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The Resilience Concept: From its historical roots to theoretical framework for critical infrastructure design

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THE RESILIENCE CONCEPT: FROM ITS HISTORICAL ROOTS TO THEORETICAL FRAMEWORK FOR CRITICAL INFRASTRUCTURE DESIGN

Stefan Gößling-Reisemann — Hans Dieter Hellige — Pablo Thier

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The metaphorical processes in the history of the resilience notion and the rise of the ecosystem resilience theory

Hans Dieter Hellige

The initial article chooses a historical approach to the theoretical discussion of resilience notions by reconstructing the emergence of its manifold layers of meaning. The first part focuses on metaphor and concept transfers, each of which has produced a disciplinary conceptual tradition and a culture of resilience. The second part then describes the genesis of the system-theoretical "resilience framework" of the biologist and ecosystem researcher C. S. Holling, which still shapes the resilience discourse to this day.

Abstract 3
1 The transfer history in the genesis of the resilience notion and concepts 4
2 The early ecosystems theory between the homeostasis and resilience concepts 8
3 The origins of the ecosystem resilience theory by Crawford S. Holling 11
4 The controversy at IIASA about the principles of resilience and architectures of resilient energy systems 15
5 The completion of Holling's resilience concept as a theory of adaptive change and cyclical transformation 19
References 23

The reception of the resilience concept in the energy discourse, and genesis of the theory of resilient energy system design

Hans Dieter Hellige

The second article reconstructs the roots and the development steps of the concept of resilience in energy systems, starting in the alternative energy discourse in the early 1970ies and ending in the first elaborated theory of resilient energy system design by Amory Lovins in 1982.

Abstract 33
1 Transfers of metaphors and guiding concepts in energy and communication infrastructure systems 34
2 Lovins' integration of guiding concepts in the early alternative energy discourse: downscaling, decentralization and ecosystem resilience 36
3 The first integration of the 'Energy Internet' metaphor into the resilience discourse: The „Power Systems 2000"-Scenario of the „Homeostatic Control Group" 43
4 The multidisciplinary synthesis of the resilient energy system design-debate: The distributed computing-inspired study „Brittle Power" of Lovins/Lovins 49
5 Outlook at the later energy resilience discourse and conclusion 53
References 54

On the difference between risk management and resilience management for critical infrastructures

Stefan Goessling-Reisemann and Pablo Thier

Risk management and resilience management share important features and they both aim at preparing systems for uncertain threats or stressors and their impacts. Still, the level of uncertainty regarding stressors and impacts, the type of systems addressed and the systems' dynamics allow for a distinction between the applicability of either risk or resilience management. The third article provides a short introduction to the specifics of each strategy for coping with uncertainty and presents guidelines for designing a resilient critical infrastructure.

Abstract 59
1 Introduction 59
2 From risk management to resilience management 59
3 Resilience management 64
4 Scientific and practical challenges 73
5 Conclusion 76
References 77

The metaphorical processes in the history of the resilience notion and the rise of the ecosystem resilience theory

Hans Dieter Hellige

Abstract

After several transfers between the disciplines of physics, applied mechanics and materials sciences as well as physiology, psychology, biology and ecology, the centuries-old notion of resilience has developed over the last few decades into a multidisciplinary universal concept with paradigmatic aspirations. The concomitant proliferation of the term and the increasing complexity and blurriness of meaning were the grounds for a series of approaches to a phenomenology and taxonomy of the various terms and concepts pertaining to resilience (see i.a. Xu and Marinova 2013; Grimm and Wissel 1997; Brand and Jax 2007). Despite the efforts of the international research group of the “Resilience Alliance” for synthesis and paradigmatic closure, resiliency has remained an ambiguous borderline concept that has initiated and promoted much disciplinary and interdisciplinary discourse, but has also encountered distinct criticism with its hegemonic claim of being a “unifying concept”. Instead of venturing a renewed attempt to clarify and systematize concepts, the following chapter chooses a historical approach to the theoretical discussion of resilience notions by reconstructing the emergence of its manifold layers of meaning. The first part focuses on metaphor and concept transfers, each of which has produced a disciplinary conceptual tradition and a culture of resilience. The second part then describes the genesis of the system-theoretical “resilience framework” of the biologist and ecosystem researcher C. S. Holling, which still shapes the resilience discourse to this day.

The historical perspective is intended to provide insights into the epistemic and societal contexts of metaphor and concept transfers and the genesis of resilience cultures, in particular into implicit or explicit social expectations of stability and vulnerability as well as into intentional self-regulation and crisis management strategies. The historical review also portrays the specific problems of “analogical reasoning”, which were not least caused by multiple transfers and metaphorical short-circuits between natural, economic and societal processes. All in all, the aim of this chapter is to demonstrate that the notion of resilience, like many other concepts in the natural sciences, technology and life sciences, is not a timeless structure with fixed meaning and functions, but rather that it too belongs to the social constructs that are subject to historical change and must be reflected accordingly.

1 The transfer history in the genesis of the resilience notion and concepts

The history of the notion of resilience is the outcome of a chain of transfer processes taking place between diverse fields of knowledge and science. Arising from the verb "resilire" in classic Latin as a figurative designation for a variety of retrograde motions (jumping back, rebounding, reflecting, returning), the word is found from the year 1430 in late medieval and early modern French as a juridical term for contract termination and, in general, for the restoration of the original legal situation – as the verb "résiler", as the noun "résiliation" or, more frequently, "résiliment" (Grand Larousse 1989, pp. 5020 f.; see for the history also Lindseth 2011; Hempel and Lorenz 2014 and especially Alexander 2013). It is likely that the English philosopher Francis Bacon introduced the term "resilience" independently of the juridical tradition of terminology as a metaphorical abstraction when he undertook a comparison of mechanical, optical and acoustic feedback in "Sylva sylvarum, or Naturall Historie in Ten Centuries", which was his most widely read work at the time. With his neologism, which was abstracted from the individual physical phenomena of rebound, reflection and echo, he founded the physical tradition of the resilience notion (Bacon [1627] 1631, § 245, p. 66). The philosopher and educationalist Johann Amos Comenius took over the term from Bacon with the same meaning in his work of natural philosophy "Synopsis of Physicks", published in 1633 and 1651 in Latin and English, making the term "resilentia" or "resilience" known on the Continent for the first time (Comenius 1633, p. 174; Comenius 1651, p. 189).

During the second half of the 17th century, "resilience" or "resiliency" became common terms for physical counter-reactions of any type and for a return to the initial state. For Samuel Gott, the author of a natural history and cosmology that was strongly influenced by Bacon and published in 1670, resilience ("return or restitution") constituted the generic term for the "elasticity" of gases and liquids on the one hand and the "springiness" of solid bodies on the other. In the consideration of retroactive forces ("retreat or resilience"), he already included electricity (Gott 1670, pp. 209, 282). Further instances of "resiliency" and "motion of resilition" in natural philosophy treatises on the reactions of gravity for pendula, springs or thermometers by Henry More (1676, p. 143) and Matthew Hale (1677, pp. 103, 150, 255 f.) show that the notion of resilience was already well established in the early modern physics of England. For Robert Greene, "resiliency" meant the balancing behaviour of the forces acting in elastic bodies and materials "where the Expansive Force is Vigorous and Strong, but yet is so far Ty'd down by the Contractive, as not to move Considerably out of the Space, which the Body possesses". (Greene 1727, p. 293; similarly already in Greene 1712, p. 165). For Greene (1727, p. 635) as for Richard Allstree before him (1684), the physics term was already applied as a metaphor to the soul-forces, where "resiliency of the soul" with Allstree and "resiliency in the mind" with Greene denoted the ability to regain one's courage after emotional stress. Although resilience in the sense of mental recovery from stress, shocks and burdens appears repeatedly in the literature of subsequent times, actual research into psychological resilience only began in the middle of the 20th century.

About 1800, the physical resilience concept also gave the impetus for the terminological tradition in applied mechanics and materials science. The decisive arc from natural philosophy and physical theory to the "mechanical arts" was forged in 1807 by the leading English physicist Thomas Young in connection with empirical investigations to determine the breaking strength of beams and metal cylinders. On the basis of impact tests, Young defined resilience as the ultimate capability of a material to withstand an moving force, e.g. a falling weight, and formulated the first rules of thumb for the relationships between the stiffness, hardness, brittleness and resilience of a material (Young 1807, pp. 143 ff., p. 629). As with Young, the technological and scientific research efforts that followed him regarding the vague resilience notion defined by natural philosophy were constrained to measurable and calculable quantities; the empirical testing conditions increasingly demarcated the extent to which resilience was understood in mechanics and materials science.

Building on Young's work, the versatile English engineer Thomas Tredgold developed, from 1822 on, measurement concepts as well as loading and impact experiments for calculating the resilience characteristics of beams, supporting structures and the various kinds of iron and steel used in the construction of ships and steam engines. He devised the first "modulus of resilience [...] which represents the power of a material to resist an impulsive force" (Tredgold [1822] 1824, p. 82; see also [1820] 1828, p. 73). Tredgold's computation methods and numerical factors were augmented by the mathematician, physicist and applied mechanician Henry Moseley (1843, pp. 491 f.) through a "modulus of fragility", with which the "elastic limits" were to be determined more closely. These and later empirical investigations into the characteristics of resilience then, in the middle of the 19th century, culminated in the fundamental manuals of technology and science written by William Rankine, who developed a refined calculation concept for the the moduli of strength, stiffness, pliability, elasticity, and resilience (see Rankine 1858, pp. 273 f.; Rankine 1876, p. 492 ff.). Here he defined "resilience or spring" as an "exact measure of the capacity of a material for resisting shocks by tension" (Rankine 1862, p. 513), whose magnitude corresponds exactly to the mechanical work needed for the maximum permissible test pressure (Rankine 1862, p. 226). With his systematic research into the endurance limit of materials, Rankine created the foundation for the subsequent loading and impact tests and the resilience concept of materials science, with which the maximum load limits could be explored and also safety margins defined. Rankine's and Young's research into resilience was also used in William Thomson's (Lord Kelvin's) elasticity theory and in his natural philosophy, where this was closely based on their quantitative perception of resilience for the determination of "extreme resilience" (Thomson [1877] 1878, p. 13; see also Thomson 1895, pp. 228 ff.).

By specifying the various forces and by virtue of the differentiated calculation methods, the resilience concept was reduced more and more to a small, specialized area and thus strongly constrained in its complexity, so that, over and above the shock and stress-resistance motif, it only offered minimal potential for more extensive metaphorical transfers. At the same time, however, there were also trends towards a renewed expansion of meaning, especially in America. Here the influential engineer and scientist Robert Thurston, who laid the groundwork for the technical training system in the USA, distinguished between the "elastic resilience" as a component force and the "total resilience" as the sum property (Thurston 1879, p. 15): "resilience is measured by the sum of the products of all resistences", of "compressive resilience, elasticity, and plasticity" (Thurston 1884, vol. 1, p. 105). Each material depends on its very special properties, therefore "no general law can express resilience for all materials" (ibidem, p. 106). All in all, "total resilience" represents the entire "value of the material for resisting the shock" and is therefore of great economic significance (Thurston 1874, p. 34).

Through the materials sciences, the notion of resilience attained a greater dispersal in the English-speaking countries, from where it was also adopted in France. If one takes the specialized literature registered by Google Scholar/Books as a basis, the "material resilience" also formed the prevailing usage of the term in the technical, natural and life sciences in the period that followed, up until the 1940s/50s. Since 1900, however, "resilience" was no longer used solely for material properties but also for diverse "resilient mechanisms" (e. g. US Patent 1284628, 1917, p. 3): initially for moving mechanical components, such as keys and switches, and then also for entire switchgear and controlgear and the products such as dampers ("shock absorber or resilient device"), with reliable operation being implied (Schlink 1919; US Patent 2556925 A, 1947). Despite these extensions, this did not lead to a "unifying concept"; even the efforts of Robert M. Hoffman (1948) towards creating a "Generalized Concept of Resilience" did not progress beyond the horizon of mechanics and materials science.

Further metaphorical processes resulted rather from physiology and medicine, in which a physiological resilience concept had developed from the physical "resilience" from the end of the 18th century, and especially from the 19th century. Initially, this was closely limited to the resilience of lungs and blood vessels, but later referred more generally to the pressure, stress and load response of organs and the body as a whole. In the physiology of the 1920s and 1930s, a comprehensive theoretical concept arose on the self-regulation of body functions and, ultimately, of all organisms. The decisive impulse to expand the mechanical metaphor was given by the American physiologist Walter B. Cannon, who viewed the theorem of the "milieu intérieur" – already posited 1859 by the French doctor and physiologist Claude Bernard ([1959] 1974, p. 84) at the middle of the 19th century, i.e. regarding a self-regulating and protectively stabilizing organism – as a welcome paradigm for the restitution of stability in all areas of life and as a guiding idea for the "social organism". In 1926, Cannon himself called it "*homeostasis*", since in contrast to Bernard's "milieu intérieur" Cannon [1926] (1973), p. 246, my emphasis) it does not return to the original state but, through small adjustments, produces a *similar* (Greek: "homeo" "stasis") condition after each loading event (Fleming 1984, pp. 623 ff.; Cooper 2008, pp. 424 ff.). Based on the model of internal regulatory processes in living organisms, "homeostasis" denotes a principle of equilibrium that, within certain boundary parameters ensures the stabilization of process states and system functions in the face of changing external conditions, especially "stress and strain" factors, with the aid of internal regulation, control and adaptation processes (Flechtner 1966, pp. 44 ff.). Occasionally, Cannon also spoke of "resiliency", though only in the limited meaning of "restorative actions" of blood vessels and organs (e.g. in "The Wisdom of the Body", 1932, p. 50). In contrast, homeostasis received during the "New Deal" reform era the status of a self-regulation and stabilization principle spanning the fields of biology, technology and society, and was thus also the decisive stimulator for homeostasis and resilience concepts in psychology, bio-cybernetics and biological ecology.

Although the resilience notion had already been used repeatedly since the 17th/18th century to describe the emotional strength and robustness of individuals, communities and entire peoples against shocks and unusual burdens, these occurrences usually remained generalized statements on emotional character traits and mentalities. Psychological science only began at the end of the First World War to show interest in the issue of regaining individual and social-psychological stability, with the emphasis on recovery from war experiences and catastrophes. Psychology now recognized "resilience" as an element of the emotional behaviour repertoire and made the first efforts towards the targeted enhancement of the personal and collective "resistance and resilience to disasters" (see Gürtler et al., 2010, pp. 129-137). Nevertheless, the "mental elasticity or resilience" only came into the focus of psychological research via the reception of the homeostasis concept (Miles 1935, p. 279). From the late 1930s up into the 1950s, there was a veritable boom, especially through Cannon's magnum opus "The Wisdom of the Body" (1932) that pushed the notion of resilience into the background for a long period.

Turning away from its strong orientation hitherto towards the humanities, psychology now took the physiological mechanisms relating to stabilization of the body functions as a model for the psychological adaptation processes, and hence became a field of study more oriented towards natural science, namely the "consolidation of the self-controlling system" or "psychological equilibration" (Bentley 1938, p. 359). The striving towards stabilization of the "internal environment" was even accorded the rank of "one of the most universal of all behavior drives." (Richter 1941, p. 110). And yet, there were also admonishing voices, who referred to the limits of such "analogical reasoning", pointing out that the use of physiological-medical analogies had often led research into blind alleys (Fletcher 1938, p. 7). Since the middle of the 1950s, the focus of psychological research then shifted again from the homeostasis idea back to the resilience concept, whereby overcoming "disasters" and "breakdowns" of the psyche through a strengthening of the individual ruggedness and the activation of defence mechanisms against the "systemic vulnerability" came into the centre of attention. Resilience rapidly established itself in psychology as a term of art for the capability of a system to overcome acute disruptions and stress situations, and as a measure for the systemic probability of survival (Höhler 2014). Contrary to the resilience notion as used in physics and materials science, the psychological term now also received broader acceptance in the German-speaking countries.

