A formal discussion of the Sarewitz-Nelson rules

Isabel Almudi[1]*, Francisco Fatas-Villafranca*, Julio Sanchez-Choliz*

* *University of Zaragoza. Gran Via 2, 50005 Zaragoza, Spain.*

Abstract

In this paper, we formally discuss the *Sarewitz-Nelson rules for technological fixes* (SN-rules). In their original form, the SN-rules are formulated from practical experience and 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. 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 part of a contribution to the economic theory of technology policy. From a formal point of view, we discuss the necessary and/or sufficient character of the rules and we use concepts from the theory of fuzzy sets to obtain quantitative indicators which can facilitate the application of SN-rules. We finish our work by presenting two tentative applications.

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[1]IA (ialmudi@unizar.es). FFV (ffatas@unizar.es). JSC (jsanchez@unizar.es).

1. Introduction

In many important circumstances of life, agents have an incomplete or even wrong understanding of the environment in which they operate. Specifically speaking, this is the case for contexts in which *genuine novelties* can occur (Witt, 2009). In these situations, standard decision-making procedures (Rational Choice Theory, SEU-Theory, Game Theory, Bayesian Learning) are of little help (Simon 1982; Dosi *et al*. 2005). As Arrow (2012) and others recognize, the *ignorance and genuine uncertainty* that agents face in innovative environments challenge, in an intrinsically difficult way, the processes of problem solving, policy-making and choice.

This *inevitable ignorance* (Shackle, 1979), inherent to radically innovative environments, has raised controversy over how to formulate a theory for technology policy which is wide-reaching and useful enough for practical applications (Hall, 2012). As Foray (2012) points out, policy initiatives have been only superficially connected with the standard economic theory of technology policy (the so-called *Arrow-Nelson paradigm*[2]), and there are certain challenges which this paradigm may not be able to answer sufficiently: for example, the case of formulating *targeting* policies, in a period of Grand Challenges, instead of maintaining *neutrality* in technology policy (Trajtenberg, 2012). It could be said that the Arrow-Nelson paradigm answers those questions related to the *rate* of inventive activity in a better way than those related to its *direction* (Nelson, 1962). This is so, or at least in part, due to the fact that the Arrow-Nelson paradigm (as a piece of its time) arose from a theoretical framework particularly focused on some (but not all) of the fundamental mechanisms of technological progress (Nelson, 2006).

As Richard Nelson (2012) himself explains, the Arrow-Nelson (benchmark) paradigm for

[2] To sum up, Arrow (1962) and Nelson (1959) proposed that the externalities, the acute risk and the moral hazard attached to the funding and production of new knowledge could result in underinvestment in R&D and in a lower than socially-desirable innovation rate. Therefore, IPR protection and subsidizing R&D in basic activities followed as policy prescriptions. These paradigms and prescriptions still lie at the very basis of the most influential approaches to innovation economics and growth (Aghion and Howitt, 1998).

technology policy did not consider, amongst other aspects, the following three features of technological change which have been confirmed over the last fifty or sixty years: firstly, radical uncertainty precludes the application of the *optimization hypothesis* in technology choice and policy, since the bounds of the still unknown (and unknowable) prevent the agents from deciding *ex ante* over a defined set of (and even probabilistically stated) alternatives; secondly, far from being a fully designed - or, at least, deterministically tractable - dynamic process, it is increasingly clear that technical change develops as an *evolutionary process*; finally, the *extreme unevenness* in the rates and patterns through which human know-how progresses in different fields is an unavoidable characteristic of technical change. Contemporary innovation scholars increasingly recognize these crucial features, while the (Neo-classically-inspired) Arrow-Nelson framework could not at the time it was developed. Nowadays, the aforementioned findings suggest that, to improve our understanding and management of technology choice and policy (including our ability to focus R&D efforts in certain directions), we must reflect on what technology itself is, how it progresses, and how we can deal with technology assessment and decision methods (Steinmueller, 2010; Dosi and Grazzi, 2010).

