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RSCAS 2012/70
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
Loyola de Palacio Programme on Energy Policy

WHAT TYPE(S) OF SUPPORT SCHEMES FOR STORAGE IN ISLAND POWER SYSTEMS?

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EUI Working Paper **RSCAS** 2012/70

ISSN 1028-3625

Printed in Italy, December 2012
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
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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.

Keywords

Storage; Feed-in-Tariff; Island power systems

I. Introduction

The integration of massive photovoltaic and wind power raises problems in island power systems in Europe. These systems can only accommodate a very limited capacity of RES power. 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). This technical constraint can reach different levels according to the size and the maturity of the island system. In the example of Reunion Island, the limit is 30% of intermittent RES that can be integrated in the system. When the 30% limit is reached, the system operators will cut intermittent RES production surplus to maintain the balance between generation and load. This technical constraint limits the integration of more renewable energy in Island power systems and makes more difficult the achievement of objectives of energy independence and reduction of GHG emissions. 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 at low price. Second if the integration of more intermittent RES means inserting in parallel flexible thermal power plants, the CO2 net balance could be negative for the island systems. Another solution that we study here is to rely on electricity storage[1].

Storage facilities have multiple positive impacts on the electricity systems. First electricity storage logically allows to insert more intermittent RES while participating in the global balance between generation and load in a more predictable way. Second, storage can flatten the load curve of the system. The renewable or baseload power plants are then more called on to fill in the storage facilities during low consumption period. And during periods of high consumption, the stored energy is returned to the system reducing then the need of peakload power plants that relatively emit more CO2 than renewable or baseload ones. Despite the potential attractivity of energy storage, the technologies adapted to massive deployment in islands are still in the infancy of industrialization.

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 Sioshansi (2010) sums up the diversified services that storage can bring into power systems and highlights the inconsistencies in the actual market designs, which prevent a market based development of storage. One important reason is the lack of adapted mechanisms that would allow the investor to capture the overall value of storage by providing multiple services to the power system. The efforts to aggregate several revenue streams often encounter the regulatory frames which forbid the exchange of information between the regulated and deregulated actors. Sioshansi (2010) helps us to understand that the combination of services could lead to a better perspective for the development of storage.

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[1] When it is possible, another solution that brings more flexibility is to connect islands together (e.g. the Canaries islands) or to connect them to the continental system (e.g. the main Baleares islands connected to the Spanish network).

Following this line, He et al. (2010) develop a first reflection on a business model taking into account this problem in power systems. The core idea of their model lies in organizing an auction chain in which the right to use available capacities of storage is auctioned among different actors. To sum-up, the integration of storage in the power system is facing threefold market failures. 1° The storage can help the development of intermittent RES and reduces CO2 emissions from other power plants but the pricing of CO2 still does not allow to internalize this positive externality and to overcome the investment and management cost of storage. 2° The scientific and technological efforts associated with R & D and demonstration pilots have a public good character that need an adapted treatment to be overcome. 3° Innovations in the power system such as storage face technological entry barriers due to the pre-existence of mature solutions (such as oil power plants) that can provide a similar service at actual lower cost. Its learning curve is then limited.

The existence of these three market failures then leads to wonder what the adapted form of public support and regulatory framework are for the development and deployment of storage technologies in island power systems[2]. In order to answer this question, we will rely on the work by Foxon et al. (2005) to associate the adequate support mechanism to technologies depending on their maturity. In particular, it was previously done for renewable generation technologies (Finon, 2009; Finon and Perez, 2007). We will also rely on the work by Chen at al. (2009) to characterize the maturity of the different storage technologies. Besides, in order to minimise the reliance on support mechanism while maximizing the chance of development of storage technology, we will also consider three characteristics of storage devices when designing support mechanisms for storage technologies. The first characteristic is the optimal use of storage. The public support mechanism should 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. The second characteristic that distinguishes the different storage technologies is the set of services that they can provide to the power system. Some storage technologies may be able to provide some services to the system while other may not (for instance flexibility). The public support to storage shall take into account the differences between technologies in terms of ability and maturity of service they can provide and the revenue they can earn from selling these services. The last characteristic is the degree of centralization of storage facilities. Different management schemes could be applied to storage according to the degree of centralization. Consequently support mechanisms shall apply differently in function of the degree of centralization and on the kind of actor managing storage (fully independent, integrated with production, or possibly with TSO). At last, the value for these three characteristics of storage (1. its double function of storing and removing energy, 2. the other services it can provide and 3. its degree of centralization and location on the network) will be all the higher (without support) that the market design will be efficient and storage will be exposed to market signals. A smaller reliance on support mechanism will then be needed (as shown by Hiroux and Saguan, 2009 in the case of wind power).