The world of physiology also gave decisive stimuli for the establishment of a cybernetic universal science, which itself had a retroactive influence on the resilience concept. Following initial discussions on Cannon's self-regulation theory in 1937 and 1942 at the New York Macy Conference, which became legendary for its interdisciplinary research approaches, and the subsequent cooperation of Norbert Wiener with the Cannon protégé Arturo Rosenblueth, the homeostasis theorem, together with military control engineering (servo mechanisms), became the inspiration for cybernetics and bio-cybernetics (Fleming 1984, pp. 639 f.). Norbert Wiener integrated homeostasis as a central concept in his main writings on "Cybernetics", because he saw in this the fundamental "process by which living beings resist to the general stream of corruption and decay", and for him it even constituted "the touchstone of our personal identity" (Wiener 1950, pp. 95 f.). The "homeostatic system" (Wiener 1948, pp. 114 f.) reacts in the interests of self-preservation to changes in the environment, both through resistance to change and, in the event of unusual challenges or the influence of "anti-homeostatic elements", through new information and learning (Wiener 1948, pp. 161 f.) Besides the generalization to a "science of controls" bridging nature, technology and society, Wiener also gave the decisive stimulus for the technical realization of "homeostats" by W. Ross Ashby and the connection with information theory and digital technology (Ashby 1952, pp. 593 ff.; Pias 2003). By formulating the metaphor of "social homeostasis" (Wiener 1948, pp. 161 f.), he then triggered the re-transfer of the control and regulation cognitive pattern to economic and societal adaptation processes, which had previously been incorporated into the genesis of the homeostasis concept as the horizon of expectations (Wiener 1950, pp. 164 ff.). As a consequence of multiple transfer and re-transfer processes, the impression was given in the end that all physical, biological and social systems are regulated and controlled according to similar principles (Stamou 2012, pp. 96 ff.).

2 The early ecosystems theory between the homeostasis and resilience concepts

Wiener's self-correcting control loops, which were based on natural metaphors, were reimported into the field of biology in 1948 by the English ecologist George Evelyn Hutchinson, who became known for his work in the USA; in 1935, he had already linked them to the "ecosystem concept" developed by the founder of plant ecology in England, Arthur G. Tansley (Tansley 1935, p. 297). According to Hutchinson, physical and biological processes formed "feedback loops", with "self-correcting mechanisms" constituting permanently stabilizing "ecosystems" (Hutchinson 1948, p. 221). In the first overall view of animal ecology, which appeared in the subsequent year, the American zoologist Alfred E. Emerson clothed the "natural circular systems" of Hutchinson with the notion of homeostasis. For Emerson, homeostasis was a central process in physiology, in biology and also in ecology, a process which as the result of all-balancing evolution on every "organismic level" continuously ensures the maintenance of equilibrium conditions, thus safeguarding "ecological security" (Emerson 1949, pp. 710, 728 f.). Owing to "homologous and analogous similarities", Emerson then arrived at his concept of "*dynamic* homeostasis" as a "unifying concept" combining organic, social and ethical evolution, which, through "negative feed backs", created relative equilibria within the scope of narrow variation corridors and was therefore also suitable for the "social regulation of optimal physical and biotic conditions of the human existence" (Emerson 1954, pp. 69 ff.).

Hutchinson’s student, Eugene P. Odum, gave the homeostasis notion broad acceptance within the early ecosystem community through the second edition (1959) of his precedent-setting standard work “Fundamentals of Ecology”. This he understood – without being aware of the physiological and biological influences on the birth of cybernetics – as a stabilization concept taken from cybernetics, where he occasionally equated homeostasis with resilience. Thus he warned in 1959 against excessive demands on the natural regenerative properties as a result of “large-scale human mistakes”: “Although nature has a remarkable resilience, the limits of homeostatic mechanisms can easily be exceeded by actions of man.” (Odum 1959, pp. 25 f.) In general, homeostasis and resilience in the bio-ecological discourse were, up into the 1970s, closely linked with the notions of stable plant and animal communities and therefore often used synonymously or as a conceptual duality. The underlying “stability concept” was based on the expectation that, due to the competition of living things for food resources, the relationships between predators and prey, or parasites and hosts, must regulate themselves according to the template of the “supply-demand economy” (Pimentel 1966, pp. 26 ff.). As a homeostatic balancing mechanism exerting a permanent effect through “reciprocal adaptations between plants and animals” (Odum 1969, p. 264), it is ensured that the number of organisms oscillates about a mean value that remains relatively stable: “This automatic regulation is not rigid, the balance of nature is fluctuating, but it is always striving for equilibrium.” (McAtee 1933, pp. 452 f.; see also Nicholson 1933, p. 176; Smith 1935).

With its idea of “intra-/ interspecific oscillations” as “mechanisms of balance”, ecology corresponded largely to the fundamental assumption of the (neo-)classical economy always striving to achieve an equilibrium between supply and demand, here even applying the mathematical models of the economists to a certain extent (Rosenberg 1992, p. 180). With that, it conformed to the basic competition-driven model that Charles Darwin had already taken from the national economy and integrated into his theory of evolution (see Timmerman 1986, p. 438 ff.; Young 1985, pp. 82-88). Marx had already in 1862 described this phenomenon of metaphorical transfer in his famous comment “It is remarkable how among beasts and plants Darwin recognises his English society with its division of labour, competition, opening up of new markets, ‘inventions’ and Malthusian ‘struggle for existence.’ ” And Engels concluded in 1875: “The whole Darwinian theory of the struggle for existence is simply the transference from society to animate nature of Hobbes’ theory of the war of every man against every man and the bourgeois economic theory of competition, along with the Malthusian theory of population. [...] the same theories are next transferred back again from organic nature to history and their validity as eternal laws of human society declared to have been proved.“[1] An especially embarrassing example for ideological consequences of such tautologically metaphorical argumentation is the Social Darwinism, launched in late 19th century (see Weingart [2000] (2012) chapter 3).

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[1] Marx to Engels, 18.6.1862, in: MEW (1974), vol. 30, 249; Engels to Lavrov, 12.11.1875, in: Marx-Engels Correspondence 1875, In: Marxists Internet Archive https://www.marxists.org/archive/marx/works/1875/letters/75_11_12.htm. (Dec.11. 2017)

Against the backdrop of societal changes, massive overtaxing of the natural resources and serious environmental damage in World War II and during the subsequent post-war boom, a realignment in the world of ecosystem models occurred after 1960. Under the impact of a wave of neo-Malthusian catastrophe scenarios and disequilibrium theories, the resilience concept detached itself both from the long-established views of nature in constant balance and from the homeostasis principle relying on the cybernetic self-regulating feedback system conception introduced by Hutchinson. On the other hand, it became attached to the debates on carrying capacity, ecological disaster and enduring hazards in ecosystems, and accordingly again took over the stress- and shock-absorbing properties of the quantifiable resilience concept from mechanics and materials science as an ideal model. The rejection of the stability-oriented homeostasis guiding idea with its reliance on the return to the "principle of biotic balance" (Park 1949, pp. 507 f.) always following the corresponding disturbances led, in the course of the decade, to a general dynamization and increase in complexity of the ecological system concept and, at the same time, to a rebalancing of socio-ecological adjustments and economic innovations (see Shrader-Frechette and McCoy 1993, pp. 32-47). This paradigm shift in the ecosystem discourse was able to link up with a direction of research that, owing to empirical investigations of the dynamics and density of biological populations in their respective habitats, had already called into question the prevailing stability and equilibrium concepts since the late 1930s.

The starting point here was formed by the deliberations of Charles S. Elton in his "Animal Ecology" of 1927 regarding the frequent failure of the "normal checks" in animal populations, since "the great instability of environment" unavoidably caused strong fluctuations, as well as animal pestilences and invasions, with serious effects for the environment: "The balance of nature does not exist, and perhaps never has existed" (Elton 1927, p. 111). Stimulated by Elton's dismissal of the stability and community concepts, the American pioneer of vertebrate ecology Paul L. Errington then advanced a number of long-term studies of "predator-prey relationships" in the 1930s/40s to demonstrate that the assumption of a "biological equilibrium" constantly asserting itself in cyclic oscillations through the competition for food was untenable. On the contrary, the fundamental vulnerability of animal populations and habitats as a result of weather or climatic variations and human interventions were only balanced out by dynamic changes in the equilibrium conditions, e.g. through compensatory reproduction or through behavioural adaptations, such as intercompensation with the food sources, resulting in a "reproductive resilience" (Errington 1942, p. 179; Errington 1943, pp. 876, 900.). Since no return to a similar state occurred here, Errington never referred to homeostasis; rather, he directed his attention to the conceptual world of "material resilience" with its central motif of stress and shock absorption and the quantification of load limits. Accordingly, about 1940 he introduced both the resilience notion and also the "threshold concept" into the ecosystem discourse, namely as an independent approach to the "carrying capacity" (Errington and Hamerstrom 1940, p. 809; Errington 1945, pp. 11 f.; Errington 1946, pp. 162 f., 227, 236; Leopold [1933] 1986, pp. 51 ff.; for the threshold concept see Brush 1975, pp. 799 ff.; Dhondt 1988, pp. 338 ff.) Unlike Aldo Leopold's static perception of carrying capacity as a fixed maximum density, Errington also considered "threshold *changes*" at this time (Errington 1946, pp. 162 f., my emphasis). With the observation that these depended strongly on the variability of animal populations and food sources, he also echoed the "diversity-stability hypothesis" going back to Darwin, which experienced its great breakthrough in the middle of the 1950s (MacArthur 1955). He came to the conclusion that, for all the human interventions in nature with regard to possible extremes of weather, it was essential to maintain "buffers" and "thresholds of security" to prevent collapses of the ecosystem (Errington 1945). With that, he anticipated views that are often assigned solely to the Canadian ecologist Crawford S. Holling.

3 The origins of the ecosystem resilience theory by Crawford S. Holling

Whereas the early resilience studies were still largely descriptive and usually based on statistical series, a systematic application of mathematical and analytical methods also came about in the field of ecology, in a manner similar to that of the stress and loading examinations in the materials sciences. Here the aim was to achieve more precise forecasting of the balancing of population drops after serious disturbance events. The objective soon shifted from upholding the status quo in the sense of "American conservationism" towards the utilization of natural productivity and resource management. For instance, the zoologist and ecologist Oliver P. Pearson simulated in 1960 (pp. 507 f.) the effects of interventions of varying intensity by "hunting regimes" on the "resilience" of animal stocks in order "to provide the necessary increase in resilience" with the aid of a special analog computer he had developed. In this regard, he did not expect a return to the former equilibrium, but rather an oscillation about and levelling off at a "new equilibrium at a population density". Depending on the applicable resource management, a number of equilibria would then be possible, and the goal was now to find out how, with the aid of system analysis methods, the natural yields could be increased without infringing boundary or threshold values and thus jeopardizing the resilience of ecosystems (see Watt 1966, pp. 6 ff.; Watt 1968, pp. 50; Pimentel 1966, pp. 26 ff.). In contrast to the stability models of homeostasis, resilience hence became a corridor for the intensity of use of the natural productivity and a research instrument for optimizing ecosystem services. Although the key person in this paradigm shift, C. S. Holling, found primary elements of the ecosystem resilience theory to be already available, he was the first to integrate them, from 1965/66, in several phases to obtain a closed system (i.e. process model) and integrated strategy concept for resource management. Through this work, he became one of the conceptual founders of "ecological economics", which to a great degree has shaped the socio-ecological – and even the general – understanding of resilience up to the present day.

Holling's baseline was also provided by empirical studies on the regulation mechanisms in the predator-prey systems, which he initially incorporated in a purely descriptive manner into the dissertation and then, in the subsequent studies, refined through more and more complex systems of equations, integrating them with system analyses and system techniques to yield predation models. Whilst he did address Errington's "thresholds of security", he did not yet include these and the resilience notion in his own explanatory approach (Holling 1957, pp. 127 ff.). The constant growth in the complexity of population dynamics prompted him to seek recourse to the theory of dynamic systems and to the thorough application of computer models and simulations, with which he ran through various theoretical assumptions on the empirical material. As the cause of the complexity, he recognized the non-linearity of the dynamic behaviour, which resulted from the multifarious interdependencies of the "components of predation": "thresholds, limits, lags and discontinuities" as well as historical, spatial and structural characteristics of biological systems (Holling 1964, p. 335). Nonetheless, he did not as yet divest himself of the prevailing stability concept; like a number of authors before him, he viewed high biodiversity as the best prerequisite for a "stable regulation of prey populations" (Holling 1965, p. 53).

The first presentation of his theoretical approach in the year 1966 coincided with a convergence towards the environment and growth criticism of the 1960s. For the first time, he now used the notion of resilience, but assumed a close interaction with homeostasis: "These mechanisms are homeostatic or feedback processes that tend to resist change and promote stability." (Holling 1966, p. 196) The "resilience of mother nature" still appeared to be relatively intact to him on the whole, because it was the outcome of the evolutionary adaptation of organisms and animal populations to changes in the environment and to human interventions (Holling 1966, p. 196). In particular, the "complex interactions" and the large number of "interconnections" in the food chains had created the "overall stability" and thus the "resilient nature of ecological systems" (Holling 1966, p. 197). Even at a later stage, he shared the "Gaia" hypothesis of a "global biochemical homeostasis" (Holling, 1986, pp. 293 f.). However, in the immediate present, he viewed it as being acutely at risk, owing to the threat of overpopulation, the depletion of non-renewable resources of energy and material and, not least, through the nuclear threat: "These effects seem great enough and extensive enough to threaten that resilience of ecosystems that had provided such efficient buffer for man's ignorance." (Holling 1966, p. 197) Thus he had found access to the conceptual world of the "Limits to Growth" debate of the Club of Rome.

Appointment to an endowed chair of the Ford Foundation for the "Resources and the Environment" programme in 1967 and, above all, the prospect of a major research project with UNO funding, which opened up to him in 1970, at the "International Institute for Applied System Analysis" (IIASA) in Laxenburg near Vienna then led to a shift in his research agenda towards resource management and strategies for change processes. Here the comparative view of ecological and social systems, as well as their interactions, gained him a series of new insights, which in 1971 culminated in a clear conceptual demarcation of stability and resilience, and to a "turning point in complexity theory" (Schrickel 2014, p. 9; on the following Holling and Goldberg 1971):

- Until now, ecosystem theories generally followed calculable physical-mechanistic system and stability models. As a result, homeostasis and cybernetics aroused the incorrect impression of uniform regulation principles in engineering and in ecosystems. However, a fundamental distinction must be made between the stability orientation of simple physiological and technical “control feedback systems”, which act within a naturally occurring or defined narrow spectrum “near equilibrium” and the resilience orientation of ecological systems that are determined by “multi-equilibria” undergoing constant change. After disturbances, they do not return to a state of equilibrium, the “point of equilibrium is shifting and changing over time”. Depending on the environmental conditions, their “domains of stability or resilience” vary with time and thus require a permanently flexible adaptation to change (p. 225).
- Ecosystems are not modular systems; they owe their resilience above all to their inhomogeneous structures, interdependencies and their network character. Large-scale selective interventions always lead to side effects and unexpected consequences. The strategies of incremental change, linear efficiency gains and economies of scale practised by government and industry have led to a strong reduction of the ecological complexity in nature management and to the establishment of “large monocultures” in industry and commerce (p. 224). This often disregards the “borders of resilience” and reduces the potential for stress and shock absorption.
- Through its efforts to control non-linear processes by applying methods of system analysis, ecosystems theory has fallen into the hypercomplexity trap. Planning and management could only escape it by focusing on the “ecological control schemes”, i.e. on “smaller scale interventions and decentralized efforts rather than large scale monolithic approaches.” (p. 224). Instead of centralized planning and control, ecological and social processes should be entrusted more to decentralized self-regulation and self-organization: “the system can cure itself if given a chance” (p. 228).
- This results in the institutional consequence for science as well as for business and society: “We must reduce the size of our institutions to ensure their flexibility and respect for the system of which they are a small interacting part.” (pp. 228 f.).

