Energy for the Future.

The Sarewitz-Nelson Rules and the Energy Storage Problem.

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Abstract

In this paper, we apply the *Sarewitz-Nelson rules* (SN rules) to assess alternative technological solutions for the energy storage problem. We present the SN rules within a framework of reflections on what we actually understand technology and technological progress to be. As we will see, the SN rules allow us to analyze the potential of progress along alternative technological paths. As an application, we use the SN-rules to assess the potential of progress for five technologies which seek to solve the problem of storing energy on a large scale. These technologies are: *pumped hydropower, advanced batteries, flywheels, compressed-air* and *superconducting magnetic energy storage*. As we will show, although *pumped hydropower* and *advanced batteries* are often considered as the most likely future solutions for the storage problem, the application of the *Sarewitz-Nelson* rules suggests that, at present, there is no clear technological fix to solve the problem. Therefore, investments in basic science would seem to be crucial for modern societies to solve the problem of storing energy on a large scale. We close the paper by posing some policy implications regarding the transition towards a more sustainable energy system.

Keywords: Innovation, Sarewitz-Nelson rules, energy storage, technology policy.

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1. Introduction.

It is widely recognized that the remarkable technological progress experienced by a significant part of the world over the last two centuries has been the key driver of economic growth and the increase in living standards. It is less well recognized that the advance of technology has been extremely uneven across different technologies, sectors, and human activities (Nelson, 2003). Recent contributions within the realm of innovation studies have insisted that, in order to understand this unevenness, it seems important to reflect on the nature of technology and technological progress: what its features are, how it is applied, and what the mechanisms underlying technological advance are (Metcalfe, 2010).

The results obtained along these lines highlight two different – although mutually reinforcing - mechanisms underlying fast technological advance (Nelson, 2008): on the one hand, those areas where technical advance has been fast are usually supported by a solid body of understanding condensed in specific applied sciences; on the other hand, highly dynamic sectors and technologies show especially favorable conditions for experimental work and the replication of practice. Moreover, it is often argued that the *body of understanding* and the *body of practice* underlying technological progress *co-evolve* together.

Despite the significant advances obtained with this co-evolution approach to technological change, there are still many aspects that we do not understand (Dosi and Nelson, 2010). For instance, intriguing questions arise as to which specific conditions make certain social problems amenable to a technological fix (Kleinman *et al.*, 2010). Likewise, doubts remain as to how to discriminate between alternative technological paths if we look at their uneven potential for technological advance (Nelson, 2011).

In this regard, Daniel Sarewitz and Richard R. Nelson (2008a, 2008b) have recently proposed three simple rules to distinguish between problems that are likely to be solved through improved know-how and, thus, be responsive to R&D investments, and problems that are likely to resist this approach. Moreover, the Sarewitz-Nelson criteria may allow us to discriminate *ex-ante*, even under conditions of strong uncertainty, between technological alternatives seeking to solve a specific problem. As we will explain later, in Section 2, the *Sarewitz-Nelson rules* (SN-rules) are the as follows:

(R1) The *cause-effect* rule. Basically, it states that promising technological options must largely embody the cause-effect relationship connecting the problem to its solution. Furthermore, technological options embodying this relationship will be more amenable to technological improvements, the stronger the body of scientific understanding supporting research.

(R2) The *standardized technical core* rule. In brief, this rule asserts that technological research is at its best when it takes place around a specific technical core embodied in a standard device, artifact, prototype or procedure. The technical core fosters replicability and allows for easy off-line exploration.

(R3) Finally, what we shall call the *enlightening testability* rule. This rule states that technology is expected to advance more fluently when sharp criteria to discriminate between tentative technological changes exist. Furthermore, the efficiency and clarity in obtaining experimental results make the social assimilation of a technology easier.

As Sarewitz and Nelson (2008a) argue, for those technological avenues of advance –or specific social problems- for which the three rules are not met, we should not expect to find efficient technological solutions in the near future. Clearly, the application of the SN-rules may bring about interesting implications for technology policy. In this paper, we will use the SN-rules to assess alternative technological solutions for the *energy storage problem*.[2]

As a human activity, energy storage has existed since early times in history. Traditional storage systems (reservoirs, dams) have been in use for a very long time. Nowadays, the need to integrate renewable resources into existing energy systems is putting pressure on the development of new (or improved) storage technologies (Inage, 2009). The reason is

[2] Sarewitz and Nelson have already applied their *rules for technological fixes* to the problem of atmospheric CO_2 concentrations, warning about the fragility of policies based exclusively on national agreements to reduce emissions (Sarewitz and Nelson 2008a). These authors have also highlighted the limits of technological fixes for some persistent literacy and health problems (Sarewitz and Nelson 2008b).

