A formal discussion of the Sarewitz-Nelson rules

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Abstract

In this paper, we formally discuss the *Sarewitz-Nelson rules for technological fixes* (SN-rules). In their original form, the SN-rules were formulated from an implicit theoretical framework such that they define a broad technology assessment heuristic. This formulation has advantages and disadvantages. In this work, we propose that it is possible to make advances in the interpretation and use of the SN-rules, if we formally consider them as a procedure for technology screening, integrated within a wider process of technology choice and policy-making. This conception helps us to assess the nature and applicability of the SN-rules in different contexts, and allows us to position them as a contribution to the economic theory of technology policy.

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JEL-Code: *O13, O33, O38.*

1. Introduction

In many circumstances of life, agents have an incomplete understanding of the environment in which they operate. This is the case when technological innovations can occur: in innovative environments, *radical uncertainty* challenges problem-solving, policy making and choice (Arrow, 2012; Witt, 2009; Dosi et al., 2005; Simon, 1982). This *inevitable uncertainty* (Shackle, 1979) raises controversy over how to formulate a theory for

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technology policy which is useful enough for practical applications (Hall, 2012). As Foray (2012) and Trajtenberg (2012) point out, policy initiatives have been only superficially connected with the standard theory of technology policy (the Arrow-Nelson paradigm)[2]. Moreover, there are issues which this theory may not be able to face (*targeting* vs *neutrality* in technology policy). Perhaps the standard paradigm tackles questions related to the *rate* of inventive activity in a better way than those related to its *direction* (Nelson, 1962; 2006).

As Nelson (2012) explains, the contemporary economics of innovation highlights new features of technical change that were not clear to the standard paradigm pioneers. Some of these features are crucial for an extended theory of technology policy aimed at solving specific problems. Thus, (e.g.) this theory should incorporate the following ideas:

a) It is increasingly clear that technology develops as an *evolutionary process*;
b) *Extreme inter-field unevenness* is an intrinsic characteristic of technical change;
c) Technological progress emerges from the *co-evolution* of practice and understanding (Nelson, 2003; Dosi and Nelson, 2010; Dosi and Grazzi, 2010; Metcalfe, 2010).

Drawing upon these findings, Daniel Sarewitz and Richard Nelson (2008a, 2008b) have recently proposed three rules for technology fixes which, in our opinion, move an important step forward towards a new theory for technology policy. On the one hand, the SN-rules allow us to distinguish between problems that are likely to be solved through improved know-how, and those that are not. On the other hand, these rules may shed light on which technological options (among those aimed at fixing a problem) seem more promising as regards technological advance. The *Sarewitz-Nelson (SN) rules* may be stated as follows:

(1) The *cause-effect* rule. When trying to fix a problem through technology, it is a plus that the technology embodies a *strong link* between what it can do (if developed successfully) and providing a remedy for the problem. It may be a big plus that the link is supported by solid understanding.

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[2] Arrow (1962) and Nelson (1959) proposed that the externalities and moral hazard attached to the generation of knowledge could result in R&D underinvestment. IPR protection and subsidizing basic research followed as policy prescriptions. This vision still inspires influential approaches to economic growth (Aghion and Howitt, 1998).

(2) The *standardized technical core* rule. The possibilities for developing a technology to fix a problem increase when there is a *routinized* core which allows for operating with consistent versions of the technology in different contexts.

(3) The *enlightening testability* rule. A technology will advance smoothly when there are *sharp uncontroversial criteria to detect improvements* towards the solution of a problem. According to Sarewitz and Nelson, when these rules are not met, we should not expect technical solutions for specific problems within a reasonable time span.

In this paper, we argue that the SN-rules offer a compact proposal for technology screening which may be of help in problem-solving activities and in technology policy. Moreover, we claim that a deeper discussion of the rules, and an attempt to formalize their implications, may make it easier to apply the rules in different contexts and to connect them with (apparently) unrelated disciplines. In what follows, we analyze the relationships between the SN-rules and the co-evolution approach to technological change. Then, we discuss the necessary and/or sufficient character of the rules for technological advance. We find that these conditions are neither necessary nor sufficient for advances to be made. Instead, the SN-rules offer a method to detect which routes are technologically not advisable to solve specific problems. This helps us (by exclusion) to define groups of promising *parallel efforts* which should be carried out (Nelson and Winter, 1982; Nelson, 2012). Finally, we explore how to make the SN-rules operational in the realm of *targeting innovation policies*.

As we will see, the ambiguity which unavoidably accompanies the verification of the rules can be handled by considering recent advances in modern decision theory (Gilboa, 2004; Basili and Zappia, 2009). We draw upon these advances to illustrate how the SN-heuristic can be integrated within a wider process of technology choice in problem-solving activities. More precisely, drawing on the concept of *Fuzzy Set* (Zadeh, 1965, 1978), considering recent developments in *information fusion theory* (Brouson-Meunier *et al.* 1999, 2000), and incorporating alternative *epistemic states* of the decision maker (Ellsberg, 1962), we integrate the SN-rules within a process of technology assessment and choice.

Let us anticipate that what we propose is neither a Rational Choice model nor a SEU-model; instead, we delineate a procedure of detection (by exclusion) of sets of parallel efforts that, according to the SN-rules, seem promising for fixing (domain-specific) problems through technology. We obtain two indicators which can accompany the broad SN-heuristic. In the final part of the paper, we illustrate how to combine the SN-rules with our formal method by analyzing two cases: the so-called *dyes puzzle*, and the *energy storage problem*. As we will see, the formal approach not only complements but also sharpens the broad heuristic. For example, in the energy storage problem, we find subtle differences that we discuss in due course.

The structure of our work is as follows: we present the SN-rules in Section 2. In Section 3, we address the formal discussion of the SN-rules. We interpret the rules as a procedure for technology screening that can be integrated within a process of (problem-solving) oriented choice. We propose a formal foundation for this process and we obtain indicators which synthesize the results. These indicators have certain properties which allow us to systematize the application of the SN-rules in problem-solving activities. In Section 4, we illustrate the applicability of these indicators in technology choice and policy. Finally we present our conclusions.