The further systematization of Holling’s resilience concept was already influenced by the large-scale research institution IIASA, at which he worked from 1973 to 1975 and then again as its head from 1981 to 1984. Here he was confronted with a scientific culture oriented towards Big Science and Big Technology that radically contradicted his ideal of science and his understanding of resilience. This was so because the IIASA programme was dominated during these years by the mega-project of the “Energy Systems Group”, which, under the leadership of the nuclear physicist and manager Wolf Häfele, developed a “global systems analysis” for a permanent world energy supply by 2030 that was increasingly based on fast breeder technology (Häfele and Manne 1974, pp. 3 ff.; Häfele and Sassin, 1976). In spite of differing objectives and research styles, the large-scale research operation and the cooperation relationships left a clear mark on the direction of Holling’s research concept. A special role was played by the methodology project of the informal “Resilience Group” formed by both teams, in which a debate on resilience in energy supply systems took place for the first time in 1974–76 (see esp. Schrickel 2014 and 2017).

His IIASA research proposal (Holling 1973a) and even more clearly his famous article "Resilience and Stability of Ecological Systems" from September 1973, originally conceived as a theoretical framework for Ecology Systems Group projects, already signalled the reorientation towards the development of a scientific, planning and management concept for a strategic linkage of the resilience of ecological and social systems (Holling 1973b). The aim was to create a "resource science" and a "new science of ecological management/ engineering" (Holling, Chambers 1973, 13; Holling, 1974, p. 1), which aimed at giving recommendations to companies and governmental and societal decision-makers: "We offer, as an alternative, the process of adaptive environmental management and policy design, which integrates environmental with economic and social understanding at the very beginning of the design process, in a sequence of steps during the design phase and after implementation." (Holling 1978b, p. 1). The planned "resilience framework" should result in an "ecosystem engineering" concept targeting a system architecture of a "decentralized technology", which exibit the „properties of resilience and stability and the ability to survive under great uncertainty [...]: diversity, spatial and temporal heterogeneity, flexibility, small scale processes" (IIASA 1973, pp. 13f.).

For use in planning and management the "resilience framework" was operationalized by means of dynamic models, ecological indicators, approaches to measurement concepts and standards for the evaluation of economic and social costs and the efficiency of environmental protection measures (Holling 1973c; IIASA 1973, p. 10). An essential precondition for choosing trajectories and defining usage zones of ecosystems was an reliable determination of the margins of changing equilibrium points, which he now modelled by the physical metaphors of „potential fields" or „basins of attraction" (Holling and Goldberg 1971, pp. 224 f.; Holling 1973b, pp. 3 ff., 20). Furthermore a first taxonomy of "components of resilience" was developed for ecological and social systems. The "persistence promoting mechanisms" included: 1. system-internal feedbacks and adaptive capacities ("boundary components"), 2. buffer zones of non-perturbed parts of the system ("restorative components"), and 3. system-external alternatives on the basis of diversity of resources ("contingency components") (Holling 1974, pp. 6 ff.; Clark et al., 1975). With the help of these instruments, the socio-ecological system design was intended to work towards ensuring that future events could be absorbed "in whatever unexpected form they may take." (Holling 1973b, p. 21). "The resilience concept", he envisioned in the face of unexpected perturbations, "provides a way to develop a planning framework that explicitly recognises the, area of our ignorance rather than the area of our 'knowledge." (Holling 1973a, p. 3). The further expansion of this framework in the subsequent years was strongly influenced by the intensive theoretical debates at IIASA.

4 The controversy at IIASA about the principles of resilience and architectures of resilient energy systems

The theoretical discussion at IIASA between the Ecological Systems Group and the Energy Systems Group was characterized from the outset by major differences and conflicts. Holling and his research group generally rejected nuclear energy, large-scale technical monocultures and centralistic system architectures as being incompatible with the resilience goal. Initially, their guiding idea was rather focused on decentralized, small-scale, communicative supply structures. Häfele's Energy Systems Group, on the other hand, advocated large-scale system architectures that aimed, in the long term, at the global organization of a nuclear-dominated energy supply. At the beginning of 1974, however, Holling's draft theory of September 1973 led to a cross-project methodological discussion on the principles of resilient energy systems and, in general, on the concept of resilience. Häfele saw this as an opportunity to eliminate the massive legitimacy deficits of his energy policy programme, which was burdened with high risks and uncertainties, and to give it the appearance of an ecosystem-compatible energy system architecture with the help of the resilience notion. In the methodology workshops of both project groups, he effectively hijacked the term and tried to modify it to justify large-scale overall solutions for world energy supply: "IIASA's notion of resilience here applies to large energy systems rather than to single, weakly interacting small entities." (Sassin et al., 1977, p. 4; see also Schrickel 2014, p. 19 or 2017, p. 145 f.) The realignment affected the way of addressing the unknown and unpredictable as well as dealing with risks and errors, measuring concepts and design principles for resilient energy systems.

Since the high-risk large-scale deployment of the fast breeder technology could no longer be verified by trial-and-error engineering methods, due to the many unknown factors and non-linearities, Häfele felt that there was a structural agreement with ecosystems, and therefore he wished to replace his own little-accepted concept of "hypotheticality" with the recognized notion of resilience: "The Energy group has been much influenced by the Ecology group, and in particular by the notion of resilience conceived by C. S. Holling to express a systems behavior that strives for the capability to absorb shocks. The system changes through absorption but continues to exist." (Häfele 1976, pp. 83 f.). Häfele immediately incorporated the term into his energy-economic model and, with that, even hoped to create an exemplar for other sectors of the economy (Häfele 1974). The notion of resilience even found its way into the much-discussed energy scenario "Energy in a Finite World" in 1981. Häfele also saw many similarities with Holling in the assessment of risks and appraisal of errors. Because the unpredictability of the "maximum credible accident" and the "residual risks" of nuclear technology mean that disturbances cannot be ruled out from the beginning, it is necessary to minimize the consequences and costs through resilient design principles in analogy to ecosystems, so that they remain ecologically compatible and socially acceptable in the context of the other risks (Häfele 1975, p. 8). He therefore argued in favour of introducing resilience as a third level of risk management alongside the "engineering of safety" and "probabilistic methods" (ibidem). Here the intention was to have it apply to non-linear systems with thousands of system states. A prerequisite for this, however, was the quantification and system-related operationalization of the resilience concept, which was still purely qualitative (Clark and Swain 1975, pp. 7 f.). Häfele's team therefore tried to achieve a precise mathematical definition of "Holling's very general and rich resilience concept" as well as a breakdown of the overall resilience into calculable "basins of resilience" (Grümm 1976, p. V). Contrary to Holling's intention, such a "resilience concept in rigorous mathematical terms" was ultimately based on a tendency towards a deterministic understanding of resilience (Grümm 1976, p. 7; see also Häfele 1976, p. 84). Finally, Häfele used the resilience concept to justify and legitimize the energy system architecture he had conceived. In doing so, he implicitly developed a catalogue of criteria for the design of resilient energy systems that was mainly oriented towards nuclear large-scale technology:

- Comprehensive CO_2 avoidance through successive substitution of fossil fuels by nuclear energy
- Maximum utilization of finite nuclear fuels through closed-loop recirculation and the breeder technology, which would create a virtually infinite source of energy – a "sustainable energy source" in Häfele's sense of the term
- Resource diversity through the use of all energy sources within the optimal range of operation in each case
- Secure energy supply thanks to the base-load, reserve and buffer capacities of the energy mix: "This will ensure stability and resilience of the total energy system." (Häfele 1981, p. 96)
- The use of economic renewable energies and the integration of "small-scale technologies" not adequate by themselves into an ever-available nuclear energy system and electricity grid: "A fine-grained electrical generation network has so much resilience that it can virtually function as an energy storage system as well." (Häfele 1981, p. 140)
- In the long term, total CO_2 avoidance and substitution of fossil fuels by means of coal gasification, methanation and hydrogen technology, on the basis of virtually unlimited nuclear energy with the long-term goal of attaining zero-emission energy supply.

Despite all his satisfaction with the important role of the resilience concept as a theoretical bracket for both IIASA projects, Holling resisted Häfele's appropriation and remodelling of his theorem. He asserted the basic distinction between stability-oriented "engineering resilience" and instability-based "ecological resilience". He insisted on his "fundamental goal toward which all his work was oriented, [...] to design 'a world without hypotheticality' [...] In this sense, he saw the work of many engineers, even (and perhaps especially) the most visionary, as antithetical to his own goals." (Clark and Swain 1975, pp. 8) His guiding idea of "resilient/ adaptive design", on the other hand, relied on technical systems that are not dependent upon a strict avoidance ("*fail-safe design*") of errors – which are not predictable anyway – but upon systems that allow for errors, keep options open and thus enable learning effects (a "*safe-fail strategy*" or "designing for flexibility") (Clark and Swain 1975, pp. 16 ff.; see also Holling 1974, p. 7; 1978a). Accordingly, Holling did not accept the use of the resilience concept for nuclear energy, because this sector was fraught with extremely high failure costs and operated with dangerous unknowns, especially when used on a large scale, and because of the risk of proliferation, necessitating complete control: “Our trials are capable of producing errors larger and more costly than society can afford.” (Holling [1976] 1982, p. 9). Holling therefore referred to the high-risk proposals of the Häfele team for huge nuclear parks, for floating “energy islands” that supply entire continents, and for hydrogen pipelines spanning the globe as being “bad science fiction”. Above all, he considered Häfele’s methodology of using hypotheses, prognoses and alternative scenarios as the basis for strategic path decisions to be nothing less than fatal (Holling [1976] 1982, pp. 9, 15). For Holling, these foundations were even mythical in character, because they only partially described reality and were hardly tenable, an assessment that was confirmed a few years later by several criticisms, in part devastating, of the energy scenarios put forward by the “Energy Group” (Lovins 1981; Keepin 1984, pp. 231-134; Häfele and Rogner 1984; Wynne 1984).

However, within the framework of the “Methodology Project” at IIASA, Holling scarcely managed to achieve a counter-draft to the Häfele team’s “global structure resilience” beyond the defence against a large-scale reinterpretation of his resilience concept (Sassin et al., 1977, p. 4). Only one contribution among his numerous IIASA papers and other essays dealt specifically with questions of energy technology and policy, and even in this he left it at general recommendations for system architectures, which he had gained from ecosystem studies. The impetus for his lecture “Myths of Ecology and Energy” in October 1976 was provided by the first official reaction of the engineering community to the “soft vs. hard energy path” controversy triggered by the English physicist Amory B. Lovins (Lovins 1976; more on this Hellige below). During the workshop on the architecture and dimensioning problem of the future energy system, Holling found himself positioned between Lovins, as the radical advocate of decentralized renewable energies, and Alvin M. Weinberg, as the proponent of a highly centralized nuclear energy system. Although Lovins had already dealt intensively with the interrelationship between energy and ecosystems and referred in his contribution to the ecodisaster theory and the ecosystem resilience concept, Holling only supported Lovins in the question of the dangers of nuclear technology, but not regarding his future model of a purely solar decentralized energy system architecture, with which he himself had previously sympathized (Lovins [1976] 1977; Holling [1976] 1982).

Holling considered the argument between the hard/soft path supporters to be a mere pseudo-discussion, which he attributed to the respective one-sided models of equilibrium and views of nature. Whilst the representatives of the centralistic “Big is Necessary” strategy presumed a “myth of stability near equilibrium” and a “benign and infinitely forgetting nature”, the "Small is Beautiful" position were based on a “myth of instability” and a highly endangered “ephemeral nature”, and therefore focused exclusively on renewable energies and a “fine-scaled, local autonomy” ([1976] 1982, p. 9 f.). As a way out of these mutually obstructive extreme positions, Holling offered his “myth of nature resilient”, which was based on the assumption of stable zones within the boundaries of the “multi-equilibria world” and thus allowed for both “Big is Necessary” and “Small is Beautiful” system architectures. Large-scale solutions would only have to focus on “boundaries” between “desirable” and “undesirable stability regions" and recognize their dependency on local interactions: "small is necessary for big to be" (ibidem, p. 12 f.). Decentralized forms of organization, on the other hand, required integration into a larger system as a buffer for local activities. Ultimately, the decisive factor for a resilient system architecture was that it could master the complexity and retain the ability to change, and also use it productively (ibidem, p. 14).

For the organizational design of resilient system architectures, Holling drew on the *hierarchy* metaphor that Herbert A. Simon had designed in his "Architecture of Complexity", which had set a precedent during the 1960s and 1970s as a counter-model to centrally controlled and decentralized self-organized forms of organization (Simon 1962). Like Simon, Holling regarded the hierarchically structured division of labour as a universal master template of physics, chemistry, biology and society, since it facilitated the "evolution and survival of complexity" and enhanced flexibility and resilience (Holling [1976] 1982, pp. 14). For him, the maxim "hierarchies of function versus aggregations of scale" formed the ideal organizational guiding idea for technological, environmental and social systems as well as the best solution for the problem of dimensioning and structuring energy systems. In a "richly articulated hierarchical structure loosely analogous to a complex ecosystem", the lower or local levels would have scope for action and development without endangering the whole system (ibidem, pp. 14 f.). Thus Holling referred to a social science theorem for the system structures of biological and ecosystemic systems. With his theoretical "crossing over", he created a well-received basic model of structures and dynamics that were of an ecosystemic nature as well as relating to general systems theory, but he did not concretize this model for resilient energy and technology systems. The further development of the general principles of resilience to obtain a design theory of energy technology and sociotechnical systems was thus not carried out by Holling and the research group assembled around him, but only in a second attempt in the alternative energy technology community by Amory Lovins on the basis of metaphor transfers specific to technology and infrastructure (see Hellige below).

5 The completion of Holling's resilience concept as a theory of adaptive change and cyclical transformation

The reorientation from predictable to unpredictable system conditions, and from ordinary to extreme disruptive events, then led to a departure from the previous management goals of stabilization and homogeneity of structures towards the strengthening of robustness, self-healing powers and the readiness for change in unclear structures. It was no longer a question of avoiding fluctuation and crises, but, on the contrary, of consciously allowing and using them as factors to increase resilience. Based on a comparison of the system dynamics of fish and insect populations, Holling had concluded that stable "self-contained systems" with low variability and low disturbances are most likely to collapse in the event of unexpected shocks, while ecosystems continually exposed to unexpected "traumas and shocks" survive due to the "internal resilience" they have acquired (Holling 1973a, p. 2 f.; see also 1973b, pp. 6 ff.). It is precisely the instability, variability and heterogeneity arising from permanent competition and selection pressure that increase the "capacity to persist": "Therefore, a major strategy selected is not one maximizing either efficiency or a particular reward, but one which allows persistence by maintaining flexibility above all else. A population responds to any environmental change by the initiation of a series of physiological, behavioral, ecological, and genetic changes that restore its ability to respond to subsequent unpredictable environmental changes." (1973b, p. 18; see also Holling 1974, pp. 4 ff.)

This resulted in the rule that the more homogeneously an environment develops in space and time, the lower the pressure to adapt, the willingness to change and the corresponding level of resilience. For Holling, resilience ultimately proved to be an evolutionary and social selection product, and in retrospect he saw the essence of his ecosystem research in a quote incorrectly ascribed to Darwin: "It is not the strongest of species that survive, nor the most intelligent, but the ones most responsive to change" (Holling 2016, p. 63)[2]. It was this application of biological and ecological arguments to economy and society which later encourages the "neoliberal concept of insecurity by design" (Evans and Reid 2014, p. 2) and the Darwinistic re-interpretation of resilience as permanent challenges of flexibility, adaptability and transformability (see Zolli and Healy 2012, pp. 7-11 and about "new liberal biopolitics" chapter 5 and 6).