that renewable energy sources –such as solar and wind power- share the characteristic that the times when energy can be captured and converted efficiently do not always correspond with the periods of high demand; therefore, large capacities for energy storage are needed to match generation and demand. The difficulties emerge because the technological problem of storing energy on a sufficiently large scale has not been solved. As a consequence, although renewable energy could play a key role in mitigating problems like greenhouse gas emissions or making the global energy system sustainable, they will not be a viable option unless energy can be stored on a large scale (Ibrahim *et al*., 2008; Mowery, Nelson and Martin, 2009). In fact, innovation in the energy storage area is swiftly becoming a crucial issue for the upcoming challenges we face (Lester and Hart, 2011).

At present there are several technological alternatives – at different stages of development – which aim to take on the energy storage problem. However, they are either not sufficiently developed or their large scale application is controversial (see Tester *et al*., 2005). Looking at the usual technologies involved in energy storage studies (see e.g. Lindley, 2010), we have decided to assess the possibilities of developing and applying five promising technological options: *pumped hydropower*, *advanced batteries*, *flywheels*, *compressed-air systems* and *superconducting magnetic energy storage*. Uncertainties regarding the future development of these technological options together with the difficulties in the generalization of their use on a social level, means we cannot affirm which one could solve the storage problem within a reasonable time scale. As we shall see, the Sarewitz-Nelson rules form an ideal analysis model to evaluate the development potential of the different alternatives and allow us to draw some policy implications[3].

As we justify in our paper, one of the main results that we obtain is that, although *pumped hydropower* and *advanced batteries* are often considered as the most likely future solutions

[3] It should be noted that we do not aim to offer a conventional cost-benefit analysis, nor an instantaneous comparison of the advantages and disadvantages of the different technological alternatives. In fact, given that none of the options are currently sufficiently developed and/or free of social controversy, the SN-rules can offer new perspectives unseen in more conventional analyses.

for the energy storage problem, an application of the *Sarewitz-Nelson* rules reveals that, at present, there is no clear technological fix to solve this problem. While some options rest on imperfect bodies of knowledge or are context-dependent; others lack a unique standard technical core, or present important problems regarding experimentation and their capacity to enable the development and social assimilation of the technology. As we justify in our conclusions, as a policy recommendation, our analysis seems to point towards the need to invest in long-term basic science projects without promising immediate applicable results. The need to undertake as soon as possible, with the necessary intensity, this kind of programs might be crucial if modern societies want to solve the problem of storing energy on a large scale in a reasonable future time scale.

The paper is organized as follows: we start by revising the notion of *technological progress* from a co-evolution perspective, and we present the Sarewitz-Nelson rules (Section 2). Then, in Section 3, we go into the examination of the storage problem and the possible technological fixes for it. Once we have discussed the criteria and the technological alternatives, we devote Section 4 to applying the Sarewitz-Nelson rules to the energy storage problem. The technical information publicly provided by certain organisms such as the US-Electricity Storage Association (ESA), the International Energy Agency (IEA), or the US National Renewable Energy Lab (NREL), allows us to describe the technologies and apply the rules to assess the alternatives for the problem. We end the paper by establishing our conclusions and offering a discussion of some policy implications.

2. Technological progress and the Sarewitz-Nelson Rules

Let us start by stating what we mean by *technology* (or know-how, more broadly speaking). When we talk about a technology, we refer to a specific range of *techniques* and *understandings* – incorporated in products, processes, routines and ways of organization - which allow for a specific activity to be carried out in "*t*", in a specific way and with specific levels (within variability limits) of quality and efficiency (Dosi and Grazzi, 2010).

According to this vision, *technological progress* in a specific area may be characterized as a cumulative process of knowledge renewal - and its applications - which emerges from the interaction between a *body of technical practice* and a *body of understanding*. More precisely, as Nelson (2003) and others argue, *technological progress* needs to be understood as a co-evolutionary process, where human purpose and understanding co-evolve with the complex system of current technological practice.

The co-evolution approach to technological progress means, on the one hand, that both the body of understanding (condensed in applied and basic sciences), as well as technical practices, will be developed according to the *evolutionary principles* of (guided) variation, retention, replication and *ex-post* competitive selection (Dosi and Nelson, 2010). On the other hand, the statement that scientific understanding and current practice co-evolve means that *the processes of evolutionary change in both realms are not independent*. More precisely, the progress of (basic and applied) scientific understanding, and cumulative experimental learning - both at the industry shop-floor level (on-line) and at the R&D lab-level (off-line) - mutually reinforce each other, bringing about progress in know-how. Thus, in those sectors in which technological progress is rapid, technology tends to move towards those areas where understanding has become strong, whilst the specific applied sciences advance by manipulating current technological practice experimentally.
This type of co-evolution process can be synthesized in Fig. 1.