2. The Sarewitz-Nelson Rules

When we state that technologies advance through the co-evolution of practice and understanding, we are assuming that there are mutually dependent selection processes at work in both realms (Nelson, 2005). Typically, primitive technical cores emerge, first, from empirical experience; then, practice and understanding co-evolve through mutual incremental learning (Vincenti, 1990). As Nelson (2008) points out, these processes of co-evolution do not operate with the same smoothness across human activities. Observing the evolution of different fields, we see that, in those sectors in which technological progress is rapid, the bundle of technical applications tends to evolve towards where understanding becomes strong, whilst scientific understanding advances and helps to improve practice by the experimental manipulation of current technologies (Nelson, 2011). In an attempt to detect *blocking* factors in the co-evolution processes underlying (technology-based) problem-solving activities, Sarewitz and Nelson (2008a, 2008b) have proposed three simple rules which draw upon contemporary explanations for technical change. Basically, the SN-rules we can presented as follows:

2.1.-The cause-effect rule (R1)

For a technology to be efficient in problem-solving, it is necessary that it incorporates the essential variables (cause-effect mechanisms) to solve the problem at hand. Thus, to invest in a specific technological direction, it is a big plus that there is a strong and clear link between what a technology will do (if it evolves successfully), and the remedy it can provide for the problem –a strong link reasonably supported by scientific understanding.

2.2.-The standardized technical core rule (R2)

In evaluating technological options for dealing with a particular problem, it makes sense to consider which ones seem amenable to developing a routinized core. Sarewitz and Nelson point out to the importance of standardized technical cores -procedures, prototypes- which contribute to evaluating the promise offered by a certain technology. Typically, primitive technical cores come first and, then, incremental learning takes place.

2.3.-The enlightening testability rule (R3)

A technological option will be more promising to fix a problem, the easier it is to evaluate its results with unambiguous criteria; we need clear notions regarding what improving and becoming (problem-solving) effective means.

As Sarewitz and Nelson (2008a, 2008b) argue, when technologies meet the three rules, we could expect R&D investments to lead to fast progress toward the resolution of the problem to which the investments are aimed. On the other hand, when the rules are not met, R&D programs should not be expected to succeed in the near future.

In their original formulation, the SN-rules are proposed as a broad heuristic emerging from an implicit theoretical framework. This formulation has advantages and disadvantages. On the one hand, it is flexible and intuitive and fits in with appreciative theoretical work. On the other hand, the possibility of sharpening the rules remains open, seeing up to what point they are applicable without ambiguity, and assessing how far they reach as part of a theory for technology policy. We shall devote Section 3 to discussing these issues. Later, in Section 4, we will show how it is possible to analyze specific cases by combining the SN-heuristic with our generalized method.

3. A formal discussion of the SN-rules

In this section, we argue that the SN-rules may be a very useful and compact instrument for interacting with domain-specific experts seeking to fix problems through technology. In subsection 3.1 we discuss the nature of the rules. Then, in 3.2, we pose our vision on how the SN-rules could be formally applied within a wider process of technology choice.

3.1.-Are the SN-rules sufficient and/or necessary conditions for technological advance?

Innovation studies allow us to state that *it is not correct to consider the SN-rules as a group of sufficient conditions that guarantee technological progress* (Basalla, 1988; Dosi and Nelson, 2010). As we have explained, the processes of technological change always have a degree of radical uncertainty and are affected by the appearance of unpredictable novelties. Given the complexity and non-determinist character of these processes, we cannot interpret the SN-rules as a group of conditions guaranteeing advances towards the technological resolution of specific problems.

On the other hand, the SN-rules *are not a group of necessary conditions either*. The history of technology shows that, sometimes, significant technological advances have been made even though the SN-rules were not fulfilled. One of the clearest examples is the discovery of the electric battery by Alessandro Volta; here, at least rules R1 and R2 were not met as there was no body of understanding supporting research, and the initial experimental results were coincidental, rather than being produced around a standardized technical core.

Therefore, we can state that the SN-rules are neither necessary nor sufficient conditions for technological advance. What they are, though, are rules which synthesize a group of features which may appear in one way or another in the co-evolution process underlying technical advance to solve specific problems. The sharper these features are, the smoother this process will be, and the easier for technological advance to fix problems. On the other hand, if these features do not appear, the co-evolution process may slow down or even become blocked. In any case, it seems clear that the element of chance in technology investments poses a big challenge for *ex ante* project selection. It is often the case that public agencies (or private agents) seeking to fix problems through technology have to ask experts to gather technical information; often they obtain controversial and vague answers. In what follows, we argue that the SN-rules are a useful map for policy-makers (and other agents) when they interact with experts. However, if these agents want to use the SN-rules in a systematic way: how should they proceed?

3.2.-The SN-rules as a screening procedure within a wider process of choice

Let us start by considering that R&D policy and technology choice are often problem-specific. Thus, experts in the field and users are the ones who "know" about the possibilities of specific technologies. In order to apply the SN-rules, it will be necessary to aggregate the information provided by the different actors regarding the SN-criteria. This poses the following question: how to build an aggregator which can capture the imprecise information resulting from the experts' opinion regarding the *three different issues* posed by the SN-rules? The ambiguity (inherent to novelty) in the answers, and the heterogeneous aspects captured by each of the SN-rules, typically lead to a fuzzy global perception regarding the *promisingness* of specific technologies in terms of the combined verification of the SN-criteria. Accepting that we need to integrate imprecise and diverse information for technology choice and policy-making (Steimueller, 2010; Mairesse and Mohnen, 2010; Foray, 2012) we suggest the use of formal instruments to support decisions in contexts of vagueness and ambiguity. In what follows, we argue that *fuzzy sets theory*, *aggregation operators* and *information fusion theory* provide ways to address this task.

Although we are aware of the limitations we face when formalizing heuristics, we believe that our formal proposal (see below) has some advantages[3]:

a) It facilitates and supports the unambiguous comprehension of the original appreciative Sarewitz-Nelson theory.

b) It allows us to combine and fusion information of different nature (regarding the issues tackled by each of the three rules). That is, we fusion (see below) information regarding such heterogeneous things as: the existence of a standard core; the sharpness of testing and evaluation criteria; or the strength of underlying applied sciences (see Bouchon-Meunier *et al.* 1999, 2000 for examples of information fusion in distinct fields).

c) Advantages a) and b) are very important when (as it is typically the case) the degree of verification of the SN-rules is unclear and, often, controversial.

d) Formalization helps to complete the original arguments, revealing interactions and implicit suppositions in the combination of the rules (see below).