Recent contributions condensing these findings insist that we could take a step forward in our theories and management of technology policy if we considered that technical change emerges from the *co-evolution* between domain-specific bodies of technical practice, and understanding (Dosi and Nelson, 2010; Metcalfe, 2010). This means, firstly, that the uncertainty inherent to both realms leads to a *diversity* of efforts being carried out at any time; secondly, the co-evolution approach also implies that new practices and ideas *compete* between themselves and with established standards in their respective cognitive realms; and, finally, any co-evolutionary explanation for technological advance admits that those techniques and ideas that end up prevailing are the *ex-post result of interdependent selection processes* linking practice and understanding (Nelson, 2003) [3].

[3] Many recent arguments involving the concept of co-evolution incorporate elements of the perspective on technology stated by Rosenberg (1982), and can be seen empirically through specific cases like (e.g.) technical change in the realm of aircraft design and manufacturing (Constant, 1980; 1986).

In recent contributions along these lines, Daniel Sarewitz and Richard R. Nelson (2008a, 2008b) have taken a deeper look at this co-evolution approach to technological change, and have proposed three simple rules to distinguish between those problems that are likely to be solved through improved know-how and those that are not. Likewise, these Sarewitz-Nelson (SN) rules can shed light, *ex ante,* on which alternatives (among those which aim to solve a problem through technology) seem more promising as regards technological advance. As we shall try to show, the SN-rules can be interpreted as a *procedure for technology screening*, susceptible *of becoming integrated in a wider process of technology choice and policy*. This conception will allow us to assess the nature and applicability of the SN-rules in different contexts, and will place this in line with previous contributions to the economic theory of technology policy.

In brief, the *Sarewitz-Nelson rules* are the following:

(1) The *cause-effect* rule. A technological option can be expected to offer an efficient solution for a specific problem if the link between what a technology will do (if it is developed successfully) and providing a solution for the problem is clear and strong, and our understanding of this causal link is reasonably well supported by scientific evidence.

(2) The *standardized technical core* rule. This rule establishes that the possibilities for technological progress increase when there is already a standardized technical core (a routinized core), embodied in a device, prototype or procedure, which allows experimentation and the replication of a reasonably stabilized version of the technology in different contexts.

(3) The *enlightening testability* rule. This rule states that a technology will advance smoothly when there are relatively sharp and uncontroversial criteria to discriminate quickly, cheaply and objectively between improvements reached through R&D, by on-line learning or by learning through doing and/or using.

Sarewitz and Nelson suggest that when we find technological alternatives - or specific social problems - which do not comply with the three rules, we must not expect to see efficient technical results within a reasonable time span.

The relevance of these rules is clear: they provide us with an *ex ante* assessment method - in terms of the expectable technological progress for alternative technologies - which complements conventional cost-benefit analyses. Likewise, the application of SN-rules offers valuable information - even in situations of extreme uncertainty - which exclusively technical “for and against” analyses do not offer. Moreover, the fact that the SN-rules allow for decisions without the need to rely on probability distributions is an advantage, as this information is rarely available for technological choices.

Accepting the importance of the SN-rules, in our work we start out from the conviction that a deeper formal discussion of the rules, and an attempt to formalize some of their applications and implications, may make it easier to apply the rules and systematize their use in different technological fields. To develop this formal discussion, we start by considering the relationships between the SN-rules and the co-evolution approach to technological change. After this, we discuss the necessary and/or sufficient character of the SN-rules as conditions to offer hope for easy/hard 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 very accessible or advisable. This helps us (by exclusion) to define a group of more or less promising *parallel efforts* (Nelson and Winter, 1982; Nelson, 2012). This approach to technology assessment and choice means that, instead of requiring (inspired) foresight, agents and policymakers can refer to past and present knowledge as a motivation and guide to search into the unknown. The subsequent question, then, is how to make the SN-rules operational as part of decision methods in *targeting innovation policies*.

As we will see, these ideas and concerns fit well with important developments in modern decision theory (Gilboa, 2004; Basili and Zappia, 2009). Drawing upon the concept of *Fuzzy Set* (Zadeh, 1965, 1978), and considering alternative epistemic states of the decision-maker (Ellsberg, 1962) - such as their degree of confidence and caution, non-satisfaction with the current state of affairs, optimism, and relative deprivation - we integrate the

Sarewitz-Nelson methodology within a wider process of choice. After a formal examination and integration of the rules, our conclusions allow us to propose two quantitative indicators which can systematize and make the formulation of technology choice and policy easier, as well as the application of the rules in different fields of activity. We suggest possible applications to illustrate this point.