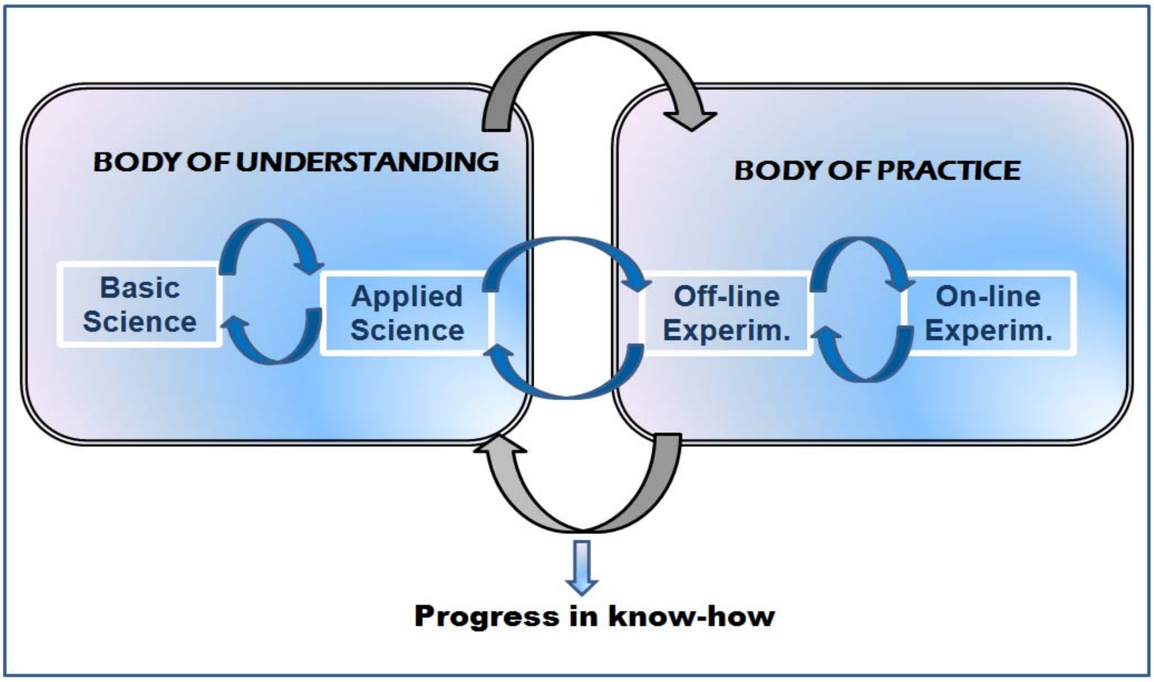

Fig. 1: Technological progress as a co-evolutionary process

Drawing upon this co-evolution approach, Daniel Sarewitz and Richard R. Nelson (2008a, 2008b) propose three simple rules - the *Sarewitz-Nelson (SN) rules* - which sharpen previous explanations for the uneven evolution of human know-how. On the one hand, these simple rules may be able to clarify whether certain social problems can be solved through technological progress or not. On the other hand, even when technological fixes are feasible, the SN-rules may be useful to discriminate between alternative technological paths by assessing the uneven potential for easy/hard technological advance. In this paper, we will use the SN-rules to shed some new light on which of these paths could be the most promising technological solution for the energy storage problem (see Sections 3 and 4). Before that, let us explain the Sarewitz-Nelson rules.

2.1.- The *cause-effect* rule (R1).

The first indicative feature of the efficiency of a technology and its chances of development is whether it incorporates the essential variables to solve the problem at hand; that is, it must incorporate the key cause-effect mechanisms linking the problem to a solution.

Moreover, our capacity to anticipate the potential of a technology and favor its development will be greater, the more developed the scientific knowledge base on which the activity is carried out as this means our level of understanding of the underlying cause-effect relationships will be firmer and more accurate. A solid scientific base will point to promising lines of progress, allow us to reject fruitless routes in advance and, often, enables experimentation with the technology (see R2 and R3 rules).

2.2.- The *standardized technical core* rule (R2).

R&D investment is more likely to fix a problem by developing a technology when it focuses on improving a standardized technical core that already exists. This technical core may be embodied in a standard procedure, device, prototype, or some kind of physical artifact. Devices or standard processes help to assess the promise of a path without building and testing a full-scale version in the real on-line operating environment. Standard technical cores allow for off-line experimentation and favor the replicability of the technology.