Besides the management orientation, the IIASA years also motivated Holling to engage in a closer partnership of ecology and economy. In addition to the idea of ecosystem services, he now saw resilience as a natural reserve *capital*, the quantity and quality of which must be determined in order not to risk an overuse of the "environmental *capital*": "It is this remaining capital inventory that buffers the development in case of the appearance of unexpected and unhappy consequences." (Holling et al., 1974, p. 60). However, in striving to combine the best

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[2] This alleged Darwin quotation circulating in management literature originated from the Professor of Management and Marketing Leon C. Megginson; see the Darwin Correspondence Project at the University of Cambridge: https://www.darwinproject.ac.uk/people/about-darwin/six-things-darwin-never-said/evolution-misquotation. (Dec.11. 2017)

of “ecology/economics modelling” (Holling 1974, p. 3), he encountered the problem that the prevailing neoclassical economy with its physics-inspired “oscillating equilibrium” dogma did not harmonize with his resilience concept. Then again, through the joint theory projects of the Ecological Systems Group and the Energy Systems Group at IIASA, Holling came to know different biology-inspired approaches of non-equilibrium economics, which influenced the further development of his theorem decisively. These included in particular the long-wave models of the main energy resources proposed by Cesare Marchetti and Nebojsa Nakicenovic, which, based on the biostatistical population curves (S curves) of Pearl and Reed (1929), represented the transformation of primary energy sources in the form of logistic substitution models (Marchetti 1975; Marchetti and Nakicenovic 1979, pp. 2 ff.). Häfele even attempted to use Holling’s non-linear models of biological and ecological detachment processes to model long-term socio-economic forecasts (Häfele and Bürk 1976; Bürk and Häfele, 1976). Around 1980, Marchetti and Häfele used Kondratiev waves and, above all, Joseph Alois Schumpeter’s theory of innovation cycles, which had been experiencing a veritable renaissance since the mid-1970s, to explain the substitution dynamics model approach, which was soon extended to means of transport and other technologies. The IIASA quickly became a centre of the debate on the theory of long waves and innovation theories, and under Holling’s direction it even became a research focus in the IIASA programme (see Vasko 1987).

Schumpeter’s innovation theory gave Holling the decisive impetus for further development of his resilience concept from a theory of dynamic ecosystem processes to a socio-ecological and socio-economic transformation theory. In the course of economic development, Schumpeter no more saw a quantitative growth process that fluctuated around equilibrium states, but rather a qualitative “process of economic change or evolution” (Schumpeter 1939, p. 138) structured by innovation, diffusion and detachment phases. His economic theory was no longer based on the central metaphor of physical equilibrium mechanics as in neoclassical economics, but on biological evolution, which was subject to constant adaptation and displacement: “Obviously, we have here a different process before us, involving different facts and concepts such as *selection* or *mutation* or, generally, *evolution*.” (ibidem, p. 36). A decisive factor for economic *life* and cyclical “evolution” is the “industrial mutation”, which “incessantly destroys the old structure and incessantly creates a new one.” (Schumpeter [1942] 1950, pp. 137 f., my emphases). In Schumpeter’s “process of creative destruction” (ibidem, p. 81-86), which stabilizes capitalism continually in a new form through constant change, Holling recognized the economic equivalence for the dynamics of his “multi-equilibria ecosystems” (Holling 1974, p. 5). Holling consequently took an active part in the renaissance of Schumpeterianism of the 1970ies and, as many followers of the reinvented „evolutionary economics“, he now viewed the entire economy „as an evolutionary system, with Schumpeterian innovations serving as one of its mutational mechanisms.“ (Simon 2005, p. 87; see also Sloep 1997 and Hodgson 2005).

This became as well the starting point for a redefinition of his resilience concept on the basis of innovation theory. Just as Holling referred to Herbert Simon for the organizational design of resilient system architectures, he also built on Schumpeter’s innovation theory for the model of the evolutionary dynamics of ecosystems. Now Holling no longer understood under "resilience" primarily "strike absorption capability", but the "property that allows a system to absorb and utilize (or even benefit from) change." (Holling 1976, p. 14). He took Schumpeter's phases of innovation, prosperity, recession, depression and recovery as an exemplar for his own transformation model of the "adaptive cycle", with which he organized the systemic services of ecosystems as a developmental model of accumulation and reorganization phases of the "natural capital": "The full dynamic behavior of ecosystems at an aggregate level can therefore be represented by the sequential interaction of four ecosystem functions: exploitation, conservation, creative destruction, and renewal." (Holling 1986, p. 307). Following Schumpeter, the "paradoxical phase" of destruction and reorganization plays the dominant role in the adaptive cycle, for in it "high risks are matched by great opportunity." (Gunderson and Holling, 2002, p. 326) Instead of change of social-ecological conditions the adaptation of behaviour, self-regulation and transformability in a chaotic, uncertain and unpredictable environment became the core of resilience thinking. In the adaptive cycle concept a process of permanent "deliberate transformation [is] breaking down the specific resilience of the old and building the resilience of the new" (ibidem, see also Folke 2016). Thus, in "evolutionary resilience" (Davoudi 2012, pp. 302 f.) a model of socio-economic development based on a biological metaphor served as an example for a phase construction of biospere and ecosystem development and so Joachim Bauer's thesis seems to be confirmed here too, namely that biologists orient their organizational models to the prevailing economic order and theory (Bauer 2008, pp. 152 ff.). Biology and Ecology had always been particularly susceptible to such metaphorical short-circuits, with which structural models of economy and sociology were transferred to "natural *balances*", "plant or animal *societies*" and "ecological *cycles*", whose models in turn served human societies as guiding ideas, being exemplary organizational patterns from nature. By this, 'learning from nature' could be a self-deception if nature previously was modelled after social examples.

Otherwise, as a result of these multiple transfers, Holling's ecosystems theory became compatible with further branches of science and hence, in the following years, developed into an initial nucleus for a cross-disciplinary theorem of cyclic transformation, which brought together the "existing theories in economics, ecosystem science, institutional research and adaptive complex system theory" into the resilience concept (Holling 2003 p. XVI; see also the precursor of the Panarchy Framework in Holling 1986, pp. 293 ff.). In the subsequent "Resilience Project", which was concluded with the "Panarchy Framework" of 2002, Holling and a group of researchers inspired by him expanded the "adaptive cycle" approach to obtain a "unifying concept", which as a new supertheory should replace the traditional physical paradigm. (Gunderson and Holling (eds) 2002; Thorén 2014). Promoted by the hegemonic system-theoretical approach of the 1999 founded "Resilience Alliance" *resilience* got an umbrella term, uniting the until then separated disciplinary notional traditions and penetrating into further sciences. Accordingly annual numbers of resilience publications increased since 2000 remarkably and displaced the till then dominating sustainability notion (Xu and Marinova 2013; Baggio et al., 2015).

This opened up new interrelationships beyond the disciplinary boundaries, but as a “boundary object” resp. “bridging concept“, resilience theory missed precision and validity and like bio-cybernetics and homeostasis, repeatedly succumbed to the temptation to overestimate the structural identities of ecosystems, economy, technology and society created by multiple transfers (see Brand and Jax 2007; Davoudi 2012). Ultimately, as Holling himself pointed out, the “metaphorical reasoning” was not without its problems: “Analogies are dangerous instruments, and this in case the transfer should be made only when the structure and behavior of urban systems appear to be similar to the structure and behavior of ecological systems.” (Holling and Goldberg 1971, pp. 226). In addition, the transition of the resilience concept to a socio-ecological and socio-economic transformation theory led to the problem that it could be decoupled from its genuine normative sustainability goals and could then be used for arbitrary social system architectures and processes of change. On the whole, the historical reconstruction of the genesis of ecosystem resilience theory raises the question as to whether strategies of sustainable management require a complex theory of evolutionary economics, which is essentially based on the economization of ecology and a bio-ecologization of economics. Through the creation of similarity relationships, metaphor and concept transfers have an important function in the generation and expansion of knowledge, as well as in the initiation of interdisciplinary discourses. With “analogical reasoning”, however, the origin of metaphors and their accompanying contexts should always be kept in mind to avoid any miscarriages through metaphorical excesses and short-circuits.

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The reception of the resilience concept in the energy discourse, and genesis of the theory of resilient energy system design

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Abstract

The concept of resilience in energy systems and the derived principle of resilient energy system design are prominent results of metaphorical thinking in technology. They combine two metaphorical processes: the transfer of biological/ecological system models to energy systems and the transfer of less vulnerable decentralized information/communication network-architectures to power infrastructure networks. This chapter reconstruct the roots and the development steps of the concept of resilience in energy systems, starting in the alternative energy discourse in the early 1970ies and ending in the first elaborated theory of resilient energy system design by Amory Lovins in 1982. The historical discourse analysis will go into details about:

- Transfers of metaphors and guiding concepts in energy and communication infrastructure systems
- Countercultural debates about small distributed, self-organized soft energy systems condensed in Schumacher's principle of „appropriate technology"
- Lovins' introduction of entropy law, thermal carrying capacity of earth, ecodisaster research and the „biological metaphor" into the discourse stimulating the first resilient energy system design debate in late 1970ies
- The first integration of the 'Energy Internet' metaphor into the resilience discourse: The „Power Systems 2000"-Scenario of the „Homeostatic Control Group" and finally
- The multidisciplinary synthesis of the resilient energy system design-debate: The distributed computing-inspired study „Brittle Power" of Lovins/Lovins

As a summary of the early history of the the resilience-debate in the energy sector, it can be concluded that how stimulating the ecological resilience concept has been for this discourse, analogies with *bio-ecological* systems do not suffice for the resilience assessment and design of *energy* systems. The theory of resilient sociotechnological systems design therefore requires resilience concepts that are emancipated from natural analogies and that are based on metaphors corresponding with the specific principles, structures and social architecture of the technology in question.

1 Transfers of metaphors and guiding concepts in energy and communication infrastructure systems

Metaphors have always played an important role in the search for solutions and in defining the “Gestalt” for system and product development. Even for large-scale infrastructure systems, the history of technology and the research into the social shaping of technology have identified an entire series of metaphor transfers, but these *system metaphors* have not been subjected to comparative examination thus far (Hughes 1989, pp. 75-83; Flichy 1994, p. 57). And yet the *structural metaphors*, analogical models of “social architectures” and *process metaphors* that are widely encountered, especially in supply, transportation and communication systems, point to interrelationships in the system structuring, the social organization of the infrastructure systems and the system dynamics of transformation processes. In the past, such metaphors have often been accorded the nature of guiding ideas which then had a normative effect on processes for the social shaping of technology, in that they questioned dominant system structures through alternative guiding concepts or legitimated “technical fixes” or technological trajectories with guiding ideas from the status quo. Over and above that, paths and goals of system dynamics were mapped out with the aid of prognoses, explorative or teleological development scenarios or even developmental laws, hence lending certain guiding ideas a paradigmatic validity.

Famous examples of technology and system metaphors in infrastructure systems include Edison’s invention of the quadruple telegraph system on the basis of the water supply network and of the electrical lighting system as a conscious analogy of the municipal gasworks. The central power station, for its part, served as a system metaphor for the central telephone exchange, which initially led to oversized exchanges in the larger cities – a system bottleneck that was only overcome by subdivision of the network and hierarchization of the network nodes. After the successful transition to the long-distance supply of electricity and the system of interconnected power exchange, the gas sector itself then followed the example set by the electricity industry, by establishing a system for long-distance gas supply as well as plans for an “interconnected gas supply system” on a national scale. In the beginning, the first computer networks were also oriented towards the existing systemic model of supply systems, i.e. the centralized system with a star topology, whereby the public time-sharing systems were even consciously based on the centre-focused utility model of the central gas, water and electricity supply points through use of the term “public computer utility”. By contrast, the American military research network ARPANET and the resulting Internet transitioned from centralistic connection structure to a decentralized multi-node network without a central control entity, out of consideration for the military vulnerability. The model for this structure was the network architecture of the classic telegraph system, which, owing to its origins, had been based on the node topology of the railway network. On the other hand, the terms “data packet” and “packet switching” in computer communications also refer to the analogies to the postal distribution of packages (see Hellige 2008, pp. 144-149). Comparison of the process of decentralization from mainframe to personal computer with the transition from rail transport to automobile traffic therefore fulfilled more of a legitimization function than that of role model. Beginning with the end of the 1960s, the first formations of local networks for data terminals and PCs were modelled on the private branch exchanges or “local areas” of the telephone system, and hence received the designation “local area networks” (LAN).

Starting in the late 1980s, conspicuously contradirectional metaphor transfers occurred in the energy and IT sectors during the course of the overlapping formation of large-scale networks and recentralization of the computer networks and the efforts towards decentralization of the power grids. For the federative amalgamations of supercomputers, with the goal of achieving a more effective utilization of computing capacities, the focus was on the model of the *early* networking of electrical power plants; one therefore used “*grid* computing” and more rarely “*utility* computing” as the guiding notions (Borbely, Kreider 2001, pp. 47 ff.). However, with regard to their centralization concepts of “network computing” in the 1990s and “cloud computing” from 2000, the major IT corporations referred to the analogy of the *late* highly centralized entity of the extensive interconnected electricity grid system as a means of justification. In contrast, the transfers of metaphors in the supply of electrical energy progressed in exactly the opposite direction. Here, the successful transition from the centralistic mainframe computing to the PC/Internet era served as a model for the intentional decentralization process (Hellige 2013, pp. 64-67). Analogously to “distributed computing” and beginning in the 1980s, “localized” or “distributed utilities” or “decentralized energy networks” arose, for which the term “microgrids” became accepted from 1997, followed from 2000 by the designations “local energy networks” or “local area grids” modelled after the LAN. In the first half of the 1990s, the Internet metaphor also commenced its rise in the energy debate, starting in the USA. The “Internet of Energy” soon developed into a programmatic guiding concept, whereby a multitude of terms and diverse social architecture concepts competed with each other from the very beginning. Initially, decentralized bottom-up architectures predominated, whereas after the year 2000 more and more centrally organized platform concepts came to the fore, especially in Germany. In the course of the development of the Internet/electricity metaphors and guiding ideas, various focal points of meaning and levels of consideration crystallized out; these may be classified ideal-typically as follows:

- Social networks of citizens’ initiatives for local and municipal renewable energy systems: “energy countercultures” in parallel with “computer countercultures”
- Computer networks as a metaphor or guiding idea for distributed energetic system structures compliant with renewable energy: “distributed energy” as an analogy to “distributed computing”
- The Internet as an analogy pattern for a *resilient architecture* of the energy system: Redundancy for lines, diversity for resources, dispensing with vulnerable central nodes
- The Internet as a *bottom-up social architecture* of a decentralized infrastructure system and model for the democratization of the energy sector (*crowd energy*)

- The Internet as a *top-down social architecture* of an infrastructure system implemented through central transaction- or resource-sharing platforms (*cloud energy*)
- The Internet as an expression of the increasing structural coupling of energy and information networks: from the additive to the universal digitalization of the energy market (*smart grid, e-energy*)
- The Internet as a model for the comprehensive convergence of energetic, information-based and economical infrastructure systems within the mega-infrastructure: *Energy Information Highway; Energy Internet; Internet of Services, Things, and Energy*

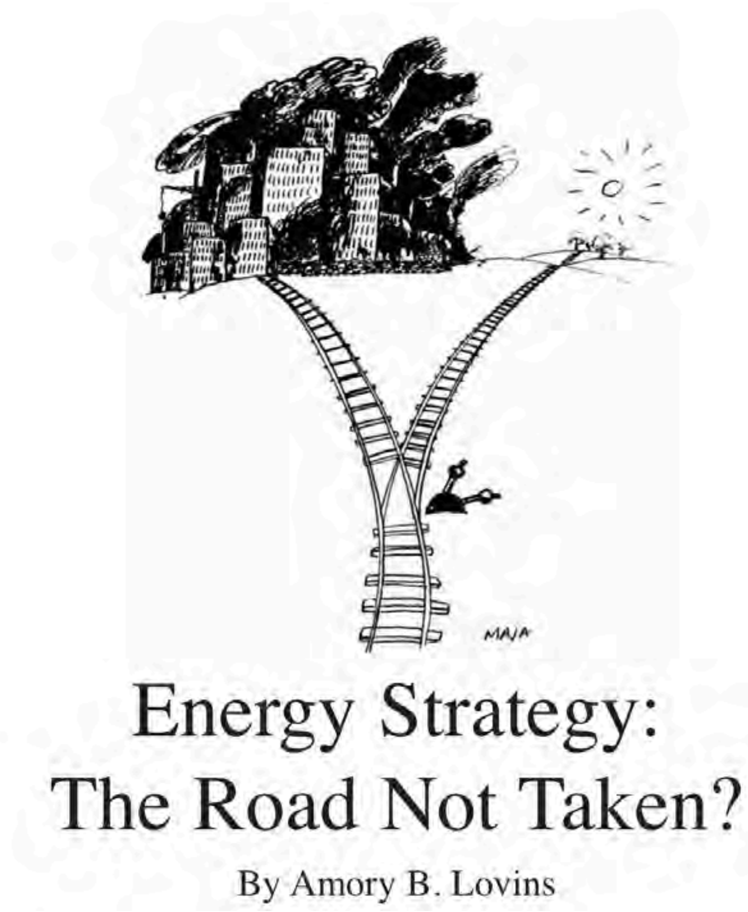
In the course of time, the transformation of the technical and social system architectures in the energy supply industry was reflected in diverse manifestations of the "internet model" and, for a time, detached itself from the resilience concept. These two metaphorical process were rejoined under the influence of extreme events, such as the catastrophes of Chernobyl and Fukushima, wide-area blackouts and, above all, 9/11. The following deliberations show in more detail the historical context in which the combination of the computer-network and Internet metaphor and resilience concept originated, and how this gave rise to a comprehensive design theory of "resilient energy systems" that proved exemplary for sociotechnical systems. However, this combination only became possible in that it let itself be stimulated by the natural metaphor, but then developed a resilience concept that was emancipated and specific to the technology.