The structure of our work, then, is as follows: starting out from the conception of technological progress as the result of a co-evolution process, we present the Sarewitz-Nelson rules in Section 2. Then, in Section 3, we follow on with a formal discussion of the SN-rules. We examine the nature and essence of the rules, and we interpret them as a procedure of technology screening. As we show, the screening SN-strategy can be integrated within a wider process of choice under radical uncertainty. 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 combined application of the SN-rules. In Section 4, we illustrate the applicability of these indicators in the field of technology choice and policy with some examples. Finally we finish with a summary of our conclusions.

2. The Sarewitz-Nelson Rules

When we state that technological progress emerges from a co-evolution process between a body of practice and a body of understanding, we are assuming that there are mutually dependent selection processes at work in both the field of technical applications and that of associated theoretical conceptions (Nelson, 2005). These processes of *ex post* selection act both within the realm of practice, on heterogeneous and changing technical applications (on-line and off-line), and within the realm of theory, where selection operates on hypotheses and different models - often incompatible amongst themselves - which aim to understand the applications and results observed in practice. To be more precise, the results obtained in practical applications allow us to test scientific theories and select certain models and rationalizations. At the same time, this evolution in the theoretical field allows for *ex ante* discrimination between possible lines of technological progress, the discovery of new lines of advance, and sharpening or improving experimentation.

As Nelson (2008) points out, the process of co-evolution we describe does not operate with the same smoothness across the board of human activity. In fact, this may be one of the reasons why we find a highly uneven evolution of human know-how. Observing in depth the evolution of different fields and sectors, we see that, in those sectors in which technological progress is rapid, the bundle of technological applications tends to evolve towards those points where understanding has become strong, whilst the applied sciences advance and become clear by the scattered experimental manipulation of current technological practice (Nelson, 2011).

In an attempt to detect certain *catalyzing or blocking* factors for *co-evolution processes*, Daniel Sarewitz and Richard R. Nelson (2008a, 2008b) propose three simple rules - the *Sarewitz-Nelson (SN) rules* - which sharpen and condense previous explanations for the uneven evolution of human know-how. Taken globally, the SN-rules state that in those activities in which technology is embodied in a more or less standardized product or process, such that on-line experimentation and replication are easy and enlightening, then technical progress (and technically-induced scientific advance) occurs normally. Furthermore, if the applied sciences linked to the activity advance alongside these progresses, thus shedding light on further ways to improve practice, the innovating dynamism will be strengthened. In a simplified way, we can establish this claim by presenting the three simple SN-rules:

2.1.-The cause-effect rule (R1)

For a technology to be really efficient, it is necessary that it incorporates the essential variables (cause-effect mechanisms) to solve the problem at hand. Thus, to warrant significant R&D investment in a specific technological direction, it is a big plus that there is a clear link between what a technology will do, and the remedy it can provide for the problem - a strong link, reasonably well-supported by scientific understanding. Let us point out, however, that as we shall see when discussing rules R2 and R3, it is not correct to think that the existence of a firm scientific base will guarantee technological development. As we shall see later, if rules R2 and R3 are not adequately met, the fulfillment of the R1 rule is not enough to ensure the development of a specific technological line.

2.2.-The standardized technical core rule (R2)

In evaluating technological alternatives for dealing with a particular problem, it makes sense to consider which ones seem amenable to developing a routinized core (for technology to be effective under a wide range of conditions). For this reason, Sarewitz and Nelson point out the importance of a standardized technical core - a standard procedure, device, prototype, or substance- which contributes to evaluating the promise offered by a certain path. Regarding the previously-mentioned 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 addition, as the technological core offers up useful experimental results and stabilizes the practice on-line, then the applied science will advance more swiftly.

2.3.-The enlightening testability rule (R3)

A technological option will be more promising, the easier it is to evaluate its results and improvements with unambiguous criteria. That is to say, considering that technologies progress with the passing of time, we need a reasonably clear idea regarding just what improving and becoming effective means. Thus, from a technology choice and policy perspective, it seems convenient to go for technological routes which offer quick and reliable information from simple, clear, and cheap experiments. This kind of results orientates further technological research and scientific progress. Likewise, effective replicability on-line and experimental clarity favor the assimilation of a technology in different social contexts, avoiding coordination problems and aligning conflicting values.

