilities. Because of this asymmetry of information, it would be efficient for a first phase of support for battery to use a tender where participants propose both a price of injection and withdrawal for their facilities.

The table below summarises the support mechanism to associate to each electrochemical storage device in the case of France.

Table 5 Support schemes for electrochemical storage devices in the French island power system

Technologies	**Technological maturity**	**Support scheme** ➔ *associated to the support scheme of intermittent renewable generation*
Fuel cells	Developing +	R&D grant
Flow batteries	Developed -	Investment grant related to the efficient use of the storage facility
Batteries	Developed +	Feed-in tariff with time differenciation Obtained from tender in a first phase

[17] As mentioned previously, the conclusion is a little bit different in continental Europe because the need for storage related to the massive integration of intermittent renewable generation is rather located at the substation between the low and medium voltage networks.

V. Conclusion

We sought to develop a support mechanism for electricity storage technologies in the European island power systems taking the French island power system as an example. We relied on the linear model of development of innovations. We came across this model with the maturity level of the storage facilities. However, we limit our investigation to certain categories of storage technologies by considering two criteria. 1° We have considered the storage technologies that can always be technically developed on island power systems. 2° We have further restricted the possibilities by considering only the storage technologies that meet the challenges of these systems where intermittent renewable energy is developing very rapidly. These challenges are namely the problems of harmonics, balancing, and the limitation of curtailment of intermittent renewable generation when network constraints appear.

In a perfect market, we then conclude that the following support scheme should be implemented: a) a R & D grant for fuel cells, b) an investment subsidy designed as a contract hedging to complete the market and system revenues for the flow battery technologies and c) an environmental feed-in premium in addition to the market price for the battery technologies. The perfect market gives a lot of information for an efficient location of the network. As a consequence, it is not necessary to couple the support of the storage facilities to the support of renewable energy (although a priori the storage units will be localised close to these production sources).

Within one of European island power markets very different from the perfect market design, namely the French island power systems, we propose a) a R & D grant for fuel cells (as previously), b) a subsidy for investment (potentially conceived as a performance contract) for the flow battery technologies and c) a feed-in tariff with different prices depending on time of day for the battery technologies. With no locational signals, it is necessary to couple the support of the storage facilities with the support of renewable energy to be sure the storage unit will be localised the closest as possible to the sources of intermittency for the power system.

The short run constraints on the French island power systems force to focus on battery technologies. Moreover, if the support of the storage industry also contributes to the establishment of a European innovative industry, one should be pushing for some technologies in particular. SAFT in France, Evonik or Litec in Germany are flagship of their national industry and their battery product lines mainly focus on lithium-ion- and nickel-based technologies. It is useless these firms to try to catch up on the NaS technology given the leadership of NGK on this stream (see Finon, 2009 for a similar analysis in the case of PV). It is then necessary to design the support mechanism and to determine the level of subsidy to encourage the storage technologies by these firms.

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VII. Appendix

Definition of ranges for the characteristics of storage technologies to compare them

- Energy density (Wh/Kg)
  - Very low (0.01 < X < 10)
  - Low (10 < X < 30)
  - Medium (30 < X < 50)
  - High (50 < X < 150) Very high (X > 150)
- Power density (W/kg)
  - Very low (10 < X < 25)
  - Low (25 < X < 50)
  - Medium (50 < X < 150)
  - High (150 < X < 1000)
  - Very high (X > 1000)
- Storage duration
  - Very weak (from seconds to minutes), Weak (from seconds to hours)
  - Medium (from minutes to hours),
  - Long (from minutes to days)
  - Very long (from hours to months)
- Power range for the installations
  - Very weak (0 < X < 50 kW)
  - Weak (50 kW < X < 500 kW)
  - Medium (500 kW < X < 50 MW)
  - High (50 MW < X < 300 MW)
  - Very high (X > 300 MW)
- Self-discharge per day
  - Very weak (X < 0.1%)
  - Weak (0.1% < X < 1%)
  - Medium (1% < X < 10%)
  - High (10% < X < 30%)
  - Very high (X > 30%)
- Capital cost (€/kW)
  - Weak (100 < X < 600)
  - Medium (600 < X < 1500)
  - High (X > 1500)
- Efficiency of a charge-discharge cycle
  - Weak (X < 60%)
  - Medium (60% < X < 90%)
  - High (X > 90%)
- Lifetime (years)
  - Very weak (X <1)
  - Weak (1 < X < 50)
  - Medium (5 < X < 15)
  - High (15 < X < 50)
  - Very high (X > 50)

- Possible number of cycles
    - Very weak (X < 100)
    - Weak (100 < X < 500)
    - Medium (500 < X < 1500)
    - High (1500 < X < 20,000)
    - Very high (X > 20 000)
- Discharge time
    - Very weak (from milliseconds to seconds),
    - Weak (from seconds to minutes)
    - Medium (from seconds to hours)
    - High (from minutes to hours)
    - Very high (from hours to days)
- Effect on environment
    - None
    - Weak (peu de déchets)
    - Important (toxic wastes to deal with, possible recycling)
    - Negative (CO2 emissions or destroyed trees – from hydro dams)
- Technological maturity
    - Chen et al. 2009. propose the graph below to detail the maturity of the different storage technologies. To be coherent with the 5 stages of the linear model of innovation that we present in section 2 of the paper, we define 5 categories of technological maturity.
        - Mature
        - Developed +
        - Developed –
        - Developing +
        - Developing -