We propose that *fuzzy sets*, *aggregation operators* and *information fusion* provide natural ways of dealing with the formal application of the SN-rules. We devote the rest of this section to presenting and discussing our proposal; we suggest specific functions which satisfy certain convenient conditions and reflect alternative states of the decision-maker. Then, we delineate a process of choice. Several indicators arise which could be of help in the analysis of real cases (more on this, later, in Section 4).

3.2.1.- Fuzzy Sets, aggregation operators and the SN-rules

<u>Fuzzy Set</u>.- In general, let X be a space of points, with a generic element of X denoted by x. Thus, $\mathrm{X}=\{x\}$. According to Zadeh (1965), a *fuzzy set* A in X is characterized by a *membership function* $f_A(x)$ which associates each point in X with a real number in the interval $[0,1]$, with $f_A(x)$ representing the “grade of membership” of x in A. Therefore, a

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[3] Given the limitations in a single paper, these advantages have been only preliminary exploited in this work (see below the interpretations of aggregation operators, the possibility of obtaining properties within the algebra of fuzzy sets, the future use of degrees of substitution, etc).

fuzzy set is a class of objects with a continuum of grades of membership between zero and one. The fuzzy set "A" is often known as $\mathrm{A} = \{\mathrm{X}, f_A(x)\}$.

In our specific case, we could apply the aforementioned definition as follows:
Let $\Phi = \{p_\tau\}$ with $p_\tau = (p_{1\tau}, p_{2\tau}, p_{3\tau})$, be the synthesis of expert opinions referring to the degree to which technology $\tau, (\tau = 1,2,...,n)$ verifies each one of the three SN-rules. Specifically, $p_{i\tau}$ $(i = 1,2,3)$ will reflect the numeric equivalent of a scale of opinion (regarding the level of fulfillment of rule i by τ) between "0" and "1". Given that the opinions regarding the fulfillment of the rules will include differences among experts, $p_{i\tau}$ could be the most frequent opinion, or the average of all the opinions given - regarding the fulfillment of rule i for technology τ.
Let us look now at how the deciding agent can characterize his/her decision-making problem. The agent must choose one (or several) of the alternatives $\tau, (\tau = 1,2,...,n)$ to reach a solution for a specific problem "P". As we have seen, each one of these alternatives is indirectly reflected in $\Phi = \{p_\tau\}_{\tau=1}^{n}$. Now, the question is how to combine the information in Φ to make a decision aimed at fixing "P". From Φ we can define a fuzzy set T.

Let $\mathrm{T} = \{\Phi, F_T(p_\tau)\}$ be the *fuzzy set "promising technological paths"* to solve a specific problem "P". Obviously this is a set which the final deciding agent must define from the information in Φ. The *membership function* $F_T(p_\tau)$ plays two roles: combining the information contained in Φ and, given the (often) imprecise information provided by experts, assigning to each technology τ a greater or lesser degree of membership to the *fuzzy set* of promising technologies, T.

The membership function $F_T : \Phi \rightarrow [0,1]$ assigns a degree of "greater" or "lesser" reliability ("promising-ness") to each technological option characterized by p_τ. It indicates to what extent the deciding agent considers each technological option τ, to be promising, given the information synthesized imprecisely in the corresponding triplet p_τ. The greater the value of $F_T(p_\tau)$, the greater the degree of membership of technology τ to the set of promising technologies. A value of “0” indicates zero membership, while at the other extreme, a value of “1” indicates a complete degree of membership. The deciding agent, though, can rarely decide whether a technology is simply promising or not; instead, they consider whether it is more or less promising to a certain degree $0 < F_T(p_\tau) < 1$.

The function $F_T(p_\tau)$ must fulfill certain convenient properties. In our case, we assume it to be continuous and increasing in each of the three arguments which make up p_τ.

Furthermore, we assume that the kind of order that function F_T establishes over set Φ verifies certain axioms both convenient and habitual in the literature on *aggregation operators* (Yager and Rybalov, 1996). To be specific, we shall suppose that function F_T verifies the following axioms (Detyniecki, 2000; Bouchon-Meunier *et al.*, 2000):

1) Boundary conditions: $F_T(0,0,0) = 0,\ F_T(1,1,1) = 1$.
2) Monotonicity: If $\forall j, p_{j\tau} \geq p_{j\tau'} \Rightarrow F_T(p_\tau) \geq F_T(p_{\tau'})$.
3) Symmetry: $F_T(p_{i\tau}, p_{j\tau}, p_{k\tau}) = \overline{F_T} \in [0,1]$ independently of order (i, j, k).
4) Absorbent element (or veto axiom): If $p_{j\tau} = 0$ for a j, then $F_T(p_\tau) = 0$.
5) Neutral element: If $p_{j\tau} = 1$ then $F_T(p_\tau) = F_T(p_\tau^{-j})$.

All these axioms admit relevant interpretations. The first one is coherent, on the one hand, with those quotas - “0” and “1” - normally established for membership functions. It also takes on two clear situations: in cases of a complete incompliance with the three SN-rules for a technology, our confidence in this option should be non-existent; however, the opposite case (maximum degree of verification of the rules), leads us to maintain the highest possible hopes for this technology.

The second axiom establishes that the function $F_T(p_\tau)$ must be such that, if one of the rules is verified to a greater extent for a technology (as compared with other options), with the other rules remaining the same, this would be reason enough to have a greater confidence in said technology. Clearly, if the deciding agent is told that two rules (with the third remaining the same), or even three rules, seem to be verified to a greater extent for one technology than another, then they would have more confidence in the former.

The third axiom indicates that all three rules are equally important, independently of the order the information is combined in.

The fourth axiom emphasizes the essentiality of the three rules. According to the veto axiom, if there is a complete non-compliance with any of the SN-rues, this would in itself block (at least in principle) the possibilities of progress of a technology, independently of the degree of compliance with the other rules.