As Sarewitz and Nelson (2008a, 2008b) argue, when technologies meet the three rules, policy-makers and practitioners could expect R&D investments to lead to fast progress. On the other hand, 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 much chance of solving the specific problem in the near future. In this sense, the SN-rules could be considered to be a high-level procedure for technology screening.

Let us note that, in their original formulation, the SN-rules are proposed as a broad heuristic emerging from practical experimenting and an implicit theoretical framework. This broad formulation has advantages and disadvantages. On the one hand, it is flexible and intuitive and fits in with appreciative pieces of theoretical work. On the other hand, the possibility of finding the sense and nature of the rules remains open - that is, seeing up to what point they are applicable without ambiguity, and assessing how far they could reach as part of a theory for technology choice and innovation policy-making.

We shall devote Section 3 to discussing some aspects of these affirmations. What can be said about the necessary and/or sufficient character of the SN-rules? Are there any examples in the history of technology which illustrate our discussion? Is it possible to advance towards some kind of process of information aggregation and choice which may allow us to systematize the application of the SN-rules in different fields?

3. A formal discussion of the SN-rules

As Nelson and Winter (1982) recognized, to recommend a reasonable policy for a particular case, expert knowledge of the array of options should be combined with sophisticated economic analysis. Moreover, technology policy should start by considering expert arguments that may persuade people to devote funds to options that seem better than others in terms of widely-accepted criteria. In this sense, we argue that the SN-rules are a useful map for policy-makers when they interact with domain-specific experts to identify blocking factors or promising technological options. Policy-makers (or decision-makers in general) can use the collected information to enlighten their specific processes of technology choice. We begin this section, in subsection 3.1, by discussing the essence and nature of the SN-rules. Then, in subsection 3.2., we pose our vision regarding how the SN-rules could be formally applied within a wider process of technology choice and policy.

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

The history of technology, and recent contributions in innovation studies, allows us to state that *it is not correct to consider the SN-rules as a group of sufficient conditions to guarantee technological progress* (Basalla, 1988; Dosi and Nelson, 2010). As we have explained, technological progress may result from the co-evolution between domain specific bodies of understanding and technical practice. Both understanding and practice evolve in accordance with the principles of variation, replication, retention and *ex post* competitive selection, and both evolution processes are connected - in the sense that understanding influences the evolution of practice and vice versa.

These processes always have a degree of radical uncertainty and are affected by the continuous appearance of unpredictable novelties. Given the complexity and non-determinist character of these processes, we cannot interpret the SN-rules taken in their entirety as a group of conditions guaranteeing a specific direction and degree of progress in know-how. Rather, they are conditions which warn us of the hurdles we can come across if we advance along possibly impassable routes. To be precise, the SN-rules show possible blocking factors of the co-evolution process.

Hence, for example, regarding the (R1) SN-rule, when faced with a technology which does not incorporate the basic mechanisms to solve a problem, and/or is not backed by a solid body of scientific understanding, we run the risk of finding applications which are, in general, ineffective (very dependent on context) and attempts of technological advancement which are *blind.* That is, the body of understanding will not shed light upon paths of advancement, nor will it allow us to reject *a priori* unfruitful attempts. One example in this sense is that of the poor advance in the chemical dye technology before organic chemistry and its applications to synthetic dyes were developed (Murmann, 2003).

Likewise, regarding the (R2) and (R3) SN-rules, when there is not a standardized technical core, or when the possibilities of quick and clarifying experimentation are limited, neither the technology itself nor the supporting body of understanding will advance smoothly. This can be seen in the example of the problematic advances seen in the efforts to construct a large scale quantum computer (Di Vincenzo, 1995). Furthermore, the barely conclusive character of these experimental efforts can make social assimilation of the technology difficult. In this sense, we can also mention the example of the controversy regarding the genetic modification of foods.

As can be seen, the SN-rules allow us to detect blocking factors which obstruct technical progress, but they are not *sufficient conditions* in themselves to guarantee that progress takes place. The radically uncertain and complex nature of the underlying co-evolution of technical change impedes the obtaining of sufficient conditions for progress. The SN-rules merely inform us roughly about the possibilities of development and warn us about the obstacles we can find if we advance in certain directions.