With regards to the previous rule (R1), let us mention that the stronger the body of scientific understanding guiding technological exploration around the core, the more fruitful this search is expected to be. In turn, as the technical core offers useful experimental results, so the applied science base will advance more quickly.

2.3.- The *enlightening testability* rule (R3).

A technological alternative will be more promising and socially comprehensible - in the sense of being able to progress and overcome political/organizational obstacles attached to its social generalization -, the easier it is to assess its results based on unambiguous criteria. Regarding the potential of progress, it is important to back those technological routes which offer quick and reliable information from simple, clear, and cheap experiments. With regards to rules (R1) and (R2), we can see that this type of results guides further technological search and scientific progress. Furthermore, obtaining quick, uncontroversial and enlightening testing results allows the neutralizing of conflicts associated with social acceptation of the technology. In this way, replicability and experimental clarity favor the assimilation of technology in different social contexts, avoiding coordination problems and aligning conflicting values.

It is interesting to emphasize that the three rules are not independent but, rather, that together they shape the conditions for technical practice and understanding to co-evolve smoothly, bringing about fast technological advance. In fact, as Sarewitz and Nelson (2008a, 2008b) argue, when the rules are not met, R&D programs aiming to develop technological paths in a short/medium period of time should neither be expected to succeed, nor be presented as having a serious chance of solving the specific problem in the near future.

Bearing all the above in mind, we will devote the rest of the paper to applying the SN-rules to the *energy storage problem*. We start by devoting Section 3 to a clear explanation of the storage problem and to present some of the technological alternatives which aim to solve the problem. Later, in Section 4, we analyze through the SN-rules whether any of the alternatives can seem more promising in terms of feasible/fast technological advance. We will also put forth some policy implications regarding the role of solving the storage problem on the way towards a sustainable global energy system.

3. The Problem: Technological Alternatives for Energy Storage.

Nowadays, almost nobody argues with the benefits of advancing towards a *clean, cheap, safe* and *nationally-self-sufficient* energy system (see, e.g. the EU Directive 2009/28/EC; or the *American Recovery and Reinvestment Act*, 2009). Likewise, neither is there a current discussion about the fact that, to achieve the aforementioned system, it is necessary to increase the proportion of energy produced by renewable resources.[4] The problem is that neither are most renewable resources (wind, solar power, etc.) available all the time, nor is demand for energy constant. Therefore, it is necessary to have technology to store the spare

[4] Hence, for example, the EU Directive 2009/28/EC sets its goal to achieve a minimum quota of 20% of energy coming from renewable sources in the EU by 2020. The *American Recovery and Reinvestment Act of* 2009 foresees that, by 2025, 25% of electricity will come from renewable sources.

energy in order to match supply and demand. However, as Lindley (2010) points out, the lack of good large-scale storage technologies has plagued utility operators and societies for generations.

Until now this problem has been dealt with (unsatisfactorily and temporarily) through the combined use of polluting and non-polluting energies, from both national sources as well as foreign ones (using mixed generating systems, complex intelligent networks of connection and disconnection, etc). These, though, are all intermediate solutions (Inage, 2009). If we really aim to progress to a cleaner, sustainable and nationally-self-sufficient energy system worldwide, however, solving the problem of large-scale energy storage is a must (ESA, 2012).

A number of technologies seeking to solve the problem of large-scale energy storage already exist. According to NREL (2012) and authors such as Lindley (2010) or Tester *et al*. (2005), some of the most promising technological paths that are currently on the table are: *pumped hydropower*; *advanced batteries*; *flywheels*; *compressed-air storage systems*; and *superconducting magnetic energy storage*. However, at present, none of these technologies offers a satisfactory combination of *cheapness, storage capacity/power, safety* and *environmental cleanness*. These dimensions can be considered as the key technological vectors of advance through which each specific technology could progress to become the future energy storage system. In this respect, we will use the SN rules (in Section 4) to discriminate between the five technologies under consideration in terms of easy/hard technological advance along these key dimensions. Before doing this, we first offer a short presentation of each one of the technologies.

3.1.- Pumped hydropower (PH).

Conventional pumped hydropower consists of two vertically-separated water reservoirs. Off-peak electricity is used to pump water from the lower reservoir to the higher elevation. When the water stored in the upper reservoir is released, it is passed through hydraulic turbines to generate electricity. The off-peak energy used to pump the water uphill is stored as potential energy in the upper reservoir. High and low-lying lakes, and even the sea – sometimes used as the lower reservoir -, are used as natural elements playing a role in this technology.