The paper is organised as follow. First we identify the services that the storage could provide to island power systems to facilitate the integration of intermittent RES. We then establish the electrochemical storage technologies that can deliver these services. Second, 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. In the last section, we will also 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, we will consider the perfect market design established by Hiroux and Saguan (2009) and the market design of the French island power systems.

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[2] Note that internalizing the market failures for storage may also benefit to consumers in allowing lower prices at peak times (Sioshansi, 2010).

II. Energy storage and renewable energy

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 we will consider there is no storage and after we will introduce storage.

A. Specific problems with island power systems

According to Perez and Ramos-Real (2008) and Weisser (2004a & b), the island systems have specific economic and technical characteristics due to the insular nature of the small electrical supply networks. Other things equal, the island power systems are indeed more tightly dimensioned than the large ones because energy is there far more expensive. The island power systems are then weaker to respond or to absorb shocks and risks. Each element constituting such small networks is consequently very significant for the entire grid. The loss of a group or the loss of a single element of the network is then felt in a much stronger way than on a network of a more significant size. Insularity makes these small systems more difficult to manage than large interconnected systems for four reasons.

First, the main problem is that electricity supply in these territories is more expensive because they face high fuel transport costs to be supplied. These systems indeed are generally running with imported fossil fuels at a high price[3].

The second problem endured by small electricity systems is that the network faces a lot of voltage constraints. This is because the small size of the network induced that the voltage drops have a high effect on the whole network compared to the management of large size system.

The third problem is that the island networks do not benefit from the immediate solidarity offered by the number effect of the producers connected on the large continental network. The very short run adjustment between “power and frequency” is thus more difficult there to achieve. Isolation makes it necessary to maintain more reserve capacity to ensure adequate supply. They cannot therefore benefit from the great stability of big interconnected electricity system.

The last problem is that the above mentioned constraints require planning and management procedures that do not benefit from an important learning effect like the one experienced by mainland territories. Even worth, it is very hard to define transparent management rules or even clear safety rule for island power systems because each network is very specific (depending on its geographical size, number of inhabitants, economic activities, weather conditions, etc.). The comparison of the ongoing safety requirements of some isolated electric systems shows a high diversity (Table 1).

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[3] This is because the required quantity is generally small and not frequently delivered. For more details on this point, see Ramos-Real et al. (2007).

Table 1 Comparison of security rules for Islands

	Installed capacity in MW	**Peak demand in MW**	**Rules for primary reserve**
Cyprus	990	775	10% of total load[4]
Crete	704	471	The largest group or all the wind production presents at time T[5]
Mallorca-Menorca	1098	914	50% of the largest connected group[6]
Ibiza Formentera	197	169	
Lanzarote-Fuerteventura	346	212	
Gran Canaria	860	552	
Tenerife	775	540	

The island power systems are then difficult and fragile to manage. This makes them very sensitive to any disturbances and the introduction of any innovation should aim at increasing its stability, to increase its resistance to shocks.

B. Impact of intermittent RES and the need for energy storage

It is advisable to stress that the introduction of massive intermittent renewable energy sources, on insular networks, in particular photovoltaic and wind energy, is not an easy matter, because it increases the difficulty of management of these fragile networks. In the absence of adapted storage devices or additional flexible thermal generation units[7], the integration of intermittent renewable energy has four major impacts on the electrical system.

First, having priority on the network, the introduction of massive amount of wind and photovoltaic energy modifies the way the system is operated as a whole. The conventional producers must adapt their production curve to the real times fluctuations of wind and photovoltaic productions. They are dispatched after this priority energy. The resulting modification of the merit order induces overcosts because some power stations previously being dispatched will now be dispatched under more stressed pattern of use, operating a lot of variations and/or at suboptimal levels compared to their technical design.