The SN-rules *are not a group of necessary conditions either*. The history of technology shows that significant technological advances have been made at different times even though one or more of the SN-rules were not fulfilled. One of the clearest examples is probably the smallpox vaccine. When it was developed, the body of understanding supporting this technology and even the possibility of experimenting with a base of bacteria and virus were both very limited (in fact virtually all three rules were not met). Another example is that of the discovery of the electric battery by Alessandro Volta following the experiments of Luigi Galvani; here rules R1 and R2 were not met as there was no solid body of understanding supporting research, and the initial experimental results were coincidental, rather than being produced systematically around a standard technical core.

Given all this, we can state that the SN-rules are neither necessary nor sufficient conditions to guarantee technological progress. What they are, though, are rules which synthesize a group of features which may appear in one way or another in the underlying co-evolution process of technological progress. The sharper these features are in a specific co-evolution process, the smoother this process will be, and the easier for technological progress to emerge. On the other hand, if these features do not appear, the co-evolution process may slow down or even become blocked.

As should be clear from the aforementioned, the large element of chance in innovation owing to extreme uncertainty can pose a big challenge for *ex ante* project selection. In this sense, although technology prospects are often decided on close to governments, it is often the case that governments and public agencies ask groups of independent experts to gather crucial information for R&D policies. We have seen that the SN-rules are a useful map for policy-makers when they interact with domain-specific experts to identify blocking factors under conditions of extreme uncertainty. However, if a policy-maker or public agency (or even a private technology-chooser) wants to use the SN-rules in a systematic way when deciding between different R&D alternatives, how should they proceed? We deal with this question in the following subsection.

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

Let us start by considering that R&D policy is always field-problem-specific. Thus, experts in the field, firms and technology users are the ones who (partially) know about the possibilities of specific technological options. In order to apply the SN-rules, it will be necessary to aggregate in some (imperfect) way the information provided by the different actors. This poses the following question: how to build an aggregator which can capture the imprecise information resulting from the experts' opinion on the issues risen by the SN-rules? Although it is possible to construct a questionary based on the SN-rules, it should be expected that some disagreement about the degree of fulfillment of the rules will appear and, moreover, the extent to which each rule is fulfilled may be expressed in a qualitative, vague and imprecise way (e.g. with answers such as "not much", "to some extent", etc).[4]

Bearing in mind the aforementioned, and considering there is a real need to unite imprecise

[4]See the ambiguity regarding technological advances in Nelson, Peterhansel and Sampat (2004).

information and integrate it in a well-founded process of technology choice and policy-making (Steimueller, 2010; Mairesse and Mohnen (2010); Foray (2012)), we can use formal theoretical instruments which help us support decisions in contexts of vagueness and radical uncertainty. In this sense, certain instruments such as *fuzzy sets* or *aggregation operators theory* provide a natural way of dealing with problems in which the source of imprecision is ambiguity, uncertainty and unavoidable controversy when dealing with the unknown. Drawing upon the concept *Fuzzy Set*, we devote the rest of this section to discussing what kind of *aggregation operators* would be useful for the application of the SN-rules. Finally, we propose, in an illustrative way, specific functions which satisfy certain convenient conditions and may reflect alternative epistemic states of the decision-maker. We end by delineating a process of technology choice. Several indicators arise which could be of help in the wider process of technology choice and policy-making.

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

Fuzzy Set.- 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 fuzzy set is a class of objects with a continuum of grades of membership between zero and one. The fuzzy set $"\mathrm{A}"$ 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 the alternative 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, discrepancies, controversial aspects, ambiguities, and typical precautions in a context of

radical uncertainty, $p_{i\tau}$ could be the most frequent opinion, or the average of all the opinions given - regarding the fulfillment of rule *i* for technology τ.

The controversies and the diversity of opinions always leave the final deciding agent (e.g. a politician who has to decide on public expenditure in R&D to solve social problem “P”) with plenty of room for uncertainty. We are dealing with a situation which isn’t even one of probability risks, so the concepts of *fuzzy logic*s can be extremely useful.