Let us mention that the supporting scientific understandings for this technology are contained in Fluid Dynamics. PH-technology is an established alternative based on a solid body of scientific understanding, and presents significant advantages in terms of power, storage capacity, and efficiency. However, this technology is totally dependent on specific geological formations, and on climatic conditions, and is affected by social controversy due to its environmental impact (Lindley, 2010).

3.2.- Battery Energy Storage (B).

There are several types of batteries: Lead-Acid (LA) batteries; Nickel-Cadmium (NiCd) batteries; Lithium-ion (Li-ion B) batteries; Sodium-Sulphur (NaS) batteries; etc (see, for example, ESA, 2012). All these batteries operate in the same way as traditional ones, i.e. two electrodes are immersed in an electrolyte which allows a chemical reaction to take place, so current can be produced when required. As an example, we shall explain how the Li-ion batteries work, bearing in mind that the only difference between these and other batteries is the kind of solution used as an electrolyte and the composition of the cathode and anode.

In the case of Li-ion batteries, the cathode is a lithiated metal oxide and the anode is made of layers of graphitic carbon. The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged, Li-ions move out of the cathode into the electrolyte solution where they are free to move to the negative electrode. At the anode they combine with external electrons and are deposited between carbon layers as Lithium atoms. The process is reversed during discharge.

The body of understanding supporting battery storage is called Electrochemistry. It must be pointed out that, despite the advantages of batteries regarding energy density, life cycle and efficiency, a number of challenges remain for batteries as large-scale storage devices. Packaging, internal overcharge protection circuits, and thermal management problems are all important questions to consider. In addition, there is a problem of availability of the necessary metals which, as with many other natural resources, are scarce.

3.3.- Mechanical flywheels (FW).

A flywheel is a flat disk or cylinder that spins at high speeds, storing kinetic (movement) energy. A flywheel can be combined with a device that operates as a motor accelerating the flywheel. The faster the flywheel spins, the more kinetic energy it retains. Energy can be drawn off as needed by slowing the flywheel. Most modern high-speed FW-technology systems consist of a massive rotating cylinder that is supported on a stator by magnetically levitated bearings. The FW is connected to a generator that interacts with the utility grid through advanced power electronics.

The supporting science for this technology is Classical Mechanics. One of the main problems of this technology is that the cylinder has to spin very fast, yet be strong enough so that it does not fly apart. Thus, the choice of rim material is a delicate technological aspect – pondering distinct functionalities such as weight, size needed, rotational speeds - with the idea of optimizing either power or storage capacity. Furthermore, the transference of the energy accumulated in the system towards its specific use is quite inefficient due to energy loss through friction or magnetic forces.

3.4.- Compressed-air energy storage (CAES).

CAES-technology uses off peak electricity to compress air into either an underground structure (cavern, abandoned mine, aquifer) or an above ground system of tanks/pipes. When the gas turbine produces electricity during peak hours, the compressed air is released from the storage facility. Then, the compressed air is mixed with natural gas, burned, and expanded in the gas turbine. If there was no gas added, the temperature and pressure of the air would be problematic. The underlying body of knowledge for this technology is Thermodynamics.

Man-made storage-reservoirs are very expensive and, so, CAES locations are determined by identifying natural geological formations. Hence, one of the problems with this method is finding suitable specific natural placements. Other issues include the uncertain behavior of the gas when compressed and the inefficiencies related to heat loss through the storage walls.

3.5.- Superconducting magnetic energy storage. (SME).

SME-storage systems store energy in the magnetic field created by the flow of direct current through a large coil of superconducting material that has been super-cooled. In low-temperature superconducting materials, electric currents encounter almost no resistance, so they can cycle through the coil of superconducting wire for a long time without losing energy. A typical SME storage system has three parts: superconducting coil; power conditioning system; cryogenically cooled refrigerator. The magnetically stored energy can be released back to the grid by discharging the coil.

This technology has advantages such as the short time delay during charge and discharge or the low loss of power (high technical efficiency). However, the energy content of SME systems is currently still small (low storage capacity), and the cryogenics (super-cooling) involved can be challenging. In addition, there are problems related to the fragility of superconducting materials. The Sciences supporting this technology are Electromagnetism, Cryogenics, and Materials Science.

4. Applying the Sarewitz-Nelson Rules to the Energy Storage Problem.

Applying the SN rules will allow us to discriminate *ex-ante* between the different storage technologies described in Section 3. Our aim is to try to elucidate which storage technology (if any) is most promising in terms of easiness and likelihood for technological advance.