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). Besides, these power sources are "fatal" because their energy must necessarily be used at the time of production or to be lost otherwise. Taking

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[4] Petoussis & Stavrinos (2010).

[5] Thalassinakis & Papoutsakis (2006).

[6] Résolución de 28 de Abril de 2006, de la Secretaría General de Energía, por la que se aprueba un conjunto de procedimientos de carácter técnico e instrumental necesarios para realizar la adecuada gestión técnica de los sistemas eléctricas insulares y extrapeninsulares

[7] Some possible scenarios of developing jointly gas and RES have being studied in Marrero & Ramos-Real, (2010).

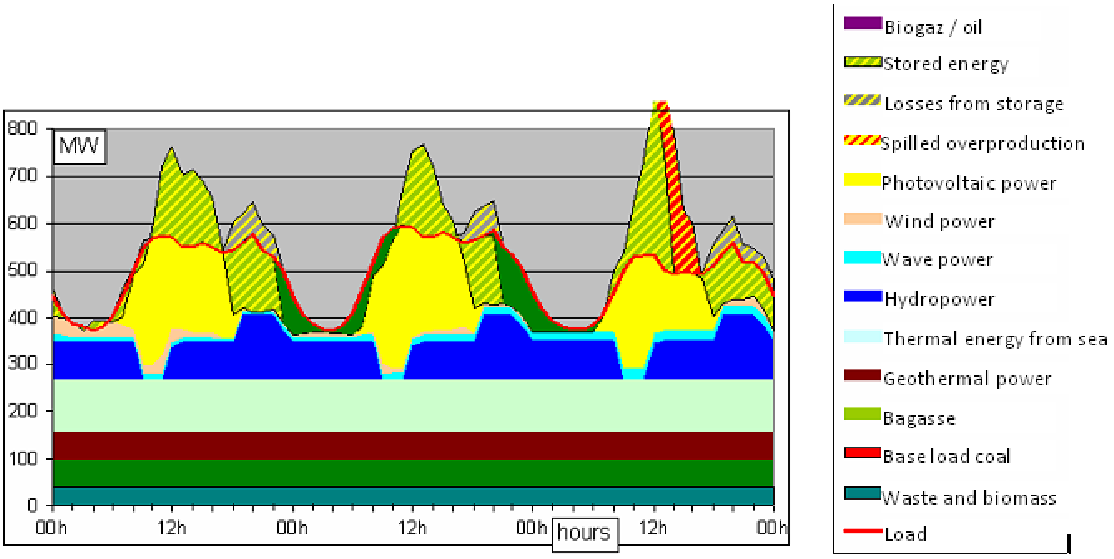
into account these characteristics, the wind and photovoltaic technologies cannot be mobilized for the adjustments of power and frequency under the current security rules.

Third 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).

At last, 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.

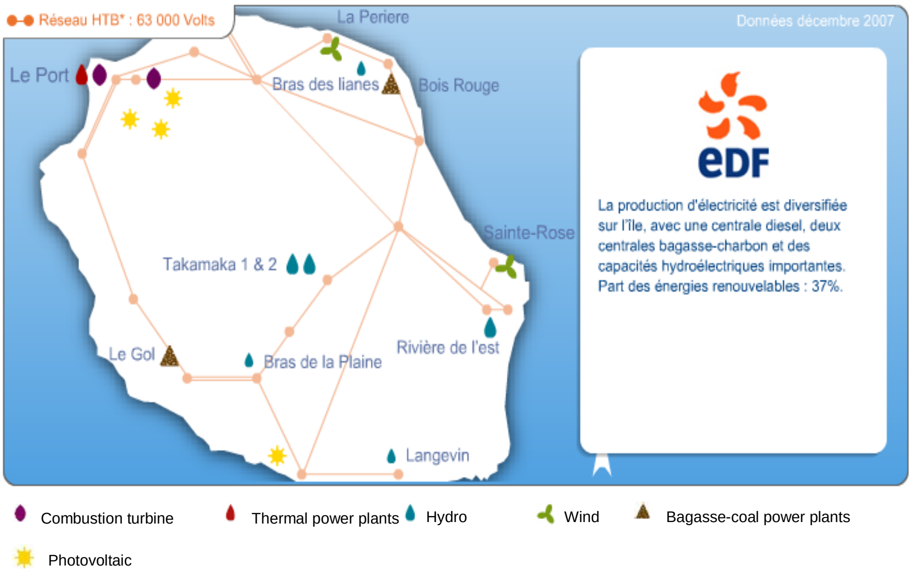
The low flexibility of baseload thermal power units does not allow for sufficient change in their production level to balance generation and load in a reliable way with a massive amount of intermittent generation. The instantaneous mismatch between production and consumption is well known for wind generation (Maupas, 2008). It is also true for PV production, although to a lesser extent. This is illustrated in figure 1, 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 1 Example de of power generation for 3 days in Reunion Island for 2050 with spilled photovoltaic production. Adapted from ARER (2008)