Finally, the fifth axiom shows that, if one of the rules is verified to the highest degree, then any blocking of possible progress would be exclusively down to the degree of incompliance of the other two rules.

We can specify additional properties of $F_T(p_\tau)$ which, respecting the general axioms, allows us to better operationalize our approach. Taking the literature on *aggregation operators* (Detyniecki, 2000), we have opted to suppose that the information relative to the three SN-rules *combines in a multiplicative*[4] *way* in $F_T(p_\tau)$.

Thus, we consider *membership functions* $F_T(p_\tau)=\prod_{i=1}^{3} g_i^{\alpha_i}(p_{i\tau})$. The functions $g_i(p_{i\tau})$ can be interpreted as the contribution to the decider's confidence in technology τ induced by the level of compliance of τ with the *i*-SN-rule. The domain of these functions is $[0,1]$ and will be delimited between "0" and "1". We assume they are increasing, continuous and differentiable. Furthermore, the weights α_i will be positive and add up to "1".

This way of defining the *membership function* multiplicatively respects the axioms (1-5) of the *aggregation operators*, and adds more properties. Thus, let $F_T(p_\tau)=\overline{F_T}$ be constant.

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[4] Let us note that (e.g.) an additive procedure would not fulfill the established axioms. Thus, the multiplicative form is not trivial; on the contrary, it is one of the few ways to capture formally the mutually reinforcing interaction of practice and understanding underlying technology development (as stated in the SN-rules).

Setting $dF_{\mathrm{T}} = 0$ for the case of the multiplicative function, it is simple to check:

$$-\frac{\frac{dg_k}{g_k}}{\frac{dg_j}{g_j}} = \frac{\alpha_j}{\alpha_k} \quad j \neq k, \quad j,k = 1,2,3. \tag{1}$$

The ratio between the weights is dependent on the specific technology-case studied and must be empirically detailed by the experts. But $\frac{\alpha_j}{\alpha_k}$ allows for a general interpretation:

It is an *elasticity of substitution between the contribution of any two of the SN criteria to the general confidence in the efficiency of a technology*. For example, in a case where we believe we can count on a technical core (R2), but it turns out to be ineffective in practice, the corresponding elasticities will inform us as to what extent recent scientific advances (R1), or the confirmation of new criteria of improvement in this technology (R3) may allow to maintain the confidence in this technology aimed at fixing a certain problem.

To sum up, functions $g_i(p_{i\tau})$ can be interpreted as *functions of reliability* on technology τ, vía the degree of compliance with the *i*-th SN-rule. The multiplicative mixture of the reliability functions allows us to obtain a *membership function* $F_T(p_\tau)$. In the following subsection, we shall give specific forms to the reliability functions $g_i(p_{i\tau})$ so as to elaborate indicators which allow us to systemize the application of the SN-rules.

3.2.2.- Specific functions and the wider process of choice

We shall begin by proposing different specific shapes (which, obviously, do not cover all the possibilities) for functions $g_i(p_{i\tau})$. The multiplicative mix of these functions will give us the specific shape of $F_T(p_\tau)$. We assume that the specific shapes of the reliability functions depend on the *epistemic state of the agent* (Ellsberg, 1962; Shackle, 1979) when this has to choose between uncertain technological alternatives to solve a problem. That is, the shapes will depend on the decider's profile: if they are more or less cautious when faced with uncertainty; their aversion to ambiguity and vagueness; the pressing need to solve social problem “P”, etc.

Then, looking at the epistemic state of the decider, we can consider, firstly, one type of specific functions common in the literature on fuzzy sets: the S-shaped (Zadeh, 1978; see also Jarne *et al.* 2005, 2007) functions. As a specific example of *sigmoid reliability functions*, we shall consider the following function:

$$g_i(p_{i\tau}) = 3p_{i\tau}^2 - 2p_{i\tau}^3 \qquad (2)$$

In this case we would have the corresponding membership function associated to the fuzzy set $\mathrm{T} = \{\Phi, F_T(p_\tau)\}$. The membership function for the case of equal weights would be:

$$F_T(p_{1\tau}, p_{2\tau}, p_{3\tau}) = \prod_{i=1}^{3}\left[3p_{i\tau}^2 - 2p_{i\tau}^3\right]^{\frac{1}{3}} \qquad (3)$$

It is interesting to point out that function (2) is defined for p_τ, is delimited between “0” and “1”, and is continuous, differentiable and increasing. It is compatible with all the axioms we set for the membership and reliability functions. Function (2) has interesting concavity properties. It is strictly convex between “0” and “0.5”, and strictly concave between “0.5” and “1”. At point “0.5”, it presents a point of inflexion[5], and it is verified that $g_i(0.5) = 0.5$.

Functions (2) and (3) reflect situations in which the decider slowly increases their level of confidence as they accumulate evidence of an increasing compliance - slowly at first - with the SN-rules. This would be the case of a decider fearful or prudent when faced with ambiguity, cautious faced with a lack of unanimity, vagueness, etc. (Ellsberg, 1962; Gilboa, 2004). This fits with the strictly convex part of function (2). It also seems reasonable that there is a point “I” (which, without losing generality, we suppose to be I=0.5) after which the function will be strictly concave, indicating that, from a sufficient degree of compliance with SN-rules onward, the decider will become optimistic regarding the promising character of the technology.

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[5] It is possible to generalize these features by defining families of sigmoidal functions (Jarne *et al.* 2005, 2007). We propose function (2) for the sake of simplicity.

Although the S-shaped function is very habitual in the literature, we can consider other alternatives reflecting different *epistemic state*s of the decider. Thus, we can consider *strictly concave reliability functions*. For this case, in accordance with the hypothesis of *satisficing behavior* (Simon 1982), we can consider situations where the decider is very unhappy with the present state of affairs and wishes, needs, new ways to proceed. In this sense, when the need to solve a certain problem, "P", is urgent or when the dissatisfaction with the current situation has surpassed certain thresholds, we can imagine that the motivation to search for new ways of doing things will grow quickly and will increase through the degree of compliance with each of the SN-rules. There is a tendency to go with the search for new ideas as soon as the first signs of viability are observed.