As explained in Section 2, applying the SN rules implies analyzing specific issues in the case of each technology. Thus, firstly, regarding the (R1)-rule, we must investigate whether the technology incorporates the key cause-effect relationships linking problem to solution. It is also interesting to know whether there is any solid supporting science allowing us to understand the “basic go” of the technology. Secondly, the (R2)-rule means we have to find out if there is any kind of standardized device, prototype or procedure embodying the technology. Finally, the (R3)-rule means taking into account the possibilities of experimenting with this technology quickly, clearly and cheaply. Likewise, it is interesting to analyze whether the strength of the experimental results is enough to neutralize any social conflict related to the introduction of a technology.

We point out that, as Sarewitz and Nelson (2008a, 2008b) state, when the results that we obtain for a specific technology suggest that the SN-rules are not met, then, R&D programs aiming to develop said technology in a short/medium period of time should neither be expected to succeed, nor be presented as having much chance of solving the storage problem in the near future. If this were to happen with all the technological alternatives, we would have to consider new ways to deal with the storage problem. In this section we shall now analyze to what extent each of the above-mentioned technological options complies with SN-rules.

4.1. - Pumped hydropower (PH).

As we have mentioned above, PH is a technology which relies on a *solid body of scientific understanding*; namely, Fluid Dynamics. In fact, PH may be considered as an established and well-understood technology given that, once the water is stored, the mechanisms for transforming potential energy into electricity with relatively high levels of efficiency (low cost per kWh of storage) are well known. In this sense, PH verifies – as we shall now explain – a part of the (R1) SN-rule.

On the other hand, although there exists a *standardized technical core* in PH-technology (i.e. standard pumped hydroelectric facilities, which implies compliance with the (R2) SN-rule), we can affirm that PH-technology is *context dependent*. That is, the standard technical core does not fully incorporate the cause-effect relationships linking problem to solution, and is not easily replicable regardless of the environmental context. This is so for two reasons; firstly, large scale PH-storage systems require specific geological formations and climatic conditions (lakes, mountains, natural water reservoirs, stable rainy conditions, etc.) which are not found everywhere and are not under technological control. Secondly, in order to make PH feasible as an overall solution for the storage problem, PH facilities must be constructed on a very large scale, which, at present, is unfeasible [*scalability problem*, Murphy (2011)]. These facts lead us to affirm that PH does not fully satisfy the (R1) SN-rule; that is, PH-technology does not incorporate the “basic-go” linking solution to problem independently of the context in which it is used.

With reference to the third (R3) SN-rule, we can ask ourselves whether the experimentation around the technical core is sufficiently unambiguous, swift and cheap to overcome some of the current shortcomings of PH-technology. In this regard, most attempts to make technological advances in PH are mainly focused on increasing the capacity of the existing PH-facilities (e.g. by upgrading old dams or reservoirs) and/or improving efficiency (e.g. by reducing leaks). Both types of improvements try to increase the efficiency of already existing installations, thus avoiding the huge costs associated with the construction of new facilities (economic costs, environmental damages and social conflicts). In spite of these attempts, it seems difficult to expect promising advances from PH-technology on a large scale. Scalability problems impose physical limitations which go beyond technological improvements in capacity or efficiency. Besides this, the fact that PH is already established as a technology, means that any advances will be relatively small and insufficient to neutralize the social conflicts related to environmental damages, etc. All this leads us to conclude that PH-technology does not allow for sufficiently cheap, effective and socially acceptable experimentation around the existing technical core. For this reason this option does not fulfill the (R3) SN-rule.

4.2.- Battery Energy Storage (B).

Battery storage technology rests on a *solid body of understanding*, namely, Electrochemistry. In addition, batteries used as storage devices are non-context dependent. That is, batteries store the spare energy as chemical energy, being able to produce current when it is required, independently of external factors – such as geology, climate, human capacities, etc. Apparently, this would lead us to conclude that batteries, as a storage technology, verify the (R1) SN-rule. However, the body of scientific understanding underlying batteries allows us to see a *scalability problem* if we try to obtain batteries which act as large scale storage devices (e.g. think about the amount of metals needed to build a battery for a nation’s energy. See Murphy, 2011). The dimensions and requirements for a system of batteries to perform as a sole large-scale storage system are huge, and physically and economically unfeasible. Therefore, battery technology does not satisfy the (R1) SN-rule: this technology does not allow for a solution to the storage problem on a necessary large scale.

As explained in Section 3, there are several types of batteries, but they all basically work in the same way; therefore, we can affirm that there is a *standardized technical core* (verifying the (R2) SN-rule), but conditioned by our previous explanations regarding the scalability problem.