Another important constraint to consider is that grid has a limited capacity. This is all the more true that intermittent renewable generation in island power system is generally concentrated in a limited number of geographical areas. 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, for instance, the South East of Reunion Island (see figure 2). It may then be needed to limit the installed capacity of intermittent renewable generation units because of the network constraints. 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. It may also be efficient to upgrade the network development up to the capacity when the cost of any increase is bigger than the value of increased RES production.

Figure 2 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. Adapted from sei.edf.fr



Of course, the introduction and development of renewable energies could be an interesting and solid instrument to make island power systems less dependent from foreign fossil fuels, more environmental friendly, and able to produce their energy in a more cost-effective manner. However, its interruptible and stochastic nature, together with isolation, will make their massive introduction rather difficult to manage, unless solutions like storage are deployed.

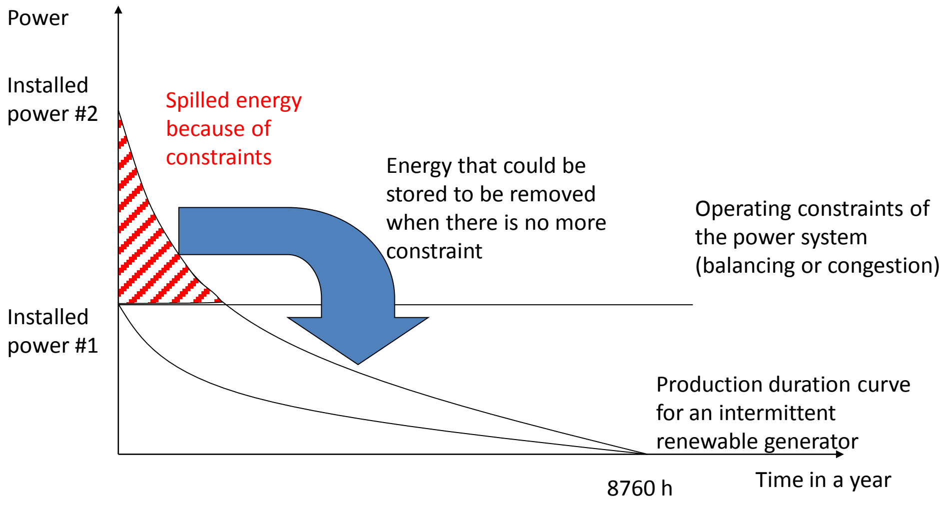
Some storage technologies enable to offset significantly the above mentioned effects of intermittent RES in island power systems. Some of them also induce other benefits for the whole power system more precisely four other types of benefits.

First, the power electronics tools required for the integration of electrochemical batteries can also control and improve the quality of the power signal despite the stochastic variations of intermittent production.
Second, some storage technologies exhibit temporal dynamics that allow them to participate actively in balancing generation and load either providing power reserves or balancing.

Third, 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 peak load generation units that emit important CO2 emissions.

Last, 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 (see figure 3). 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.[8]

Figure 3 Illustration of the impact of storage on the operation of intermittent generator in presence of operating constraints



C. 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 12 characteristics: 1) Energy density, 2) Power density, 3) Storage duration, 4) Range of nominal power of installations, 5) Self-discharge per day, 6) Capital cost, 7) Technical efficiency over a charge-discharge cycle, 8) Lifetime, 9) Maximum number of cycles, 10) Discharge time, 11) Effect on environment, 12) Maturity of technology. We summarize their analysis in the appendix and rely on it to evaluate the adequacy between the characteristics of the different storage technologies and the problems encountered on islands power system with a high penetration of intermittent renewable power sources. 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.[9] 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. It is already the case for some island power system like in the Canaries Islands (e.g. Gran Canaria or El Hierro – see Bueno and Carta, 2006). 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.