2 Lovins' integration of guiding concepts in the early alternative energy discourse: downscaling, decentralization and ecosystem resilience

The origination of the Energy Internet metaphor during the 1980s was due to the contradirectional structural dynamics in computing and electricity supply. Whereas decentralization trends were successfully realized in the world of computing through a historically unique interplay of academical countercultures, an opposition within the scientific community was successful against the ossified computer-centre regime and military resilience strategies, the structural conservatism of the energy utilities, focused as it was on growth and monopolistic power, was long able to prevail in the energy sector against the efforts in favour of a distributed or decentralized energy generation. And this happened despite the fact that a broad countercultural movement had arisen during the late 1960s in the USA and Western Europe, also in the energy sector, a movement that aimed to oppose the prevailing large-scale centrally organized infrastructure systems by means of small-scale participatory – or even self-organized – supply facilities. In this way, citizen energy projects and local self-sufficiency concepts on the basis of renewable energy sources or combined heat and electricity supply originated at the same time as the initiatives for local radio stations, open-access TV channels and the computer lib movement. A metaphorical reference was not necessary here, because all these opposition movements were oriented towards the same values: the strengthening of the local economy and autonomy ("local skills, local resources”). The common goal was to overcome monopolies and bureaucratic infrastructures (AT&T, ABC/NBC, IBM and giant power utilities) through “radical small technologies”, such as the PC, the PV system on roofs, the fuel cell, the wind turbine and the small CHP (combined heat and power) unit.

The “second era of decentralization” initiated with these spontaneous energy-policy “initiatives from below” (Sachs 1984) for local solar- and wind-based energy systems as well as municipal CHP units and district heating plants was given its first programmatic focus through the “Small is Beautiful” book by Ernst Friedrich Schumacher of 1973, which soon made its mark on the energy and technology discourse. Because Schumacher brought the “question of scale” into the centre of the debate and countered the predominant principle of the “economy of scale” with the key values of “human-scale economy”, “appropriate technologies”, regionalization, decentralization, diversification and self-reliance, he gave the loosely linked social networks of the “off-grid”, “non-utility” and “self-reliance“ movements their first comprehensive basis for argumentation (Schumacher 1973, pp. 47-50). Prompted by Schumacher’s work, the “Institute for Local Self-Reliance” was already founded in 1974 by David J. Morris; this body aimed to further an integrative, decentralized husbandry of all resources and the re-municipalization of infrastructure enterprises (Morris 1982). It was accompanied by numerous appropriate technology initiatives which, with their energy and resource conservation programmes, also tied in with the traditions of the “American Conservation Movement”. The centre of the Self-Reliance movement was the State of California, which, through its promotion of the renewable energy sources and the combined heat and power generation, wished to become independent of foreign fuel suppliers and aimed to achieve a liberalization and even a democratization of the energy sector. Through this, and as a trailblazer for solar energy, the “Californian Way” also served as a model for the energy transition in Germany and Western Europe (Spitzley 1989, pp. 12 ff., 30 ff., 95 f.).

However, a broader discourse alliance extending beyond counterculture and conservationism only succeeded in the second half of the 1970s through the English physicist Amory B. Lovins, who worked mainly in the USA. Together with the political scientist L. Hunter Lovins, he achieved within only a few years an unequalled concatenation of discourses in natural science, ecology, energy technology and energy policy, thus leaving his mark on the line of argumentation used by the alternative energy movement of the subsequent decades, not least through particularly compelling guiding notions and guiding concepts. For the physicist Lovins, the starting point was the thermal capacity of the Earth, which is bounded by the thermodynamic law of entropy (Lovins, 1973; Lovins 1975 [1977], pp. 59-61). It set close limits on anthropogenic climate change and, in the long run, forced a departure from fossil energy sources. The orientation towards the physical barriers of the economic system and the considerable social costs of the energy transformations brought the two Lovins’s into contact with the debate about the “limits to growth”, which had been going on since the late 1950s, especially in conjunction with the approach of the steady-state economy of Herman E. Daly and the growth-critical objectives of the Club of Rome (Lovins 1975 [1977]).



Energy Strategy:
The Road Not Taken?

By Amory B. Lovins

Figure 1: Front page of Lovins groundbreaking article in "Foreign Affairs" 1976 (Lovins 1976)

Lovins saw the decisive obstacle for a reduction of the energy consumption as lying in the inertia of the "hard energy path" of power generation, based as it was on constant growth and centralization, which followed a self-generated spiral of growth (associated with a doubling of power station every 6-7 years), increasing consumption and rising system complexity, thus defying the principle of resilience: "For example, we concentrate our resources not on microefficiency or resilience but on managing our growth and resolving its numerous conflicts and inequities. So we weave a web of bigness and of incomprehensive, unmanageable complexity" (Lovins 1976 [1977], p. 82). With Schumacher, he therefore argued in favour of a decentralization of the supply structure and an adaptation of the generating units to the corresponding consumption levels, i.e. no strict "small is beautiful" strategy, but rather the "principle of matching and appropriateness" or "right scale" (Lovins 1977a, p. 102).

Amory Lovins extended Schumacher's purely value-oriented perspective, based on economies of scale, by including the results of the biological and ecosystem resilience research in his analysis of the "diseconomies of large scale". This was because his occupation, beginning at the end of 1975, with the examinations of Nicholas Polunin on ecodisasters (Polunin 1974, p. 177; 1972, p. 48 f.) and with the ecosystemic complexity and resilience theory of Crawford S. Holling had opened up his eyes to the significance of optimum sizes, diversity and decentralized structures for the regenerative capability of bio- and ecosystems (Lovins 1976a). From the findings gained in studying stress loading and adaptation processes in biotopes, he concluded that, also in energy systems, resilience could only be obtained by avoiding "large-scale monolytic approaches" and higher "concentration ratios". Lovins therefore integrated the "*biological metaphor"* into his concept of the "soft energy path" and thereby developed the resilience concept for the energy discourse of the counterculture: "Small energy systems adapted to particular niches can mimic the strategy of ecosystem development, adapting and hybridizing in constant coevolution with a broad front of technical and social change. Large systems tend to evolve more linearly like single specialized species (dinosaurs?) with less genotypic diversity and greater phenotypic fragility." (Lovins 1977a, p. 99).

In the second half of 1976 and in early 1977, Lovins came into even more closer contact with the ecosystem resilience theory, through his personal encounters with Holling. The occasion was the symposium on the dimensioning problem of future energy systems, convened by Alvin Weinberg in October 1976 immediately after the publication of Lovins' sensational paper "Energy Strategy: The Road Not Taken" in "Foreign Affairs". Early in 1977, Amory Lovins and Dennis Meadows even spent several weeks at the "International Institute for Applied System Analysis" (IIASA), in order to explore the possibilities of compromise in the hard/soft energy controversy together with Wolf Häfele's team (Sassin, Lovins et al., 1977, see Hellige above, chapter 4). As a consequence of these meetings, Lovins went beyond the criticism hitherto expressed regarding the uneconomical gigantism of the hard technology path, by applying the resilience approach and the ecodisaster theory for a systematic registration of phenomena relating to the "man-made vulnerability" of large-scale energy systems and even of the entire industrial society. In his paper, entitled "Scale, Centralization and Electrification in Energy Systems", he referred directly to Holling's argument relating to the large gaps in ecosystem knowledge: "Nature knows best, whereas we know little of the natural systems and cycles on which we depend; hence we must take care to preserve safety margins whose importance we do not yet understand, and to *design for resilience and flexibility*." (Lovins 1976 [1977], p. 48). In particular, he adopted Holling's maxim that, in view of the unpredictability of complex interdependencies and error chains, the design strategy should be so focused as "to devise systems that can absorb and accommodate future events in whatever unexpected form they may take" (Holling 1973, S. 21). To this end, Lovins declared that the supply system had to be "highly resilient and easily decoupled" and, instead of global energy strategies, utilize a regionally available resource base (Sassin, Lovins et al., 1977. p. 2).

In July 1977, Lovins expressed, in his programmatic article "Resilience in Energy Strategy", his support for Holling's philosophy of a robust system design. Since the ecosystems theory showed clearly how, owing to the nonlinearity, interdependence and unforeseeable complexity of natural processes, local disasters can rapidly get out of hand and lead to far-reaching blackouts and failures, a sustainable society need not be content with calculating the *probability* of system failure but must also take steps to ensure "that we include in our design the broader philosophy of resilience in the face of the incalculable madmen, guerrillas, Middle East wars, freak winters, earthquakes, unpredicted high-technology failures." (Lovins 1977b). For this, he recommended that in place of the usual trend extrapolations, which only extend the growth curve, scenarios be used to explore the possible consequences, because they were better suited "to test for resilience in the face of surprises — important in an era when discontinuities and singularities may matter more than the fragments of secular trend in between." (Lovins 1976 [1977], p. 87).

In the same year, Lovins detailed his design concept in his trailblazing book "Soft Energy Paths" (Lovins, Amory B., 1977a, pp. 50 f.), as the first catalogue of criteria for resilient electrical power systems. These criteria included:

- the adaptation of scale and complexity to the level controllable under all circumstances,
- the adjustment of the technical standard and the size of generation to the end consumer level that was actually needed,
- a strategic focus of the system design to the design principles of "technical diversity, adaptability, and geographic dispersion",
- renunciation of vulnerable central nodes and energy technologies with an inherently large hazard potential, and
- the prevention of dependencies on exhaustible energy sources, especially from political crisis regions.

The overarching objective of his design philosophy for a "benign, resilient and sustainable energy system" was to minimize the scope of errors and the severity of system failure from the very beginning, and thus to realize the ideal of ecosystem resilience in energy supply too: "Finally, the soft path appears generally more flexible – and thus robust. Its technical diversity, adaptability, and geographic dispersion make it resilient and offer a good prospect of stability under a wide range of conditions, foreseen or not." (Lovins 1976b, p. 88; 1977b). With that, Lovins had used Holling's theory as a basis to develop a counterconcept to Häfele's "global structure resilience"; moreover, it was embedded within a far more comprehensive, normative sustainability programme and also remained so in the time that followed. But he never adopted the innovation theoretic approach, with which Holling framed his resilience concept (Sassin, Lovins et al., 1977. p. 2-4; see Hellige above, p. 20).

Through the multidisciplinary bundling of theoretical discourses and the founding of a resilience approach for energy systems, Lovins quickly attained a significant influence on the energy debates in the USA and Western Europe. With his detailed proof of the increasing "diseconomies of scale" of the centralistic energy supply system by means of energy statistics, his thorough documentation of the technical, economic and societal risks of atomic power, and the first inventory of the available alternative energy sources, he also won the attention of experts in the worlds of energy technology and energy economy. His arguments also found expression in energy policy statements of US President Carter, prompting the latter to initiate the opening of the energy market, hitherto controlled by the major utilities, to wind and solar energy and to the local CHP units through the PURPA Act of 1978, which for the first time promoted the propagation of renewable energy sources through the mechanism of feed-in tariffs (Hirsh 1999, pp. 61 ff.). At the same time, Lovins gave important stimuli for the establishment of alternative energy research, especially in California, England and Denmark, through his thorough empirical underpinnings of the soft energy concept.

Figure 2: President Carter and Amory discussed the article "Energy Strategy: The Road Not Taken" in the Oval Office 1977 (Lovins 2016)

In Germany, too, the founding of the "Öko-Institut" (Institute for Applied Ecology) in Freiburg in 1977 by Hartmut Bossel benefited through the appreciable impetus from Lovins and the Californian energy projects, in which Bossel was directly involved for a time (Aykut 2015, pp. 72 ff.). The alternative energy report of 1980, written by Florentin Krause, a staff member of Lovins, entitled "Energie-Wende. Wachstum und Wohlstand ohne Erdöl und Uran" {Energy Transition. Growth and Prosperity without Crude Oil and Uranium}, which also initiated the first energy transition discourse in West Germany by virtue of the term and guiding idea, can expressly be viewed as the German counterpart to Lovins' "Soft Energy Paths" scenario, even though its reception was not comparable with that of the exemplar (Hockenos 2012). The focus of the German study lay more on energy saving strategies and local CHP plants, which were to be furthered above all through re-municipalization of the energy supply, whilst the resilience issue did not play a central role, but was rather reduced to the classic reliability of energy supply (see Hennicke, Johnson, Kohler 1985). As a result, the *energy transition* was understood as being more of a historic turnaround to the municipal roots and less like Lovins' perspective as a strategic choice between two energy paradigms.

In the USA, by contrast, the Lovins book directed the scientific debate concerning a return to local supply structures and to distributed energy generation towards the resilience problem above all, so that a continued resilience discourse on energy technology ensued here. In a series of studies and public hearings on the relationship between decentralization and resilience enhancement, it was confirmed clearly that centralized systems exhibited much higher vulnerabilities in relation to renewable energy systems, but at the same time the inherent problems of the utopian "small is beautiful" guiding idea, in which the mere decentralization of supply and the transition to "soft technologies" could solve the question of resilience, were expounded. The debate led to a conceptual differentiation of the ideal and an initial "taxonomy of decentralization", according to which a distinction was made between the point of energy production and conversion, the ownership circumstances and the societal supply architecture, the main energy form, as well as the degree of cross-linking and the interconnection structure in the grid (Dhi, James, Unseld, 1980, p. 1).

Moreover, Lovins' resilience concept itself was developed further during the course of the intensive debate at the end of the 1970s. For instance, the study "Reliability Planning in Distributed Electric Energy Systems" performed by Edward Kahn at the Lawrence Berkeley Laboratory differentiated between *passive* and *active* resilience, in order to better account for the dynamic nature of energy systems. Whereas passive resilience denotes the "reliability sensitivity" and the system behaviour during the absorption of stress and shocks, active resilience is understood as an "active feedback control notion" that includes corrective interventions, regulating actions and political governance of the energy system. However, in the light of the incalculable complexity of the various interventions and the lack of a "framework of the probabilistic calculation techniques" for this field, Kahn dispensed with a closer analysis of the interactions between the two types of resilience (Kahn 1978, pp. 3, 19 f., 34). In another large-scale study on a future decentrally distributed energy system in California, attempts were made, without any reference to the efforts in the IIASA, to quantify the all-too-vague "vulnerability/resilience analysis" and to extend the resilience criteria to include the renewable energies. For a sound resilience metric, this still lacked a broad *qualitative* identification of the system hazards, their interdependencies and countermeasures as well as suitable mathematical models, which to a large degree were only developed after 2000 (see i.a. Molyneaux, Wagner et al. 2012). As a result, the resilience concept of the study did not materially surpass the Lovins criteria:

“1. Redundancy or provision of extra capacity, in the form of larger units, extra units, or additional links in the distribution network.