Another justification for this kind of functions can be found in those situations Scitovsky (1976) called situations of *relative deprivation*. The motivation to search for novelty increases, somehow paradoxically, with the degree of relative *deprivation* of the deciding agent such that, in non-stimulating environments - those in which nothing has happened for a long time - incentives can quickly be triggered which make agents try new things. In these cases, the decider does not expect a 100% guarantee, but is happy with just a certain degree of reliability (identified with *sufficient guarantee).* After a certain, not particularly high, level of $p_{i\tau}$, the function of reliability would be near "1". Even low levels of $p_{i\tau}$ would generate high levels of reliability through the compliance with the *i*-rule. We are faced with an optimistic decider, or one very determined to try something new, who, with little evidence, evaluates the technologies as promising. A simple example of this kind of functions, which would verify all our previous suppositions and axioms, would be:

$$\tilde{g}_i(p_{i\tau}) = \frac{1-e^{-p_{i\tau}}}{1-e^{-1}} \qquad (4)$$

This kind of reliability function, for the simplest case of $\alpha_i = \frac{1}{3}, \forall i$ would give way to a membership function:

$$F_{\tilde{T}}(p_{1\tau}, p_{2\tau}, p_{3\tau}) = \prod_{i=1}^{3}\left[\frac{1-e^{-p_{i\tau}}}{1-e^{-1}}\right]^{\frac{1}{3}} \qquad (5)$$

which, in turn, would be associated with the corresponding fuzzy set of promising technologies:

$$\tilde{\mathrm{T}} = \{\Phi, F_{\tilde{T}}(p_\tau)\} \ .$$

Once the experts' information has been collected and processed regarding the degree of compliance with SN-rules, and after the decider has evaluated the confidence in the future of a certain technology to fix a problem, the decider can merge all this information and define the fuzzy sets $\mathrm{T} = \{\Phi, F_T(p_\tau)\}$, $\tilde{\mathrm{T}} = \{\Phi, F_{\tilde{T}}(p_\tau)\}$, etc.

The Process of Choice

After defining the fuzzy set of promising technologies, *the decision making* is not simple. In all cognitive domains in which novelty, mistakes and surprises may occur, all decisions are contingent on the intervention of factors as yet unknown. In contexts of radical ignorance, the optimization hypothesis (at least in its simplest shapes) does not appear advisable. *Instead of putting technologies in a preference order* according to the level of "promise" of each one, and choosing just the most promising technology at that moment, deciding agents could establish a certain *threshold of minimum reliability, (belief or confidence)*; that is, a minimum threshold of reliability or incentive for action $\hat{F}$, such that they could decide to carry out - via *sufficiently promising parallel efforts* - the technologies which surpass this threshold. The value of $\hat{F}$ may depend (e.g.) on budgetary constraints. In this way, the *set of parallel efforts to be developed* could be defined as:

$$\mathrm{T}^{*} = \left\{\tau : p_\tau \in \Phi \wedge F_T(p_\tau) \geq \hat{F}\right\} \quad \text{or}$$

$$\tilde{\mathrm{T}}^{*} = \left\{\tau : p_\tau \in \Phi \wedge F_{\tilde{\mathrm{T}}}(p_\tau) \geq \hat{F}\right\} \qquad (6)$$

according to the *epistemic state of the decision-maker*, which defines the specific fuzzy set depending on the shape of its membership function. This would be the final decision of the deciding agent: a set of *parallel efforts* which move them sufficiently into action and are simultaneously developable to fix a problem (Nelson and Winter, 1982).

Note that the membership functions (3) and (5) can be interpreted as indicators of the degree to which we can rely on a specific technology managing to solve a specific social problem “P”. In the following section, we shall apply the functions (3) and (5) as indicators of expected viability and we refer to them as indicators F_1 and F_2. That is, for each technological alternative we must calculate:

$$F_1(p_1, p_2, p_3) = \prod_{i=1}^{3}\left[3p_i^2 - 2p_i^3\right]^{\frac{1}{3}} \qquad (7)$$

$$F_2(p_1, p_2, p_3) = \prod_{i=1}^{3}\left[\frac{1-e^{-p_i}}{1-e^{-1}}\right]^{\frac{1}{3}} \qquad (8)$$

The deciding agent will tend to define the set of parallel efforts which can be sufficiently promising by choosing the technological route(s) which present(s) sufficiently high values of (7) and/or (8). In Section 4, we show, with two specific examples, how we would apply this approach to define the group of parallel efforts in real situations.

4. Tentative applications of the SN-rules

In this section we offer two applications of the SN-rules integrated in our wider process of choice. In the first one, we compare the technology behind the production of traditional hand-crafted dyes (a period lasting until about halfway through the 19th century) with the later technology of synthetic or artificial dyes (Murmann, 2003). At that time, the best path for dye innovation and production was not clear at all. Nowadays, we know that synthetic dyes did prevail in the end; but this was not obvious at all in a radically-uncertain environment towards the end of the 19th century (Nelson and Sampat, 2001).

This first example shows how the technology behind hand-crafted dyes barely fulfilled the SN-rules, thus explaining the low level of development and advance of know-how in this activity until halfway through the 19th century. On the other hand, from that time onwards a clear compliance with the SN-rules can be observed in the new technology of synthetic dyes. This is coherent with the advance of know-how in this activity towards the end of the

19th century and beginning of the 20th century.

In our second example, we compare different technological alternatives under consideration at present to solve the problem of large-scale energy storage (see Lindley, 2010; Ibrahim *et al*. 2008). In this case, we use the SN-rules to explain which route of technological advance could be most promising in terms of its potential development to solve the energy storage problem. As we shall see, our conclusions indicate that: at present, there are no technological paths sufficiently promising to guarantee a solution for the problem (conclusion from the heuristic analysis). Nevertheless, we can sharpen a bit this conclusion through the formal method. Thus, as we will see in 4.2, one, or even two technologies (depending on the decider's profile and, in any case, with a medium-low promisingness), could be promoted if society (or policy-makers) do not want to develop a more ambitious and valorous search for solving the problem of large scale energy storage.

Let us note that we consider these applications as attempts at illustrating the potentialities of the SN-rules within a wider process of choice. For future deeper applications of the SN-rules, it will be the relevant specialists who assess the degree of compliance with the three rules and weigh up the convenience of applying the indicators.