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[8] 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).

[9] For the most classical type of PHS, these storage devices cannot deal alone with the 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.

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[10], which is not easily compatible with the geographical constraints of island power systems.

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 in the absence of hydraulic resources. 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.[11] 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.

Table 2 summarises the benefits provided by the different storage technologies to the power system.

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

[11] 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.

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*
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	Reserves only
	At least daily storage duration	Yes	Yes	Yes	Yes	Yes	Yes
	Location flexibility	No	No	Yes	Yes	Partly	Yes

* (SMES, flywheel, supercapacity)

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).

III. What forms of public 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 first recall the theory of public support for the development of renewable innovation. Second we establish the support mechanisms to implement in a perfect market design. Finally we study how these support mechanisms must be adapted with a market design whose features are moving away from the ideal case.

A. Public support for the development of renewable innovation

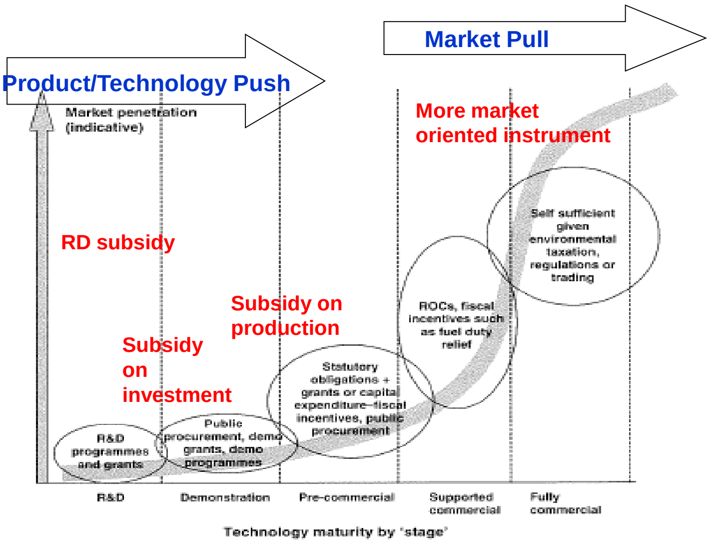
To identify the best-suited public support scheme to each development stage of an environmental innovation, we refer to the simplified version of linear model of innovation. It is a key issue to have in mind that they are multiple ways to understand and forecast the possible form of innovation stages and the determinant of the success and failures of innovations along the way to commercial diffusion. In this paper we have chosen to explore this question thanks to the simplest model of innovation diffusion following a S curve like in Foxon & al. (2006). Further studies my be needed in the future to take into account other form of innovation diffusions like disruptive innovations (Christiansen (1997)) or even the no diffusion case in presence of path dependency issues (Liebowitz, & Margolis (1990 and 1995), Garcia & Cantalone (2002), Der Panne and al. (2003) and Fri (2006)).

In our view and following Foxon & al. (2006), the S curve diffusion 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[12]. Figure 4 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.

Figure 4 The classical pattern for the adequacy between the types of support schemes for RES and the level of maturity



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

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

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[12] In this paper, we do no challenge this model but rather use it to identify the adaptation needed by the public policies.

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[13]. Besides, fading out the level of the environmental premium is a way to integrate progressively the technology as a full market-friendly one.

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

Hiroux and Saguan (2009) address the question of a textbook market design for large-scale integration of wind power in Europe. We will rely on their pioneering work to recall the design of a perfect market and to propose support mechanisms for the electrochemical storage in this perfect framework.

Hiroux and Saguan (2009) show that it is possible to support massive 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. Table 3 below recalls all the main options for designing an electricity market design and evaluates their efficiency. In a nutshell, 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[14]. And the network access fees would be zonal. The producer or storage operator 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. Any deviation from this market design would induce efficiency. These possible deviations are: the decentralization of market design, a gate closure far from real time, a dual pricing for positive and negative imbalances in real time, congestion management with zonal pricing and redispatching, shallow or deep cost allocation of network costs.