2. Replacement of large units with more and smaller ones, without increasing total system capacity.

3. Geographic dispersion of supply points within the net.

4. Fuel diversity of energy sources.

5. Technological diversity to reduce dependence on a single critical material or labor union.

6. Storage of energy, fuel, critical materials, spare parts, etc. If energy storage is provided near demand points, it not only protects against supply point failures but also against network link outages.” (Christensen, Craig, Eds., 1977, Vol. 2, p. 349).

3. The first integration of the ‘Energy Internet’ metaphor into the resilience discourse: The „Power Systems 2000“-Scenario of the „Homeostatic Control Group“

Surprisingly, in the discourse initiated by Lovins/Lovins on the concurrent examinations regarding the vulnerability/resilience problem in computer communication, no technology-spanning exchange of experience initially took place. Nevertheless, the search for “highly survivable system structures” in computer and communications networks had already begun at the height of the Cold War towards the end of the 1950s, because scenarios of nuclear war had already indicated the extreme vulnerability of the hierarchical central node structure in the classic transmission networks (Baran 1964, Vol. 5, p.1). A thorough simulation study by the RAND Corporation came to the conclusion in 1959–1964 that only a mesh network (n => 3) with a distributed store-and-forward switching regime could withstand a mass assault by long-range bombers. As the exemplar for the proposal of a highly redundant store-and-forward network with transmission in blocks, the author of the study, Paul A. Baran, used the “torn-paper relay lines” of the classic telegraph system as well as the neural networks identified by brain research. Just as other regions of the brain take over the functions of injured area to some degree, the communication infrastructure was to remain operational, even if more than half the nodes of the network were disabled (Baran 1964, Vol. 2, p.1; Hellige 2008, pp. 144 f.).

Baran’s considerations of “network vulnerability and survivability” were continued by Howard Frank’s Network Analysis Corporation, a consulting firm working for the Federal Emergency Management Agency (FEMA) and the White House crisis team. With the aid of graph theory, information theory and systems theory, Frank created a set of methods for analysing the vulnerability of infrastructure networks and, specifically, for the design of “reliable networks with unreliable components” (Frank 1973, p. 161; Hellige 2008, p. 145 ff.). The Network Analysis Corporation also optimized the network architecture of the network that preceded the Internet, the ARPANET, the topology of which was designed under survivability aspects as a multi-node network with at least three connection paths per node (Frank, Frisch, Chou 1970). The Western European packet switching networks, which originated independently thereof in a purely civilian environment, met the criteria for a resilient network design with their redundant links and system resources and blockwise message transfer. “We were right away starting from the concept that computers require small messages, so let’s build something that does that, and such things as *resilience to breakdowns* came as a bonus to us. So our viewpoint was different, but our mechanism was extraordinarily similar.” (Davis 1988, p. 6). In the time that followed for computer communication, the carrying capacity for the strongly growing network traffic was continually improved through functional layering and hiding strategies as well as by the expansion of flow- and congestion-control mechanisms. However, these approaches led neither to an extension of the resilience principles for the long-established telecommunications networks nor to an overarching resilience design theory for the reciprocally dependent communication, information and energy infrastructures – a state of affairs that has repeatedly been lamented, right up into the recent past.[1] This was despite that fact that there had already been very promising attempts around 1980 towards formulating a technology-spanning resilience concept, in which the energy/computer network metaphor appeared for the first time.

The stimulus for a first convergence of the resilience debates for computer and power networks, which had initially been completely separate, was given by research projects of the “Homeostatic Control Group” at MIT, led by Fred C. Schweppe and Richard D. Tabors as specialists for the computer control of power stations and energy systems. Schweppe, as the expert for “uncertain dynamic systems”, developed, in the scenario “Power Systems 2000” of 1978, the master model of a smart grid, which was to exploit the evolution of the “data-network communications and mini- and microcomputer technology” for a dynamization of the inflexible “electric power system”, promote the inclusion of renewable energy sources and fundamentally change the “relationship between customer and utility” (Schweppe 1973; 1978, p. 42). On the whole, the goal was to apply a information-based dynamic regulation of energy supply and demand, together with a flexible, decentralized control of electricity production and storage in order to make the supply system more economical, more ecological and, above all, more robust. The immediate inducement was given by the spectacular blackout in New York City of July 1977 and the worldwide oil crisis, which had worsened again in 1979.

For the theoretical basis of the intended coevolution of energy and information/ communication technology, the Homeostatic Control Group fell back, entirely independently of Lovins, upon the biocybernetic homeostasis principle and, from this, developed a further bio-inspired “basic philosophy” for the design of robust energy systems that were resilient to a rudimentary extent. Schweppe and his team found it promising to adopt the biological model of the constantly renewed inner balance of an organism as the antetype for a robust

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[1] See Hall, Anderson et al. 2010; Smith Hutchinson et al. 2011, p. 88; Molyneaux, Wagner et al. 2012 and above all the research report and draft for an “architectural framework for resilience and survivability in communication networks” by Sterbenz, Hutchinson et al. 2010; Sterbenz, Çetinkaya et al. 2011.

electricity supply: “Homeostasis is a biological term referring to the ‘existence of a state of equilibrium ... between the interdependent elements of an organism.’ It is appropriate to apply this concept to an electric power system in which the supply systems and demand systems work together to provide a natural state of continuous equilibrium to the benefit of both the utilities and their customers.” (Schweppe, Tabor et al. 1980, p. 1151; see above Hellige, p. 6 f.). According to Schweppe, the potential of the Homeostatic Control concept extended far beyond the energy sector; he too viewed it as a general principle of regulation that was suitable for ensuring economical efficiency, lower vulnerability of technical infrastructure systems and, at the same time, a greater participation of the consumers in economic activity: “Homeostatic Control provides the basis for a control and pricing structure which meets the future needs of the nation.” (Schweppe, Tabors et al. 1979, p. 2).

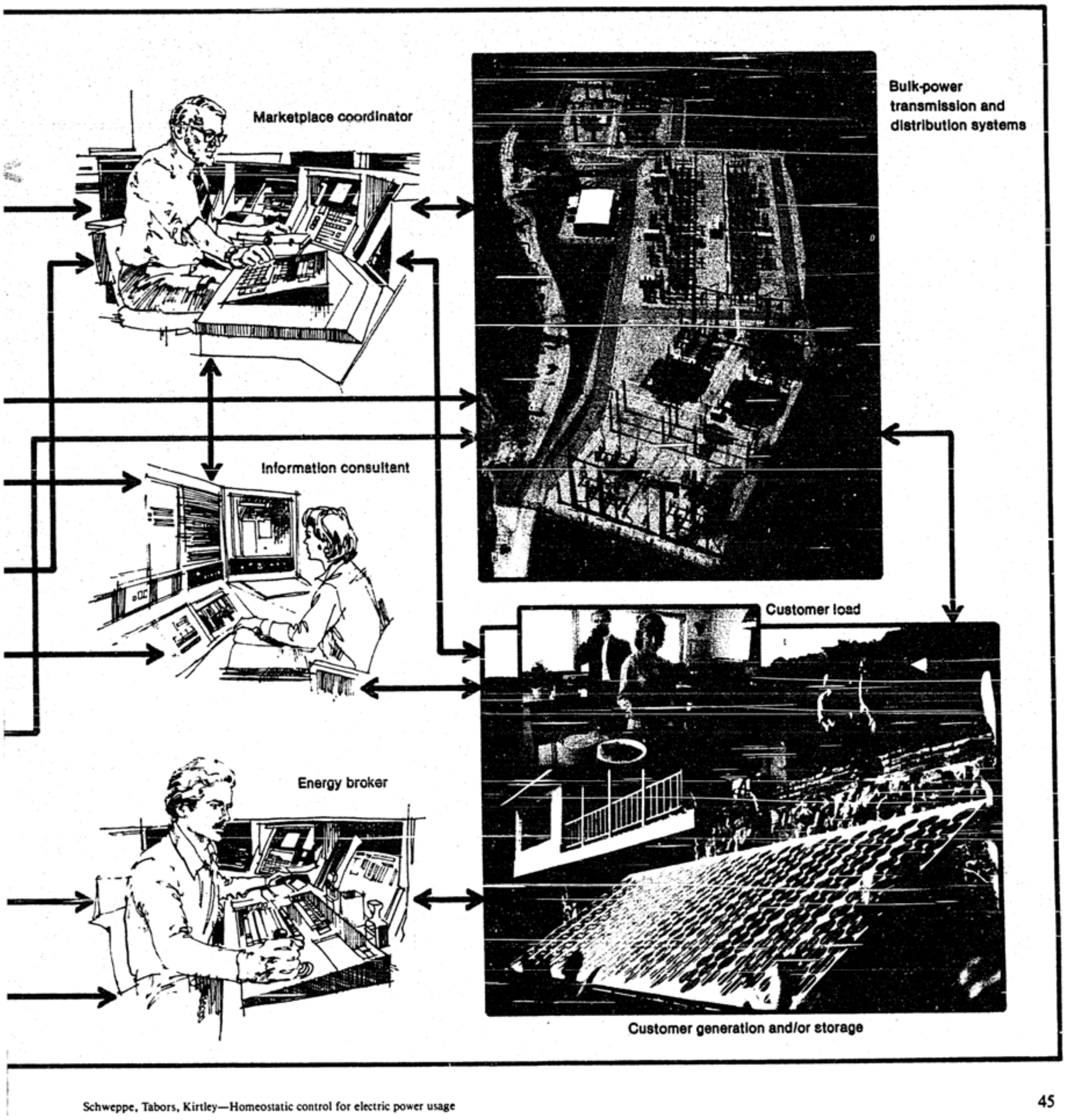
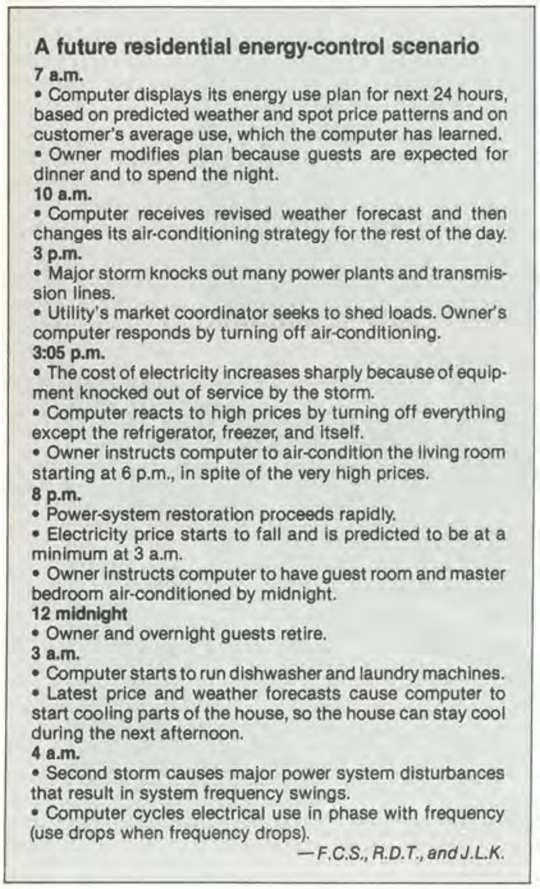


Figure 3: ‘Smart Grid’ vision of the Homeostatic Control Group at MIT of 1978/82 (Schweppe, Tabors, Kirtley 1982, p. 45)

To realize an “internally-correcting control scheme” (Schweppe, Tabors et.al. 1979, p. 5) in an energy supply system, the homeostasis scenario combined the control techniques of microelectronics and the information and interaction functions of computer networks with the regulatory mechanisms of prices. As the mediatory transaction centre, a computer-supported “energy marketplace” was proposed; this was to balance supply and demand in a resource-saving and cost-optimized manner, and thereby increasingly integrate renewable energy sources (Schweppe 1978, p. 44). In so doing, the future system around the year 2000 would in principle dissolve the separation between energy producers and consumers, so that the “two-way-utility customers” could market superfluous quantities of electricity from thermal solar or photovoltaic units, electric heat pumps, wind turbines and private energy storage systems via the energy exchange platform (ibidem, p. 43). The information technology interface for the households was a microelectronic “metering system that can interface the customer with the utility” (Schweppe, Tabors et.al. 1979, p. 10). Besides that, the ‘prosumers’ could track the energy prices as they fluctuated according to the renewable energy supply, and decide at will on the corresponding adjustment of their own consumption and their own storage or the amount of feed-in to the grid. In this way, the Homeostatic Utility Control was to integrate the stochastically fluctuating energy supply of renewables, facilitate “cogeneration” and thus help to conserve the resources of fossil fuels (Tabors, Finger, Cox 1981).



A future residential energy-control scenario

7 a.m.
- Computer displays its energy use plan for next 24 hours, based on predicted weather and spot price patterns and on customer's average use, which the computer has learned.
- Owner modifies plan because guests are expected for dinner and to spend the night.

10 a.m.
- Computer receives revised weather forecast and then changes its air-conditioning strategy for the rest of the day.

3 p.m.
- Major storm knocks out many power plants and transmission lines.
- Utility's market coordinator seeks to shed loads. Owner's computer responds by turning off air-conditioning.

3:05 p.m.
- The cost of electricity increases sharply because of equipment knocked out of service by the storm.
- Computer reacts to high prices by turning off everything except the refrigerator, freezer, and itself.
- Owner instructs computer to air-condition the living room starting at 6 p.m., in spite of the very high prices.

8 p.m.
- Power-system restoration proceeds rapidly.
- Electricity price starts to fall and is predicted to be at a minimum at 3 a.m.
- Owner instructs computer to have guest room and master bedroom air-conditioned by midnight.

12 midnight
- Owner and overnight guests retire.

3 a.m.
- Computer starts to run dishwasher and laundry machines.
- Latest price and weather forecasts cause computer to start cooling parts of the house, so the house can stay cool during the next afternoon.

4 a.m.
- Second storm causes major power system disturbances that result in system frequency swings.
- Computer cycles electrical use in phase with frequency (use drops when frequency drops).

—F.C.S., R.D.T., and J.L.K.