Let us look now at how the deciding agent (e.g. the policy-maker) can characterize their decision-making problem. The agent must choose one (or several) of the alternatives $\tau, (\tau = 1,2,...,n)$ to reach a solution for problem “P”. As we have seen, each one of these alternatives is indirectly reflected in $\Phi = \{p_\tau\}_{\tau=1}^{n}$ via the approximations of opinion p_τ regarding the degree of verification of the SN-rules for τ. The first question is how to combine (aggregate) the information condensed in Φ so as to be able to make a decision. From Φ we can define a fuzzy set T.

Let $\mathrm{T} = \{\Phi, F_T(p_\tau)\}$ be the *fuzzy set “promising technological paths”* that may lead to a solution of a specific problem “P”. Obviously this is a set which the final deciding agent must define from the information incorporated in Φ and which it is necessary to aggregate in some way. This is where the role of the *membership function* $F_T(p_\tau)$ comes into play. This function plays two roles: combining the information contained in Φ and, given the imprecise, ambiguous, and even controversial character of global 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 $F_T : \Phi \to [0,1]$ assigns a degree of “greater” or “lesser” reliability (“promising-ness”) to each technological option characterized by p_τ. It indicates to what extent the final deciding agent considers each technological option to be promising, given the information synthesized imprecisely in 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 $F_T(p_\tau)$ - as with typical membership functions - must fulfill certain convenient properties. In our case, we assume it to be continuous and increasing monotonous 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* and their role in decision-making (see 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 economic 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 must 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 only one of the rules seems to be verified to a greater extent for a technology (with all others remaining the same), this would be reason enough to have a greater confidence in this 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 the possibilities of efficient 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.

Before we propose in 3.2.2 the specific way in which a public body, policy-maker, or any other kind of decision-maker can decide between different alternative technologies - given a previous collection of information referring to the SN-rules -, we can specify additional properties of $F_T(p_\tau)$ which, respecting the general axioms, allows us to better operationalize our approach. There are clearly many possible ways to achieve the formalization of the process. However, 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 way* in $F_T(p_\tau)$.

In this way, we consider a *membership function* $F_T(p_\tau) = \prod_{i=1}^{3} g_i^{\alpha_i}(p_{i\tau})$. The functions $g_i(p_{i\tau})$ can be interpreted as the contribution to the general confidence in technology τ from its level of compliance with the *i*-SN-rule. Their domain is the interval $[0,1]$ and will be delimited between “0” and “1”. We assume they are continuous and differentiable, and increasing monotonous (as the degree of compliance with rule *i* increases, so does the confidence). We shall talk about the conditions of concavity below. Furthermore, the weights α_i will be positive and add up to “1” (they can be different from each other).

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. Setting $dF_T = 0$ for the case of the multiplicative function, it is simple to check:

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

The ratio between the weights is dependent on the specific 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 experiments and 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) will allow us to maintain this confidence.

To sum up, functions $g_i(p_{i\tau})$ can be interpreted as *functions of reliability* of technology τ , vía the degree of compliance with the *i*-th SN-rule. The multiplicative mixture of the reliability each of the rules allows us to obtain a *membership function* $F_T(p_\tau)$ which verifies convenient and habitual axioms (ax.1-5) in the literature on *aggregation operators*. 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 within the framework of a wider decision process.

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 must point out that we suppose (or interpret) that the specific shapes of the reliability functions depends on the *epistemic state of the agent* (Ellsberg, 1962; Shackle, 1979) when this has to choose (when assigning public or private funds, selecting projects, etc.) between technological alternatives under conditions of radical uncertainty. 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; their optimism and positive inclination to innovate under certain circumstances; the pressing need to solve social problem "P", etc.

Then, looking at the epistemic state of the decider, we can consider, firstly, those specific functions most 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[5]:

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

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:

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

[5] In a somewhat different context, see the use of this function in Witt (2009).

It is interesting to point out that function (2) is defined for $p_{i\tau} \in [0,1]$, is delimited between "0" and "1", and is continuous, differentiable and monotonically increasing within the domain of the definition. It is compatible with all the suppositions and 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[6], and it is verified that $g_i(0.5) = 0.5$. Function (2) is an S-shaped reliability function which transfers its sigmoidal character to the membership function via (3).