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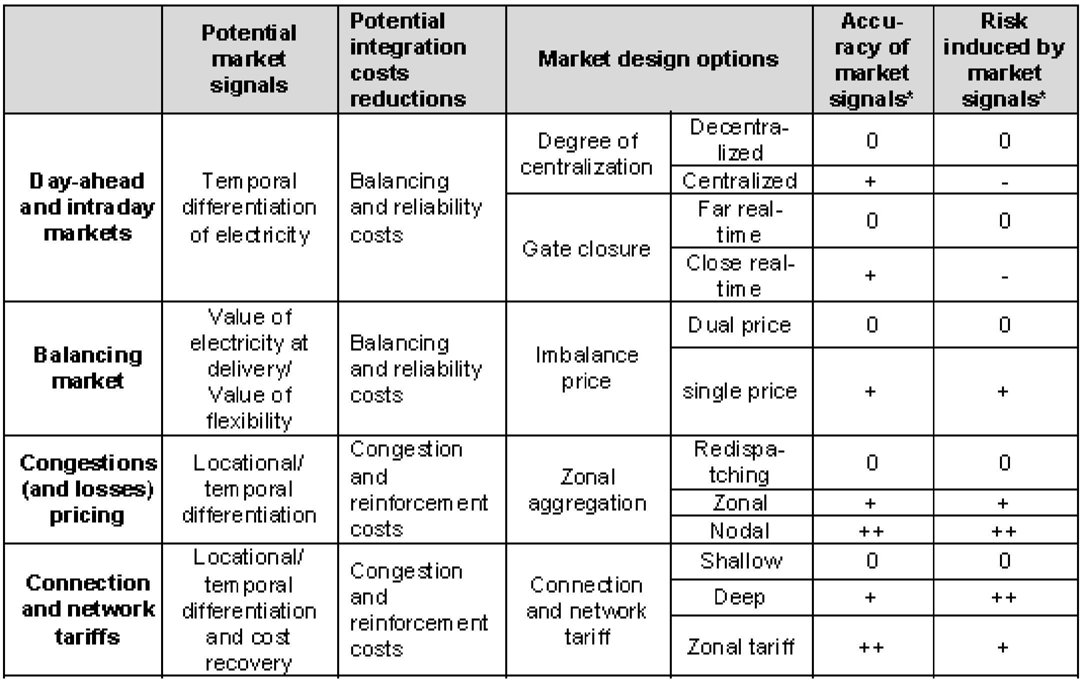
[13] See Finon and Perez (2007) for a comparison of these devises to promote RES technologies for electricity and Perez. & Ramos-Real(2009) for a case study in the Spanish case.

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

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 intraday 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	++	+

Hiroux and Saguan (2009) 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. This may discourage the adoption of these technologies as long as the support mechanism is not defined 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. The design of a support mechanism should then take into account both revenues provided by market design and the level of maturity of the technology supported.

Applying this framework to the electrochemical storage has different implications depending on the maturity of technologies. Fuel cells are still in the stage of technical development (see Chen et al., 2009). Following the Foxon et al. (2005) framework, this technology should primarily benefit from public subsidies to increase its level of R & D. The exposure of this technology to market signals at this stage of maturity is of no interest[15].

The flow battery technologies are in the early phase of pre-commercial development (see Chen et al., 2009). Following the Foxon et al. (2005) framework, the support that best suits their level of maturity is an investment grant[16]. 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

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[15] For the case of hydrogen fuel cell, a niche market can begin to develop (Chen et al., 2009). Note that the PHS technology is mature and no support mechanism seems then justified with this regard. Some obligations of storability for intermittent RES production might be enough to prompt for the development of this technology.

[16] Note that the CAES technology presents a similar level of technological maturity (see Chen et al., 2009). The same rationale could then be applied to design an adapted support mechanism.

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 (see Chen et al., 2009). 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.

Following the Foxon et al. (2005) framework, the most appropriate support for the pre-commercial 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[17].

Meanwhile, these facilities are still scarce. And this is a major difficulty because the regulator has very little knowledge on the cost of these facilities and few options to discover relevant pieces of information. Because of this asymmetry of information, we propose in the first phase of support for batteries to use a tender mechanism, where the storage operators propose a tariff of injection and withdrawal in their offers. The feed-in premium would then be calculated by the regulator based on this revealed information about the revenues asked by storage operators and the market price level (or regulated one) 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

C. 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[18] 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.

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[17] The storage operator would pay the market price to withdraw energy from the system and to store it.