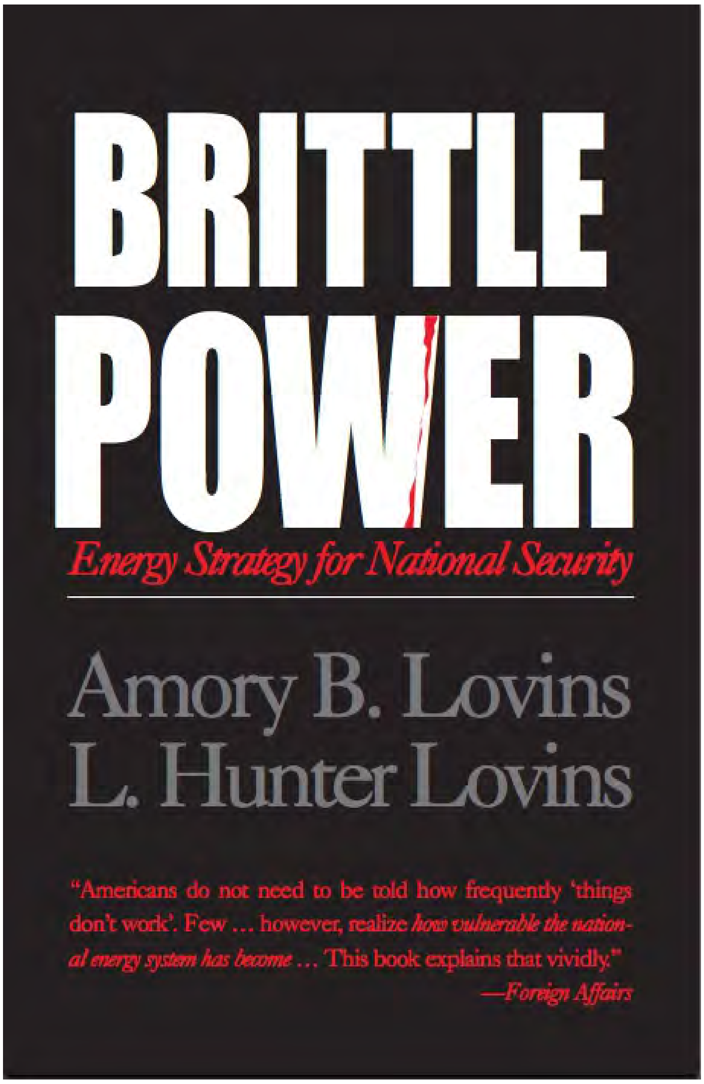
Figure 4: Everyday scenario for the “Homeostatic Control System” in the year 2000

(Schweppe, Tabors, Kirtley 1982, p. 46)

For the social architecture of the generating and control system, Schweppe's team argued in favour of a "decentralized philosophy", because, like the "distributed generation", "distributed computation" also displayed enhanced resilience attributes: "Using many small digital computers enables distributed computation, parallel processing, and greater reliability." (Schweppe 1978, p. 46) Together with the mini- or microcomputers and interactive interfaces, software and mathematical models would assure a "high degree of decentralized decision making" (ibidem, p. 43). In contrast to the established telemetric control techniques of the (off-peak) electricity suppliers, the scope of action open to the players would thus have been fully safeguarded in the homeostatic system. With great foresight, the Schweppe team even recognized the data protection problem associated with intelligent metering systems and therefore developed a "non-intrusive appliance monitor" that clustered the sensor data from several households together, in order to exclude data mining of the consumption patterns of the individual households (Hart, Kern, Schweppe 1986). Just how pronounced the awareness for this problem was in the early stage of the smart metering technology is shown by the contemporary considerations of M. Granger Morgan, Professor of Engineering and Public Policy and of Electrical and Computer Engineering at Carnegie Mellon University, regarding the "undesirable social impacts" of an "advanced load management": Because the implicit activity monitoring could lead to encroachment on the privacy of electrical customers by government agencies, private security services or criminal organizations, a "careful engineering design" should meticulously regulate the access rights from the start (Morgan, Talukdar 1979, pp. 305 f.).

The ultimate objective of Schweppe was to use price fluctuations and "spot pricing" to achieve a self-organizing energy exchange system and, at least as a general thrust, a self-regulating and largely decentralized system of energy production, distribution and storage that would meet both the economic and ecological requirements. In going beyond the homeostatic regulation function, he also wished to close the resilience deficit of the classic centralistic supply system, a flaw that had become more visible through the increasingly severity of blackouts. For this reason, he extended the "philosophy of Homeostatic Utility Control" by a series of resilience attributes, such as spare capacities ("backup sources"), the switching-on of stored energy and the sweeping disconnection of decentralized supply areas from the national grid in the event of an emergency, with a minimum supply always being maintained on the basis of own resources. According to this vision, technical blackouts would still occur in the year 2000, but, thanks to the integrated buffer capacities of the system, would no longer constitute a crippling of public life: "When there is a total blackout (technical definition), enough of these backup sources will work so that major societal interruptions and disturbances will not occur. There is a good chance that by the year 2000 the term blackout (societal definition) will be considered to be a term out of the Dark Ages" (see the section 'Anatomy of a Blackout: 2001' in Schweppe 1978, p. 45).

This farsighted and already extremely problem-aware pilot concept of a 'smart grid' was, however, rapidly forgotten – firstly, because the project manager had a fatal accident shortly after publication of the book about the Homeostatic Utility scenario and, secondly and above all, because the Reagan administration, which had been in power since 1981, again favoured the large fossil-based and nuclear power suppliers (Schweppe, Caramanis, Bohn, Tabors 1988). It was only after 2000 that the expert discourse on smart grids returned to the Homeostatic Control approach, and in recent years there has been an increase in papers referencing the bio-inspired philosophy of the Schweppe team, because here they see a suitable strategy for preventing the cascading of malfunctions and for integrating self-healing mechanisms into the complex energy systems.[2]



BRITTLE POWER

Energy Strategy for National Security

Amory B. Lovins
L. Hunter Lovins

"Americans do not need to be told how frequently 'things don't work'. Few … however, realize *how vulnerable the national energy system has become* … This book explains that vividly."
—*Foreign Affairs*

Figure 5: Cover of the "Brittle Power" Book of 1982

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[2] See also Giraldo 2005, Hines et al. 2009, Beckerman 2013, Cordova, Yanine 2013; Yanine, Caballero et al. 2014; Delgado-Gomes, Borza 2014.

4. The multidisciplinary synthesis of the resilient energy system design-debate: The distributed computing-inspired study „Brittle Power“ of Lovins/Lovins

Just as the coincidence of the global oil price crisis and the large-area blackout in the northeastern part of the USA became the impetus for the conception of the first smart grid and the energy-economic homeostasis approach, it also effected the origin of the theoretical basis and design theory for resilient energy systems around 1980, which has remained the most comprehensive construct until now. The stimulus for this was given primarily by US military circles, who, in the light of the increasing and ever more severe system failures of the electricity supply as an elementary factor for all critical infrastructures, saw the survivability of the state as being endangered. Upon the instigation of the Pentagon, the disaster control organization created by President Carter in 1979, the Federal Emergency Management Agency (FEMA), therefore commissioned a study in the very same year on the "vulnerability and weaknesses of the US energy system", with which the two Lovins's were entrusted. Concluded in October 1981 and published in the subsequent year under the title "Brittle Power: Energy Strategy for National Security", the study for the first time considered the resilience problem of energy supply within a broad technical, economic, societal and political framework (Lovins and Lovins 1981, 1982). To begin with, it once again presented the genesis of "America's energy vulnerability" as the consequence of a path dependency caused by industry encrustation reinforced by energy policy, which had led to a condition of poorly controllable complexity. In a comprehensive qualitative vulnerability analysis, general disruptive factors, error constellations and disaster causes were systematically described, after which the stress factors and potential hazards in electrical power systems were described and listed according to energy sector. Their interplay was then analysed using the mega-blackout of 1977 in New York and the surroundings as an example. The phenomenology of vulnerability factors and situations culminated in a systematic design theory for resilient energy systems and finally in an energy strategy concept to overcome the "brittle power" constellation over the long term.

For Amory Lovins, the preventive design principle of resilience was the logical consequence arising from the comprehensive catalogue of disruptive factors, failure modes and malicious attack vectors that could lead to a large-scale system failure in energy systems. Since, according to the findings of empirical disaster research, the knowledge about the system attributes, system states and complex interactions both inside and outside the system is extremely fragmentary, the *reliability* concept – which is founded upon the calculation and summation of *individual* probabilities for the failure of system components – is not able to provide sound prognoses of the probabilities of occurrence for major incidents as well as their cascading and cumulative effects. The unavoidable gaps in knowledge could therefore only be reduced through a strategy of prevention and precaution that mitigated the possible consequences of system failure from the outset. To counter the prevailing reliability doctrine of the established power system engineering, Lovins posited the maxim "embody *resilience* *in the design philosophy*, not merely reliability in the design details." (Lovins and Lovins 1982, p. 178, his emphasis). Together with Holling, Lovins defines resilience as the ability of a system to absorb shock by providing for an equilibrium between stabilizing and destabilizing forces and especially through "*local back-up, local autonomy, and a preference for small over large scale and for diversity over homogeneity*" (ibidem, p. 184, his emphasis). The balancing of stabilizing and destabilizing forces that can be achieved hereby give natural and technical ecosystems certain characteristics of stability, provided "*they are not pushed too far*, into a region of behavior where the instabilities dominate and cause collapse." (ibidem, p. 184, his emphasis).

The problems with which Paul Kahn had become involved through his differentiation of active and passive resilience prompted Lovins to base his design theory for resilient systems on a generalized scientific and technological resilience approach, through which he for the first time included computer architectures and computer networks, in addition to the biological or ecological systems and energy systems, in the systematic comparison of the resilience of systems. This was because analogies with *biological* systems do not suffice for the resilience assessment and resilience design of energy systems. Although, according to Lovins, they do yield cognitive and organizational patterns or general features of resilient systems, such as overall buffer capacity, heterogeneity, diversity, decentrality as well as limitation of scale and complexity, one cannot from this alone obtain concrete requirement profiles for *technical* system and building structures. Only through a comparison of biological, energetic and information systems did Lovins arrive at specific structural features and design principles for resilient technical systems. These included the organization of the system by means of granular, modular and hierarchical structures and flexible system architecture, the setting up of safety margins through redundant design, functional flexibility and the exchangeability of components, together with optional connection possibilities and a capability for the complete decoupling of subsystems. Fault tolerance through buffer times in process operations, simplicity and easy comprehensibility were then to ensure societal acceptance of the technical system (Lovins 1982, pp. 190-207).

However, even after this concretization of his design theory for resilient systems, Lovins had still not progressed beyond a catalogue of principles and desiderata. With a view to demonstrating their viability, he looked for an area of technology in which the resilience requirements had already been recognized and also implemented in practical terms; he found it in computer technology and data processing. Only in this field did he find an exemplar for a successful system transformation from a non-resilient, centralistic system architecture to a resilient, distributed technical and social one, such as he was striving to attain for energy supply. Data processing was accorded a key role in his argumentation as the example for "a coherent, readily identifiable decision to *change the architecture of an evolving technical system*? [...] Its lessons have strong parallels, as will be shown, to a desirable direction for the evolution of the energy system; and they emerged in response to similar concerns." (Lovins 1982, S. 208, my emphasis). This was so because evaluation of the decentralization debate in the computing community and contacts to the IBM system designer Jim Gray had shown him that the strong centralization and orientation towards high performance in mainframe computing had led to a "lack of resilience and high cost of failure", which in turn repeatedly resulted in costly computer failures and great dissatisfaction of users, and also to low flexibility in adapting to new requirements and technical innovations. In view of the all too obvious "brittleness of centralized computers", the Electronic data processing-sector, to a certain degree also within the management of the quasi-monopolist IBM, had, unlike the inertia of the power systems operators, decided to pursue a "*new approach to system architecture*", namely the migration of large-dimensioned user-unfriendly centralized systems to "*networks of interconnected minicomputers*" (ibidem, p. 212, my emphasis).

The reorientation of computing was aimed at placing "*adequate and autonomous computing power*" as closely as possible to each user and making the resulting "dispersed systems" of processor and memory units capable of communicating amongst themselves by means of fast transmission lines (Lovins and Lovins 1982, p. 210, my emphasis). In supplement, Lovins took over from Jim Gray the principle of "loosely coupled systems" (ibidem, p. 212), because with these the failure of one component did not take down the entire system: "The key to obtaining all these benefits is the *autonomy of each component in an intercommunicating network*. Each minicomputer can serve local users in isolation even if its communication networks fail. The system is therefore able to continue to deliver the services of the computing hierarchy, or most of them, despite the loss of many subsystems. This design principle, and the broader philosophy it reflects, have striking parallels in the design of resilient systems for supply energy." (ibidem, pp. 201 f., my emphases). Whilst Lovins saw the limits to the analogy of computer and energy systems, the conformities predominated for him with regard to the resilience issue: "the parallel between resilient, distributed data processing systems and resilient, distributed energy systems is illuminating." (ibidem, p. 213).

Based on the example of successful system transformation in computing, Lovins now refined the maxims and criteria for resilient system design once again, thus giving his design theory its final form:

- "A resilient system is made of relatively small modules, dispersed in space, and each having a low cost of failure.
- Failed components can be detected and isolated early.
- Modules are richly interconnected so that failed nodes or links can be bypassed and heavy dependence on particular nodes or links is avoided.
- Links are as short as possible (consistent with the dispersion of the modules) so as to minimize their exposure to hazard.
- Numerically or functionally redundant modules can substitute for failed ones, and modules isolated by failed links can continue to work autonomously until reconnected.
- Components are diverse (to combat common-mode and common-cause failures), but compatible with each other and with varying working conditions.

- Components are organized in the hierarchy so that each successive level of function is little affected by failures or substitutions among components at lower levels.
- Buffer storage makes failures occur gradually rather than abruptly: components are coupled loosely in time, not tightly.
- Components are simple, understandable, maintainable, reproducible, capable of rapid evolution, and socially compatible.“ (ibidem, p. 213).

Through the coupling of bio- and ecosystem theory approaches with a design-theory comparison of technology, Lovins had – as his detailed design criteria and recommendations verify – advanced far beyond his own initial polarity of two energy paths and Holling’s abstract reflections about energy system resilience as well (see Holling [1976] 1982). The creation of a resilient energy system had thus become a complex design task that had to integrate many technical and social aspects and, in so doing, also solve some trade-offs in design-objectives.

The concrete system comparison also allowed Lovins to give a sharper definition to the widespread and imprecise “semantics of *decentralization*” (Lovins and Lovins 1982, p. 215-218, my emphasis). He now distanced himself more strongly from the naive equation of decentralization with small sizing, individual self-sufficiency and anti-industrial agrarian/ utopian ways of life. He now distinguished eight dimensions of “decentralization”: The *unit scale*; the degree of *dispersion* of the system functions; the *interconnectedness* of the components; *composition* and configuration of the system; *locality*; *controllability* by the users; *comprehensibility* and *transparency* of the system; and the low *dependency* on external entities. With this differentiation of the terminological dimensions, he firstly wished to draw a sharper distinction between the complex interrelationships of the technical and social architectures of systems and, secondly, to decouple the design of decentralized energy systems from the fundamental question of the overall organization of future society. The example of the successful transition by the highly concentrated mainframe computing to a network of interacting user-controlled microcomputers had shown him that a comparable transformation to decentralized resilient supply structures with fundamentally changed “producer-user relations” should in principle be possible in the energy sector under the existing societal conditions.

5. Outlook at the later energy resilience discourse and conclusion

However, the transformation of energy, climate and environmental policy initiated by President Carter, who wanted to strategically link the sustainability programme with a resilience offensive in infrastructure policy, was radically scaled back in the 1980s by the Reagan and Bush senior administrations, which focused entirely on fossil and nuclear energy. The alliance of energy and resilience discourse initiated by the two Lovins's had also dissolved again into a series of separate discourses: the re-regionalized movement for renewables, specialist debates on deregulation, distributed utilities, smart energy and smart home as well as only narrowly specialized discussions on the issue of energy-related resilience (see Weinberg, Ianucci, Reading, 1991). It was not until the second half of the 1990s that a new "big strategic shift" to renewables and climate change took place. Under the influence of the "Information Highway" programme of Bill Clinton and Al Gore, the Energy Internet metaphor experienced its major breakthrough around 2000, resulting in various plans and concepts for digitally controlled energy exchange networks based on the Internet and the World Wide Web: "Energy Internet", "Power Web", and federated "Local Area Grids" (see i.a. Borbely, Kreider, 2001; The Economist 2004; Thomas, Mount, Zimmerman, 2004). The "Critical Infrastructure Protection" initiative of the US President in 1997/98, which accompanied these convergence scenarios, once again brought about a coupling of the distributed energy and resilience discourse. The programmes launched in 1999 by the Electric Power Research Institute (EPRI) and the Department of Defense (DoD) for "Self-healing Energy Infrastructure Systems" were once again strongly promoted after 9/11 and the Northeast Blackout of 2003 (see i.a. Amin, 2001; EPRI Roadmap 2003, chapter 3; Tsoukals, 2008). The new upswing for a combination of resilience cultures related to energy and information technology also prompted a new edition of the "Brittle Power" book by Lovins/Lovins in 2002. However, it was only after a renewed energy policy rollback under President Bush junior that systematic efforts began in 2010 for information-supported, resilient energy system architectures, which subsequently stabilized. However, aspects of resilience are still taken into account very differently and in many cases are reduced to pure crisis management while neglecting sustainability goals.