These shapes of functions (2) and (3) reflect the fact that 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 first section, strictly convex, of functions (2) and (3). 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.

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 (although we are not trying to use up all the possibilities and we could consider other kinds of functions).

For the case of strictly concave functions, and 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, or searches for new ways to proceed. In this sense, when the need to solve a certain problem, "P", is urgent or when the

[6] It is possible to generalize any of these features by being able to define entire families of sigmoidal functions (see Jarne *et al*., 2005, 2007). We merely propose function (2) for the sake of simplicity.

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, and development of, new ideas as soon as the first signs of viability have been 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 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:

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

We may consider one kind of function or another, and once the experts' information has been collected and processed regarding the degree of compliance with SN-rules, and after the decider (according to their profile) has evaluated the confidence in the future of a certain technology, the decider can merge all this information and define the fuzzy sets (according to their specific *epistemic state*) $\mathrm{T} = \{\Phi, F_T(p_\tau)\}$, $\tilde{\mathrm{T}} = \{\Phi, F_{\tilde{T}}(p_\tau)\}$, 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 order preferentially 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.

In this way, the *set of parallel efforts to be developed* could be defined as:

$$\mathrm{T}^* = \{\tau \in \Phi : F_T \geq \hat{F}\} \quad \text{or}$$
$$\tilde{\mathrm{T}}^* = \{\tau \in \Phi : F_{\tilde{\mathrm{T}}} \geq \hat{F}\} \qquad (6)$$

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 (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.

Finally, we would like to point out that our proposal merely aims to complete the original broad heuristic proposed by Sarewitz and Nelson (2008a,b) and integrate it, as a theoretical application, into a wider process of decision-making (technology choice and policy). The indicators (7) and (8) must never be applied dogmatically but as a complement of the general heuristic. In the following section we propose two tentative applications of the SN-rules completed with our indicators. As we shall see, the information our formal proposal brings, complements the results of the general heuristic of Sarewitz and Nelson.

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 (see e.g. Murmann, 2003).

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 progressively observed in relation to the new technology of synthetic dyes, is coherent with the development and 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). 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. To this end, we process the available technical information regarding the storage problem (see e.g. Ibrahim *et al*., 2008) in the light of our discussion of the SN-rules. As we shall see, our conclusions indicate that, at present, there are no technological paths sufficiently promising to guarantee the solution of the problem of storing energy on a large scale in the near future. This conclusion raises concerns and possible controversies and should make us reflect on the challenges for the future from the perspective of technology choice and policy.

Regarding the two applications we propose, we must remember that, as pointed out by Metcalfe (2014), modern economies are *ignorance economies* in which specialized professional teams know a great deal about very precise subjects (that is, in reality, they know a great deal about very little). As a result, we must consider our applications as attempts at illustrating the implications and potentialities of the SN-rules within a wider process of choice. For future deeper applications of the SN-rules, we point out that, in each case, 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, choosing suitable weights and proxy variables.

4.1.- Alternative technologies for dye production.

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 enlightening systematic experimentation, and so we can conclude that, for natural dyes, there was a low level of compliance with the (R3) SN-rule too.

As a consequence of the above-mentioned, and as pointed out by (e.g.) Murmann (2003), 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. As we shall see, these circumstances can be interpreted as coinciding with an ever-greater fulfillment of the SN-rules.

The development of, firstly, organic chemistry and, afterwards, 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. In this way, 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 (e.g. the dye industry; see Nelson and Sampat, 2001). The degree of experimentation and 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.

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 can obtain Table 1:

Table 1: Alternative technologies – dyes

Alternatives/Rules	**R1**	**R2**	**R3**	F_1	F_2
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 (which coincide in this case, independently of the epistemic state) as:

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

Nowadays, we know that synthetic dyes did prevail in the end but this was not so obvious *ex ante* towards the end of the 19th century [see Murmann (2003), Nelson and Sampat (2001)]. As we shall see in the following example, the proposed methodology reveals more information in very unclear situations.

4.2.- The problem of energy storage.