4.1.- Alternative technologies for dye production.

In this first case, we compare the technology behind the production of traditional hand-crafted dyes, with the later technology of synthetic dyes. Nowadays, we know that synthetic dyes prevailed in the end; but this was not clear in the uncertain environment at the end of the 19th century. Let us analyze the case by combining the SN-heuristic and the formal method.

Until roughly halfway through the 19th century, dyes were obtained from natural products (plants, insects, minerals) grown or found in certain geographical regions. The procedure for making or extracting these dyes was based on know-how exclusively acquired through practice and after a long process of trial and error (sometimes over centuries). This meant that the range of colors and the specific characteristics of each one - wash-resistance, brightness etc - were extremely dependent on the natural product used and the skills and knowledge of the workmen who produced it. That is to say, the result of the production process was highly context-dependent. This situation implies that neither the exact mechanisms underlying the production process, nor the precise chemical composition of the products were known. There was very little understanding of the key cause-effect mechanisms underlying the natural production of dyes. This leads us to conclude that the (R1) SN-rule was not verified sufficiently in the traditional artisanal manufacture of dyes.

In a similar way, it is difficult to confirm the existence of a standardized technical core; if one existed, it would be of a regional or local character. This means there was a low level of compliance with the (R2) SN-rule. Finally, the scant theoretical knowledge of the molecular structure of dyes and the processes of obtaining them offered few possibilities of improvement via guided-systematic experimentation and replication of practice. Any improvements were more likely to come from a localized and "blind" process of trial and error. This kind of experimentation went on, but we cannot consider it to be systematically enlightening; we can conclude that, for natural dyes, there was a low level of compliance with the (R3) SN-rule too. As a consequence, the traditional process of dye production (up to the mid 19th century) offered a limited number of colors which were difficult to obtain and, in general, presented problems regarding their adherence properties and light-resistance etc. It is also worth remembering the scant evolution of these production processes until the last third of the 19th century.

Towards the mid 19th century, a coming together of certain characteristics favored the swift development of know-how regarding the production of synthetic dyes. These circumstances can be interpreted as coinciding with an ever-greater fulfillment of the SN-rules.

Thus, firstly, the development of organic chemistry and chemical engineering made it possible to find the molecular structure and exact composition of the dyes, leading to their chemical production in laboratories. The development of these scientific disciplines led to the understanding of the key cause-effect mechanisms underlying the production of dyes. Certain fundamental technological principles were laid down and the replicability of the technology was increased independently of the context of production. These changes clearly represent a significant fulfillment of the (R1) SN-rule.

Secondly, knowledge of the structures and molecular compositions of dyes, and the identification and definition of the processes of manipulation of the *active components*, allows us to state that a standardized technical core starts to appear - initially for specific colors such as indigo and mauve, but soon generalized to cover all the palette of colors. The technical core would be the process of searching for the active components - as well as the substances themselves- which determines every color, together with the molecular manipulation process for greater adherence, brighter colors etc. These developments represent a high fulfillment of the (R2) SN-rule in the second phase of dye chemistry.

Finally, it is well-known in the history of technology that the concept of *industrial R&D lab* emerges from the advances in organic chemistry and their applications (the dye industry; see Nelson and Sampat, 2001). The degree of testability emerging in this period of synthetic production of chemical products (including dyes) is very high. Organic chemistry allowed the understanding of basic scientific mechanisms, and chemical engineering solved multiple problems for scaling-up production substituting old processes for new, more efficient, ones. This all happened relatively quickly (between the end of the 19th century and the First World War) as the experimentation around technical cores was fast, clear, and very efficient. We can state, therefore, that there was a high level of verification of the (R3) SN-rule, which contributed to fostering the social acceptability of synthetic dyes. We can see that the increasing verification of all three rules (R1, R2 and R3) does not happen independently, but rather it reflects a process of co-evolution between domains of interdependent knowledge which act as catalysts for the progress in know-how. That is, once the (routinizable) technical core emerged, the co-evolution between practice and understanding fostered by R&D was very successful.

All the above-mentioned could be expressed - merely for illustrative purposes - in terms of the *methodology* we have proposed above. Hence, in this case, we could define our set of technological alternatives for dye production: *natural dyes* and *synthetic dyes*. Now we should consider the degrees of verification of each of the three SN-rules. To avoid entering into the identification of proxy variables, we assess the degree of fulfillment of the rules in each case using three levels; low, medium and high. We can assign to p_i the three values 0.2, 0.5 and 0.8. The previous discussion on the features of natural dyes and synthetic dyes, allows us to synthesize the information in a set Φ:

$$\Phi = \{p_{ND}, p_{SD}\} = \{(0.2,0.2,0.5);(0.8,0.8,0.8)\}$$

If we use the functions F_1 and F_2 in (7) and (8), we obtain Table 1:

Table 1: Alternative technologies – dyes

Alternatives/Rules	**R1**	**R2**	**R3**	***F₁***	***F₂***
Natural dye	Low (0.2)	Low (0.2)	Medium (0.5)	0.1751	0.3693
Synthetic dye	High (0.8)	High (0.8)	High (0.8)	0.8958	0.8709

Note that Table 1 represents the two *fuzzy sets of promising technologies* (with each one corresponding to a possible epistemic state of the deciding agent):

$$\mathrm{T} = \{\Phi, F_1\} = \{(0.2,0.2,0.5),0.1751;(0.8,0.8,0.8),0.8958\}$$

$$\tilde{\mathrm{T}} = \{\Phi, F_2\} = \{(0.2,0.2,0.5),0.3693;(0.8,0.8,0.8),0.8709\}$$

If we look at the levels of membership given by $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ for each technology (see Table 1) we can see that both the appreciative analysis and the quantification in alternative epistemic states reveal clearly that, in terms of easy technological advance, the production technology of *synthetic dyes* was much more promising than that of traditional methods. Therefore, it would have been advisable to back this technological option.