Regarding the (R3) SN-rule, we can affirm that *experimentation* with small batteries is relatively easy, since the standardized technical core exists and the theory underlying the technology can illuminate promising avenues of technological advance. In fact, many research projects are focused on finding new chemical combinations for the components of batteries, which can make batteries cleaner, cheaper, more efficient and/or smaller. However, given the above-mentioned, in spite of the advances which are to be expected from batteries as storage technology, it is not likely that batteries can become a sole storage technology on a large scale. From well-known Electrochemistry, we can affirm that the *scalability problem* prevents batteries from being a solution for the energy storage problem we have posed.

4.3- Mechanical flywheels (FW).

Regarding the case of FW-technology we are also looking at a body of practice which relies on a solid and well-known body of *scientific understanding*; namely, Classical Mechanics. However, *we cannot affirm that this technology incorporates the "basic go"* to solve, as a sole provider, the energy storage problem (so it does not fulfill the (R1)-SN rule). This is because taking the body of understanding underlying FWs, it is clear that, in practice, specific flywheels must be optimized either for power (low-speed FWs), or for storage capacity (high-speed FWs). As a consequence, the characteristics suitable for one aspect can often make the design unsuitable for the other. It is not possible to combine both features in a suitable way.

All this also leads us to conclude that *there is no unique standardized technical core* at present (so the second (R2) SN-rule is unfulfilled). This is so because, as the specific FW devices are oriented either towards power or storage, the characteristics of certain flywheels – e.g. power-oriented ones - means that the device is not sufficiently suitable for the other requirements (i.e., storage; see Baxter, 2006).

Regarding the third rule (R3), we can state that at present the main lines of advance in FW involve finding new materials to increase power or capacity, or to reduce costs. However, the *experimentation* with this technology, and its replication in practice, are not free from controversy due to the safety problems originating in the huge size of the devices and the possibility that they may explode or go out of control. These problems, together with the existence of unavoidable physical limitations to reach a suitable size, means we should not expect great advances from experimentation with FW as a large scale storage technology. Therefore, FW does not fulfill the third (R3) SN-rule satisfactorily either.

4.4.- Compressed-air energy storage (CAES).

One of the first difficulties we find regarding CAES-technology is that the underlying *body of knowledge* (Thermodynamics) does not offer a thorough understanding at present of the causal mechanisms which govern the dynamics of heat when the gases are compressed. This, together with the fact that CAES facilities are extremely *dependent on context* (specific geological formations, suitable underground reservoirs, large and safe chambers) leads us to affirm that this technology does not verify the (R1) SN-rule. Neither is it supported by a well-known body of scientific knowledge, nor does it incorporate the *basic-go* linking problem to solution independently of the context of its application (Baxter, 2006).

Regarding the (R2) SN-rule, we can affirm that there is a *standardized technical core* (CAES standard facilities), although in each case it must be adapted to the specific requirements of the land, geology, proximity to an electricity grid, etc. It must also be pointed out that CAES-facilities generally involve very high capital costs. In fact, at present there are very few of this kind of facilities in operation.

Finally, *experimentation* and *replication* with this technology is not easy: firstly, testing with CAES-technology is highly dependent on finding suitable sites; secondly, it is expensive; and finally, above all, it is socially controversial – for both environmental and safety reasons. It must also be noted that CAES still uses a fossil fuel (gas) to generate electricity; therefore, the emissions and safety regulations are similar to conventional gas turbines, and it is unlikely that these problems will be solved by experimentation in a reasonable time span. Consequently, we cannot affirm that CAES-technology verifies the (R3) SN-rule.

4.5.- Superconducting magnetic energy storage. (SME).

Superconducting technology is a relatively new technology with a very promising range of applications in many fields (transportation, computers, energy systems, etc.). However, as a technology for storing energy on a large scale, it presents many problems. Firstly, there isn't a sole *standardized technical core is not unique*. To be precise, there are currently two types of superconducting storage devices: those made from low-temperature superconductors (0 to 7.2K), and those made with high-temperature superconductors (10 to 150K). Therefore, the (R2) SN-rule is not fulfilled.

Secondly, there is not a solid and unified *body of understanding* underlying superconducting technology. Thus, while low-temperature superconductivity is explained by the *BSC* theory (Bardeen *et al.*, 1957), this theory alone is not able to explain high-temperature superconductivity. Without a body of scientific understanding in this direction, we cannot affirm that this technology verifies the (R1) SN-rule.