Our second application deals with the so-called *energy storage problem*. Although techniques to store energy have existed since early times in history, nowadays the need to integrate renewable resources into modern energy systems is putting pressure on the development of new technologies to store their surplus energy. The reason is that renewable energy sources - solar, wind power - share a common characteristic; the times when energy can be captured and converted do not always correspond to the periods of high demand. Therefore, large capacities for energy storage are needed to match generation and demand. 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 or is free of controversy for their large scale application. To be specific, we have evaluated five technological 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, and even the sea - sometimes used as the lower reservoir - 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* in PH (standard PH-facilities, which implies high 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 (lakes, mountains, stable rainy conditions, etc.). 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 (offering a medium level of satisfaction).

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. Most attempts to make technological advances in PH are currently mainly focused on increasing the capacity of the existing PH-facilities and/or improving efficiency. In spite of these attempts, it seems difficult to expect promising advances on a large scale. Scalability problems impose physical limitations which go beyond technological improvements. Furthermore, any advances are relatively small and insufficiently important so as to be able to neutralize the social conflicts linked to environmental damage, etc.

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. 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. The body of understanding supporting battery storage is Electrochemistry. Hence, batteries rely on a *solid body of understanding*. In addition, batteries used as storage devices are non-context dependent. This would, apparently, lead us to conclude that batteries verify the (R1) SN-rule. However, Electrochemistry principles allow us to see a *scalability problem* if we try to obtain batteries which act as large-scale storage devices. The dimensions and requirements for a system of batteries to perform as a sole large-scale storage system are enormous; they are physically and economically 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, once again, we find only 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 and the theory underlying the technology illuminates avenues of advance. However, given the above-mentioned, 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 (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. 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. Another difficulty 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) leads us to conclude that this technology 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 specific requirements of the land. Then, we may consider that CAES-technology 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. 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 in a significant way. 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 with a very promising range of applications in many fields (transportation, computers, energy systems, etc.). However, it presents many problems as a possible large-scale energy 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 and unified *body of understanding* underlying superconducting technology. Thus, while low-temperature superconductivity is explained by the *BSC* theory, this theory alone is not able to explain high-temperature superconductivity. Without a body of scientific understanding in this direction, we can affirm that this technology verifies the (R1) SN-rule at a low level.

Finally, *experimentation* around superconducting energy storage devices is difficult because of the expense of testing (low-superconducting devices need to be cooled below 7.2K, and high-superconducting ones below 150K). Therefore, we can affirm that 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:

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

Likewise, considering Section 3 and the application of our methodology in subsection 4.1, 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. Thus it is to be expected that there would be some degree of controversy in the final decision. Finally, as is also to be expected, the values of $\boldsymbol{F_1}$ for all the technologies in Table 2 are lower than those of $\boldsymbol{F_2}$, given that the “cautious” decider always 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, although certain technologies are clearly more promising than others.

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. For example, although we have taken great steps in mankind's exploration of the Universe, we have made few improvements in techniques for the teaching of reading. Reflections on the development of human know-how have led an increasing group of innovation scholars to characterize technological change as the result of a co-evolution process between bodies of theoretical understanding and practice. Richard R. 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 aimed to find out to what extent the *Sarewitz-Nelson rules* can offer us a method of assessment *ex ante* of the potential for technological progress we can expect from different technology options trying to solve a specific problem. We see that applying the SN-rules offers valuable information for decision-making even in highly innovative and radically uncertain contexts. We also 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 started our 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 these rules are neither necessary nor sufficient conditions for technological advance. 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. 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 innovation 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 our empirical knowledge regarding the way technological progress evolves and, as its foundations, properties and limits are explicit, we believe it can provide a contribution to the economic theory of 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 rules and a formal analysis suggests that none of the chief alternatives currently on the table is sufficiently promising to ensure a clear solution for the storage problem. Depending on the epistemic state of the decision-maker and supposing a threshold of neutral incentive (0.5), we see that, even in the case of optimistic decision-makers prone to innovate, the set of parallel efforts to be developed is a reduced one (Batteries and Pumped-Hydro) and offers little confidence. This may indicate two things:

the threat of implausibility hangs over the possible current solutions - which makes it necessary to find something significantly new for the future; or the 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, political and scientific debate which goes much deeper than previous and 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 very few matters - then, understanding and improving the coordination mechanisms between different realms of knowledge 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 and make them operative in technology choice and policy represent important steps in this direction.

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