In terms of our methodology and taking $\hat{F} = 0.5$ for the sake of simplicity, we can define the set of parallel efforts as:

$$\mathrm{T}^* = \tilde{\mathrm{T}}^* = \{SD\}.$$

Nowadays, we know that historically (as predicted here) synthetic dyes did prevail in the end, but this was not so obvious *ex ante* towards the end of the 19th century. As we shall see in the following example, the proposed methodology reveals more information in very unclear situations. We conjecture that the usefulness of our approach may increase (in future applications) as the number of technological alternatives becomes larger.

4.2.- The problem of energy storage.

Our second application deals with the so-called *energy storage problem*. Nowadays the need to integrate renewable resources into modern energy systems is putting pressure on the development of large-scale storage technologies. Large capacities for energy storage are needed to match generation and demand with energy sources like wind or the sun. This problem has not been resolved technologically (Ibrahim *et al.*, 2008). At present there are several options on the table, but none of them has been sufficiently developed. We have evaluated five options: Pumped hydropower (PH), Batteries (B), Mechanical flywheels (FW), Compressed-air energy storage (CAES) and Superconducting magnetic energy storage (SME). As we will see, the Sarewitz-Nelson rules offer an ideal method to assess the potential of these different options.

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 one. When the water stored in the upper reservoir is released, it is passed through hydraulic turbines to generate electricity. High and low-lying lakes are used as natural elements playing a role in this technology. The supporting science for this technology is Fluid Dynamics, which is a *solid body of understanding*. Therefore, PH partly verifies the (R1) SN-rule. On the other hand, although there exists a *standardized technical core* (standard PH-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 dependence as well as the fact that it is impossible for PH to be feasible as an overall solution for the storage problem (it would call for an unfeasibly large amount of reservoirs) leads us to conclude that PH does not fully satisfy the (R1) SN-rule. Furthermore, PH-technology shows a low level of fulfillment of the (R3) SN-rule. It is not possible to experiment cheaply, efficiently and in a socially acceptable climate around the technical core.

Battery Energy Storage (B).

There are several types of batteries: Lead-Acid (LA) batteries, Lithium-ion (Li-ion B) batteries, Sodium-Sulphur (NaS), etc. 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. The body of understanding supporting batteries is Electrochemistry, a *solid body of understanding*. In addition, batteries are non-context dependent. This would, apparently, lead us to conclude that batteries verify the (R1) SN-rule. However, Electrochemistry allows us to see a *scalability problem* if we try to obtain batteries which act as large-scale storage devices. The dimensions and requirements for batteries to perform as a large-scale storage system are enormous; they are physically unfeasible. Therefore, battery technology only satisfies the (R1) SN-rule to a medium level. On the other hand, given that all batteries basically function in the same way, we can affirm that there is a *standardized technical core* (verifying the (R2) SN-rule), but this is conditioned by the scalability problem. Thus, we find a medium level of rule-satisfaction. Finally, regarding the (R3) SN-rule, we can affirm that *experimentation* with small batteries is easy, since the standardized technical core (at least on a small scale) exists. However, in spite of the advances which could arise from batteries, it is not likely that they can become a sole storage technology on a large scale. Therefore, we consider that this technology only offers a medium level of fulfillment of the R3-rule too.

Mechanical flywheels (FW).

A flywheel is a flat disk or cylinder that spins at high speeds, storing kinetic 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, a well-known *body of understanding*. However, we cannot affirm that this technology incorporates the *"basic go"* to solve, as a sole provider, the energy storage problem (so it fulfills the (R1) SN-rule only to a medium level). This is because, from the body of understanding, it is clear that in practice the 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.

This leads us to conclude that *there is no unique standardized technical core* (so the (R2) SN-rule is only complied with to a low level). This is so because the highly specific FW devices are always oriented either towards power or storage.

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 unavoidable physical limitations making it extremely difficult to reach a suitable size, mean we should not expect great advances from experimentation with FW as a large-scale storage technology. Therefore, FW only fulfills the third (R3) SN-rule to a low level too.

Compressed-air energy storage (CAES).

CAES-technology uses off peak electricity to compress air into either an underground structure 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. The underlying body of knowledge is Thermodynamics.

Man-made storage-reservoirs are very expensive and, thus, CAES locations depend on the existence of suitable geological formations. CAES facilities are extremely *dependent on* *context* and this leads us to affirm that CAES only verifies the (R1) SN-rule at a low level.

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 requirements of the land. Then, we may consider that CAES verifies the (R2) SN-rule at a medium level.

Finally, *experimentation* and *replication* with this technology is not easy. Testing with CAES-technology is highly dependent on finding suitable sites; it is expensive; and, above all, it is socially controversial - for both environmental and safety reasons. Consequently, we can affirm that CAES-technology only verifies the (R3) SN-rule at a low level.

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. A typical SME storage system has three parts: a superconducting coil; a power conditioning system; and, a cryogenically cooled refrigerator. The magnetically stored energy can be released back to the grid by discharging the coil.

Superconducting technology is a relatively new technology but presents problems as a possible large-scale storage solution. Firstly*, there is not only one standardized technical core*. To be more precise, there are currently two types of superconducting storage devices: those made from low-temperature superconductors, and those made from high-temperature superconductors. Therefore, the (R2) SN-rule is only fulfilled at a low level.

Neither is there a solid *body of understanding* underlying superconducting technology. Thus, while low-temperature superconductivity is explained by the *BCS* theory, this theory is not able to explain high-temperature superconductivity. Without a solid body of understanding, we can affirm that this technology verifies the (R1) SN-rule at a low level.

Finally, *experimentation* around superconducting energy storage devices is difficult (low-superconducting devices need to be cooled below 7.2K, and high-superconducting ones below 150K). Therefore, the (R3) SN-rule is only fulfilled at a low level, since it is not possible to experiment cheaply, quickly and firmly on existing technical cores.