[18] 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.

It is clear that the market design of the French island power systems is very different from the perfect market design.[19] EDF is the vertically integrated utility. EDF operates a significant part of the power plants and it also operates transmission and distribution of electricity. Third party access to these networks is regulated. The connection tariff is a deep cost one[20] for low voltage network[21], an average deep cost[22] one for medium voltage (for facilities for up to 12 MW) and deep cost for installations in high voltage[23]. 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 any organized 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 power market price signals. Moreover no short run locational signal can be provided.[24] This problem is only partly solved when EDF SEI publishes the accommodation capacity of the island network substations.

More importantly, 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 system, it appears easier to associate systematically the support for a storage device to the intermittent renewable generation.[25]

Given the considered market design we described, the three support mechanisms previously proposed with a perfect market design are modified as follow. First, 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.

Second, 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). This frame could be adapted in the case of storage. We can then compensate the absence of time varying power prices defining several time ranges (late night, day and early night for

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[19] Source: sei.edf.fr

[20] 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.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

instance). The performance of the storage facility would be consequently 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.

At last, 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. The regulator will then have to set the feed-in tariff according to the information about the level of maturity of the technology he is able to obtain from other stakeholders, consulting them for instance.

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 differentiation Obtained from tender in a first phase

IV. 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 a case study. In order to do so, 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.

Of course our work call for additional works in other isolated islands, where market designs can be very different from the one we have analysed here. In a broader perspective, the role of storage and the efficient way to support it should also be analysed in larger interconnected systems. Finally and more generally, the links between innovation and regulatory decisions in electricity systems are still poorly studied and require further researches.

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Appendix

To make easier the reading of the analysis by Chen et al. (2009), we placed each technology in a range as defined below that corresponds to each of the following characteristics: 1) Energy density, 2) Power density, 3) Storage duration, 4) Range of nominal power of installations, 5) Self-discharge per day, 6) Capital cost, 7) Technical efficiency over a charge-discharge cycle, 8) Lifetime, 9) Maximum number of cycles, 10) Discharge time, 11) Effect on environment, 12) Maturity of technology.

- Range for the 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)
- Range for the 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)
- Range for the 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)
- Range for the 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)

- Range for the 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%)
- Range for the capital cost (€/kW)
  - Weak (100 < X < 600)
  - Medium (600 < X < 1500)
  - High (X > 1500)
- Range for the efficiency of a charge-discharge cycle
  - Weak (X < 60%)
  - Medium (60% < X < 90%)
  - High (X > 90%)
- Range for the lifetime (years)
  - Very weak (X <1)
  - Weak (1 < X < 50)
  - Medium (5 < X < 15)
  - High (15 < X < 50)
  - Very high (X > 50)
- Range for the 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)

- Range for the 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)
- Range for the 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)
- Range for the 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 -

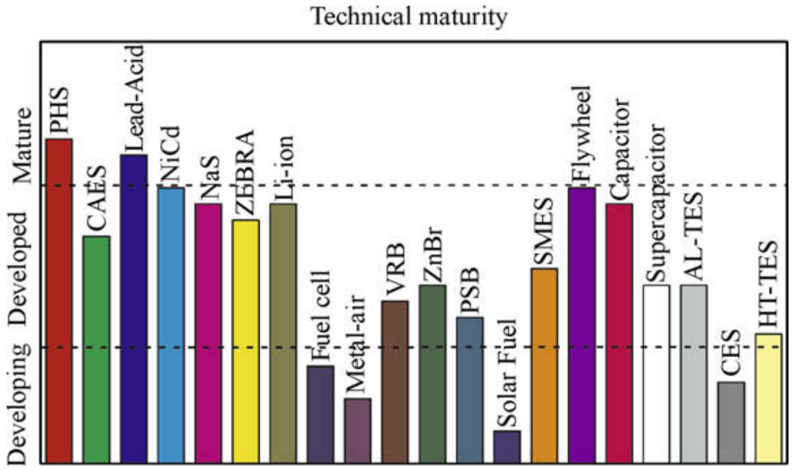

Table 1 Evaluation of the different storage technologies

	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 +

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