Finally, *experimentation* around superconducting energy storage devices becomes difficult because of the expensiveness of testing (low-superconducting devices need to be cooled below 7.2K, and high-superconducting ones below 150K). Therefore, we see that the (R3) SN-rule is not applicable, as it is not possible to experiment cheaply, quickly and firmly on the existing technical cores. Additionally, the lack of a unified theory hinders the search for new materials with superconducting properties at higher temperatures. The possibility of finding superconductors which work at room temperature is being considered; if these materials are eventually found, storage costs and experiments would become much cheaper. But, as of now, the lack of a general theory means it is unrealistic to expect to obtain fast results in this direction. Given all this, it is not to be expected that we will find a SME storage device operating on a large scale within a reasonable time scale.

4.6. – To sum up.

We can affirm that none of the technological alternatives studied fully verify the Sarewitz-Nelson rules. The bodies of understanding around batteries and flywheels show clear limitations for either technology to become a large scale storage device. Likewise, the lack of a solid body of understanding supporting superconducting magnetic energy storage, and the difficulty of testing regarding this technology, means we do not expect results in the short- or mid-term in this field. Finally, pumped hydro and CAES-technology do not fully embody the “basic go” linking solution to problem, as they are dependent on the context of the application of these technologies. Testing around these technologies is expensive and may involve social and environmental controversy. Given these facts, we can see that the analyzed technologies are not promising routes to fix the storage problem in a reasonable time frame.

5. Conclusions.

The enthusiasm for renewable energy is driven by solid reasons, such as the availability of these energy sources – in diverse forms - almost everywhere, the minimal environmental damage that renewable clean technologies produce, and the fact that the production of these energies does not deplete the planet’s natural resources. However, without the ability to dispatch renewable energy on demand, power shortages and outages will occur, and renewable energy will not be a viable option. Large scale storage technologies are needed. As we have seen, alternative paths to fix this problem exist (e.g. *pumped hydropower*, *batteries*, *compressed-air systems*, *flywheels* and *superconducting magnetic energy storage systems*). Given that none of these technological alternatives is sufficiently advanced and/or free of social controversy at present, we have decided to explore the technological possibilities of the different options (in terms of fast/easy technological advance) by applying the SN rules. This kind of analysis brings a new look at applications of the SN-rules, as well as a way to bring new arguments to the debate regarding the transition to more sustainable energetic systems.

As we have discussed in this paper, one of the main results that we have found is that, although *pumped hydropower* and *advanced batteries* are often defended as future solutions for the energy storage problem, an application of the *Sarewitz-Nelson* rules reveals that, at present, there is no clear technological fix to solve this problem. Some of the technological alternatives are context dependent (*pumped hydropower* and *compressed-air*) and/or do not embody (sufficiently well-known) cause-effect mechanisms linking problem to solution. Other alternatives are limited by the lack of knowledge underlying the technology (*superconducting magnetic energy*) or by the difficulties for experimentation, their safety or large-scale use (*flywheels*). Finally, using *batteries* as a general storage system poses important problems regarding the availability of metals - like lithium - or regarding scalability to reach the required dimensions for a large scale storage solution. As we have seen, a rapid advance is not to be expected in any of these technological alternatives.

As a consequence of the aforementioned, and given that none of the options are likely to become a large scale storage technology, what other solutions are on the table? Proposals are often made regarding integrating multinational smart grids or, even, reducing energy consumption (as a way to avoid large scale storage problems). However, none of these solutions stands up to the application of the Sarewitz-Nelson criteria, which means they cannot be held up as technological fixes for the energy storage problem. Both solutions are lacking a standardized technical core embodying the basic-go of the technology; they require high levels of coordination and social commitment which makes them highly dependent on context and political circumstances; and neither is there a solid body of understanding supporting experimentation and research around these *prototechnologies* (see Nelson, 2011). In our opinion, both the smart grids as well as proposals to reduce energy consumption represent a tacit acceptance of the fact that at present we do not have a technological fix for the energy storage problem.

Despite this, we do not believe in giving up on finding a general technological solution for the storage problem. In fact, if we do not make significant progress in know-how regarding how to store energy on a large scale, it is unlikely that the political aims of the growing incorporation of renewable sources into the energy systems can be achieved. Moreover, if we do not progress in the pursuit of a technological fix for the storage problem, it will be difficult to move towards a clean, safe, cheap, self-sufficient and sustainable energy system. Taking all this into account, and considering the results we obtain by applying the SN-rules, we believe there is a clear policy recommendation regarding the storage problem: more investments in basic science seem crucial if modern societies want to learn how to store energy on a large scale. Furthermore, this effort in basic investigation should be aimed at fields which seem to offer a wide margin for development. Finally, given the state of these questions, it is unadvisable to promise public opinion that there will be fast results in this aspect. On the contrary, it is necessary to make the public aware of the difficulties and effort needed in the transition towards a more sustainable energy system.

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