Drawing upon the previous appreciative discussion, we can now apply the formal methodology that we have proposed in Section 3. We assess each of the SN-rules for each technological option using three levels: low, medium and high. To be specific we assign values of 0.2, 0.5, and 0.8 to p_i at the three levels. For simplicity, we sum up the *fuzzy sets of promising technological options* in Table 2:

Table 2: Technological alternatives of energy storage

Alternatives/Rules	**R1**	**R2**	**R3**	F_1	F_2
PH	Medium (0.5)	High (0.8)	Low (0.2)	0.3592	0.537
B	Medium (0.5)	Medium (0.5)	Medium (0.5)	0.5	0.622
FW	Medium (0.5)	Low (0.2)	Low (0.2)	0.1751	0.3693
CAES	Low (0.2)	Medium (0.5)	Low (0.2)	0.1751	0.3693
SME	Low (0.2)	Low (0.2)	Low (0.2)	0.1038	0.2865

We can clearly see these sets reflected in Table 2:

$$\mathrm{T} = \{\Phi, F_1\} \ , \ \tilde{\mathrm{T}} = \{\Phi, F_2\}.$$

Considering Section 3, we can obtain from Table 2 the sets of parallel efforts (depending on the epistemic state of the decision-maker):

$$\mathrm{T}^* = \{B\} \ , \ \tilde{\mathrm{T}}^* = \{PH, B\}.$$

Note that, in this case, the two sets do not coincide. This is because, in this situation, while a “cautious” decider would only bet on Batteries (and reluctantly so, due to its low level of “promising-ness” 0.5), a more optimistic decider would go with Batteries and Pumped Hydro. Observing Table 2, it is clear that the levels of membership of the chosen technologies are much lower than in our first case (dyes). The sets of *parallel efforts* do not inspire so much confidence as in subsection 4.1. It is to be pointed out that the epistemic state of the decision-maker significantly conditions the decision and that, given the chosen threshold $\hat{F} = 0.5$, none of the chosen technologies in T^* and $\tilde{\mathrm{T}}^*$ clearly exceeds this value. Finally, as is also to be expected, the values of F_1 for all the technologies in Table 2 are lower than those of $\boldsymbol{F_2}$, given that the “cautious” decider assigns levels of reliability lower than a decider who is more prone to innovate.

The formal discussion allows us to detect the best options and their limitations easily. What is more, it complements and facilitates comprehension of the prior appreciative analysis. Given all the aforementioned, and the low/medium values of our indicators, we cannot assure that the analyzed technologies are likely to fix the large-scale storage problem within a reasonable time frame. Nevertheless, and depending on the decider’s profile, batteries and pumped hydro emerge as more (tightly) promising options.

5. Conclusions

In our introduction we pointed out that innovation studies have shown how technological progress evolves surrounded by radical uncertainty and showing extreme unevenness in different fields. Reflections on the development of human know-how have led an increasing group of scholars to characterize technological change as the result of a co-evolution process between bodies of understanding and practice. These recent findings should be incorporated in a new extended theory for technology policy. Richard Nelson and Daniel Sarewitz (2008a,b) have taken a significant step in this direction. They propose three rules for technological fixes which we present as: (R1) the cause-effect rule; (R2) the standardized technical core rule; and (R3) the enlightening testability rule.

In our work, we started out in the belief that a deeper formal discussion of the rules, together with an attempt to formalize their implications, could make their application easier and systematize their use in different technological fields. We opened the formal discussion by reconsidering the relationships between the SN-rules and the co-evolution approach to technological change. Next, we discussed the necessary and/or sufficient character of the SN-rules, reaching the conclusion that what the rules do synthesize is a collection of features which appear more or less defined in the co-evolution process underlying technological progress. The more defined these features are in a specific case, the smoother this process will be, and the easier it will be for technological progress to emerge and fix specific problems. On the other hand, if these features are not found (that is, if the degree of verification of the rules is low, or even non-existent), then the process of underlying co-evolution can slow down or even stop. Thus, we can state that the SN-rules allow us to detect certain catalyzing and/or blocking factors regarding technological advance as a co-evolution process.

These first conclusions lead us to consider the SN-rules as a procedure for technology screening which can be integrated in a wider process of technology choice and problem-oriented policy-making. We are aware that the decision framework we propose is not the only one possible, but it does integrate new aspects: the SN-rules as a screening method, alternative epistemic states for the decision-maker in the reliability functions, a well-supported procedure of mixing information until the fuzzy sets of promising technologies are arrived at, and the application of the concept of parallel efforts in a context of radical uncertainty. The framework we propose is consistent with empirical knowledge regarding the way technological progress evolves and, as its foundations, properties and limits are explicit, we believe it can provide a contribution towards a theory for technology policy.

After proposing this formal-theoretical framework which integrates the SN-rules, we apply it - as a complement to the appreciative application of the SN-rules - to two interesting cases. The first one (the case of dye production techniques towards the end of the 19th century) is a classic and well-studied example of dynamic competition between alternative technology options in a radically uncertain context. Applying the SN-rules together with the quantitative analysis leads to the clear choice *ex ante* of the technology which did in fact become the dominant one. Moreover, the stagnation of the dye industry until the end of the 19th century can be partially explained by its low compliance with the SN-conditions. On the contrary, the growth of the dye industry from then onwards is seen through an increasing level of verification of the SN-rules.

Our second case (applied to the energy storage problem) offers us information about a present-day unresolved problem which raises questions of technology policy in real time. In this case, applying the SN broad-heuristics we obtain that none of the chief alternatives currently on the table is sufficiently promising to ensure a clear solution for the storage problem. We sharpen a bit this conclusion through the formal method. Thus, as we have shown in Section 4, one (*B*), or even two (*B*, *PH*) technologies (depending on the decider's profile and, in any case, with a tight promisingness), could be promoted if we do not engage in developing a true ambitious and valorous solution for the large scale storage problem. Both complementary conclusions may indicate two things: the threat of (almost) implausibility hangs over the current tentative solutions - which makes it necessary to find something significantly new for the future; or we need to combine (in a way we do not know well yet) several of the current alternatives. This involves considerable difficulties. Whatever the case may be, given the importance of this problem, and bearing in mind the difficulties and delay in finding a solution to it, we believe it is essential to start up a social and scientific debate which goes much deeper than current debates regarding this issue.

Finally, our closing reflection is that, if we agree with Metcalfe (2014) in that modern economies are *ignorance economies* - in which knowledge is disseminated among highly specialized teams who know a lot about few matters - then, improving the coordination mechanisms between different realms becomes crucial. This calls for new theoretical concepts and fresh policy instruments. We believe that the Sarewitz-Nelson rules and the efforts to systematize these criteria represent important steps in this direction.

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