The history of the reception of the resilience concept in the energy discourse thus shows that there has been no continuous scientific and technical progress in this regard. The models and design concepts, which had already advanced considerably at the end of the 1970s, were repeatedly pushed back by the inertia of established industry structures and the adherence to centralistic infrastructural system architectures. The historical review clearly shows that socio-technical design theories for resilient energy systems develop within a societal and energy-economic environment. As a result, they are themselves socially shaped in respect of their normative orientation and their instruments. From the historical reconstruction, it can also be concluded that metaphoric transfers can be an important stimulus for the emergence and orientation of the resilience discourse in the energy sector, but that one-to-one transfers from bio-ecology to technology, as C.S. Holling himself aimed for, do not lead to the desired goals (see Hellige above, p. 17 f.). On the contrary, socio-technical design theories must filter out matching structural elements and principles and otherwise emancipate themselves from natural analogies, and consequently refer back to metaphors that correspond to the specific principles, structures and social architectures of the technology in question. The historical recollection of the genesis of design theories and the metaphors on which they are based will thus make it possible to uncover metaphorical excesses and to avoid taking wrong turns through the inappropriate application of external contexts.

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On the difference between risk management and resilience management for critical infrastructures

Stefan Goessling-Reisemann and Pablo Thier

Abstract

Risk management and resilience management share important features and they both aim at preparing systems for uncertain threats or stressors and their impacts. Still, the level of uncertainty regarding stressors and impacts, the type of systems addressed and the systems' dynamics allow for a distinction between the applicability of either risk or resilience management. This chapter provides a short introduction to the specifics of each strategy for coping with uncertainty and presents guidelines for designing a resilient critical infrastructure.

Keywords

risk management, resilience management, critical infrastructures, resilient design, uncertainty

1 Introduction

Critical infrastructures are the lifelines of our society: energy, water, communication, transportation, health services, food supply and more. Protection of these infrastructures against known and unknown threats in order to prevent failure and recovery of service after a disruption are important for any society's survival. Events like Katrina, Sandy, Fukushima, the Indian Ocean Tsunami 2004, the terrorist attack from 9/11 and many more have brought the brittleness of our critical infrastructures to the attention of policy makers, scientists and engineers. There are some developments that fuelled the discussion on critical infrastructures even further in the recent past: growing interdependence of infrastructures, increasing digitalization, cyber-physical terrorist attacks, growing number of extreme weather events, uncertain climate change impacts and human failures leading to large-scale disruption of service. All of these stressors are characterized by uncertainty to differing degrees, ranging from known stressors with known probabilities and quantifiable impacts to the completely unknown. Along this gradient, new ways of managing risks are discussed, where traditional risk management is at the one end of the scale and resilience management is at the other. We believe it is possible to prepare for the completely unknown by applying resilience management strategies, while we acknowledge that this line of research is still in early development.

2 From risk management to resilience management

Risk management for critical infrastructures, is concerned with identification and analysis of hazards, incidents and accidents acting on systems, their respective impact on system performance (or system service) and mechanisms to either avoid or mitigate negative impacts (International Organization for Standardization 2009). External and internal influences that have the potential to cause damage to the system or seriously limit the system's performance, or system service, are called stressor in this article. Stressors thus not only include point-in-time influences, like events or accidents, but also slowly developing conditions that cause stress on the system resulting in potential failure.

Risk analysis and management is focused on stressors which can sufficiently be described in terms of frequency of occurrence, size and duration and impact on the system. These characteristic parameters are usually given in terms of probability density functions (PDF), which can be derived from observation or models. The management of risks is based on the quantitative analysis of these stressors and impacts with the help of scenario analysis. Further elements include assessment, evaluation and communication of risks and a decision making process for finding mitigation measures (Aven and Renn 2010).

The resilience management approach for critical infrastructures is rather new and less well developed (Linkov and Palma-Oliveira 2017). It distinctly differs from risk management in some key points: the type and characteristics of stressors assessed, the level and uncertainty of quantification of impacts and the typically addressed systems.

2.1 Type of stressors

Resilience as a principle for managing complex systems was born out of the necessity to cope with hard-to-predict stressors with low probability and high damage potential (Lovins and Lovins 1982)(Linkov and Palma-Oliveira 2017). Typical stressors of this type include earthquakes, storms or terrorist attacks. The difficulty in predicting a stressor or its impact can present itself in different forms:

- unknown probability of occurrence (frequency),
- unknown probability of extent and duration of stressor,
- unknown impact on system,
- unknown system state or interdependence with other systems

The probability of occurrence in risk management is usually considered static in terms of its mean value (average frequency) and shape of distribution. Resilience management relaxes such assumptions and also covers events with unknown or changing frequencies, at the cost of predictability of course. Resilience management also tries to find responses to stressors that are changing their frequency of occurrence, even when the rate and direction of change is not known. The change in weather related extreme events is a typical example which is addressed in resilience management, see Figure 1. For coincidental stressors, e.g. an earthquake hitting a system already experiencing a heat wave, the uncertainty in the frequency of occurrence is amplified even more.

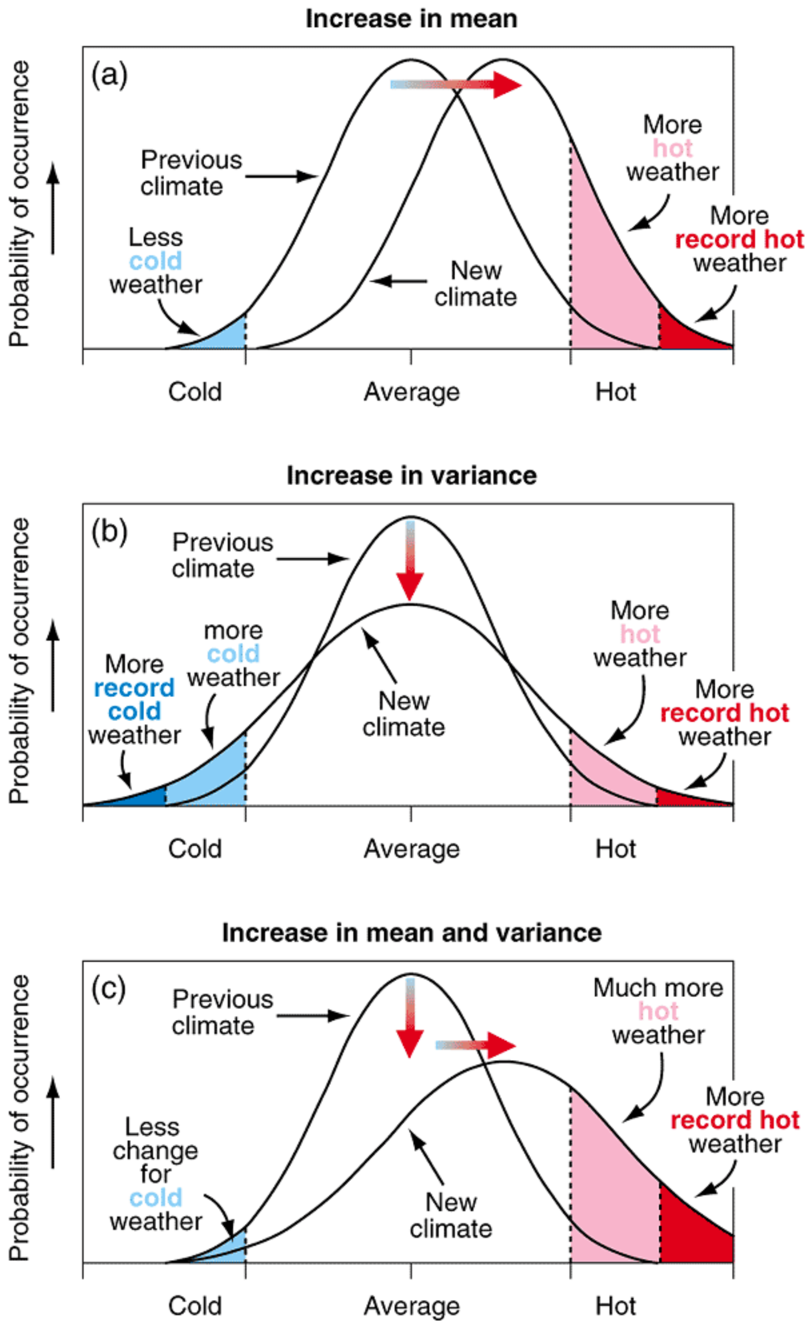

Figure 1: Changes in probability distribution for temperature under a changing climate. A changing climate could mean both, a change in mean temperature and a change in the shape of the probability density function. The effects on the frequency of heat waves would be dramatically different. Source: (Houghton et al. 2001)

Resilience management also aims at preparing systems for stressors which cannot (yet) be described in terms of probabilities of occurrence. One typical class of such stressors are malicious attacks, either physical or cyber-physical. Other stressors might arise from emergent behaviour of complex self-adapting systems which are hard to predict and which act on the system under management, see (Kröger and Zio 2011) and (Helbing 2013) for examples.

At an even greater level of uncertainty, resilience management tries to prepare systems for hitherto unknown stressors, so called “unknown unknowns” or “black swans” (Taleb 2007(Aven 2015). “Unknown” in this context can either refer to stressors that have never been experienced by the system under management, which could be known in theory (e.g. from simulation models or from trend extrapolation) but are not considered in decision making processes. “Unknown” could also mean “cannot be known” due to undeveloped scientific understanding or due to unpredictable emergent behaviour of the system under management itself. The latter might be relevant especially for interdependent systems-of-systems (Kröger and Zio 2011).

Besides the unknown frequency of occurrence, the size distribution of stressors might also be unknown, i.e. the extent and magnitude of the stress acting on the system under management. An example are denial-of-service attacks on cyber-physical infrastructures, which might possibly be very large, with no current estimate of what can be expected. Neither the typical nor the maximum size of such an attack might be known, posing a serious challenge for preparation. A milder, but still challenging case of uncertainty exists where the size or intensity of the stressor is changing over time but with an unknown rate. The not yet fully understood climate change induced change in duration and intensity of heat waves, dry spells or periods of heavy rain are examples.

2.2 Quantification of impacts

The level of quantification of system impacts changes with the complexity of the system under stress and its interdependence with other stressors, as is e.g. typical for critical infrastructures. For highly complex systems with strong internal and external interdependencies the power of describing and assessing impacts and damages for stressors diminishes to a point where meaningful analysis becomes impossible. Preparing systems based on such quantified analysis then fails and alternative ways need to be found (Heinimann and Hatfield 2017). A good example are the unknown implications of an attack on a future cyber-physical energy system consisting of heavily interlinked information technology (ICT) and industrial control (ICS) infrastructure. Currently there does not exist an adequate model to capture the cascading effects in these interdependent critical infrastructures and current knowledge on potential cascading failures is based on the few incidents that have occurred so far (see Fischer and Lehnhoff in this volume). For cyber-physical systems the uncertainty in impact quantification is dynamically increasing with the interconnectedness of cyber and physical and due to the inherent time delay between malicious attackers exploiting not-yet publicly documented vulnerabilities and security teams fixing these vulnerabilities. The cat-and-mouse makes not only prediction of the next attack difficult, but also prohibits fundamentally the assessment of potential damages.

Impact and damage assessment is further complicated in systems with highly dynamic development and where individual human decision making plays an important role for the dynamics and stability of the system. When the system itself is in rapid development, the impact of stressors on the system performance is ever more difficult to assess the more we look into the future. With increasing complexity and interdependence, human decision making in such systems can lead to operational failures when the system state cannot be communicated transparently to operators. Then consequences of action or inaction cannot be reliably estimated and small disturbances can cascade into large-scale disruptions (Kröger and Zio 2011).

2.3 Typical types of systems addressed

The systems for which risk management is most successful are usually linear in their response to stressors and have limited complexity. The risk approach relies on quantification of stressors and their impacts, so that non-linear responses or even chaotic behaviour of systems pose limits to the risk-based approach. Systems which are exhibiting critical transitions resulting from internal complexity, e.g. tipping points, are difficult to analyse and manage in terms of traditional risk approaches. Small deviations in the environment or the state of these systems can lead to catastrophic failures. Systems with self-organized criticality, such as stock markets, are a class of such systems. Also electricity grids show this kind of behaviour, apparent from the power-law distribution of blackouts (Dobson et al. 2007). In such cases, well intended changes in the system to decrease small scale blackouts might even, counterintuitively, increase the number of large blackouts. Interdependent critical infrastructures, as a system-of-systems, are also prone to such critical system behaviour (Helbing 2013)(Gao et al. 2015). In summary, the more a system or its environment must be described as erratic, chaotic and non-linear, the less appropriate is the traditional risk management approach. Avoiding failures under stress and limiting damage from failures must then be accomplished by an approach that sees complexity, non-linearity and critical behaviour as normal, not as an exemption.

Traditional risk management assumes that the system itself is rather static in terms of number of elements and relations between elements. If this system configuration is highly dynamic, the assessment of impacts from stressors becomes less and less feasible for longer time horizons. For highly dynamic systems, like e.g. energy systems in transition to renewables, there might even be a lack of understanding about which stressors might become relevant in the future, simply because the future system is poorly defined. If in such a system risk reducing decisions are to be made, they cannot alone rely on traditional risk approaches. This is especially true if such decisions cover a time frame with a great amount of structural change in the system. Again, energy systems in transition are a good example: while the amount of decentral renewable energy in the system is changing rapidly but with high uncertainty regarding its concrete path, other parts of the system must be planned with long time horizons, especially the electricity grid and other infrastructures. Risk evaluations involving future states of the energy system than become increasingly difficult.

Risk based approaches are limited as well in capturing the impacts of stressors in interdependent systems-of-systems due to the possibility of self-organized criticality and chaotic dynamics of such systems. Risk management works very well for systems consisting of only a limited number of elements and relations and becomes more and more difficult with increasing complexity. When several complex systems are interacting interdependently, the impact of failures in one system can spread to the other system and even back to the first system, creating feedback loops which have the potential to amplify small disturbances to large-scale failures in one or all of the connected systems. A realistic future case could be the oscillating behaviour of energy consumers in an electricity market with short term differential price signals, potentially leading to large load fluctuations or even blackouts (Krause et al. 2015).

More generally, cascading failures in interdependent critical infrastructures, like electricity connected to gas grids and heat networks, together connected to ICT networks, cannot be adequately captured by traditional risk management (Kröger and Zio 2011)(Helbing 2013). Preparing them for future stressors requires additional and complementary approaches.

3 Resilience management

The limits of risk management open the floor for introducing a complementary approach to dealing with stressors and their impacts on systems, especially critical infrastructures. In the resilience approach the focus is on hard-to-predict stressors and on complex, interacting or interdependent systems.

Resilience as a concept for developing socio-technical systems has its roots in several disciplines (see Hellige in this volume). There are several competing definitions for resilience, some of them only valid for specific contexts, others broader. Here, we introduce the following definition in an attempt to capture as much from the other definitions as to allow general conclusions without being too vague:

“Resilience describes a (socio-technical) system‘s ability to maintain its services under stress and in turbulent conditions” (cf. Goessling-Reisemann and Bloethe 2012)

Here, turbulence means dynamic changes in system structure and environment, irregular conditions, limited predictability, and surprises acting on the system. One can distinguish between cases where the risk management approaches is adequate and where resilience management comes into play:

When

- the uncertainty of stressor characteristics, in terms of frequency and size, or
- the uncertainty regarding the impacts and damages from these stressors, or
- the dynamics the structural change of the system under management, or
- the interdependence with other systems

is growing, then the it is rather not possible to implement the known tools of risk management and it is recommended to complement the approach with resilience management. Basically, the less you know about futures stressors and system state, the more adequate is the resilience management approach, see Figure 2.

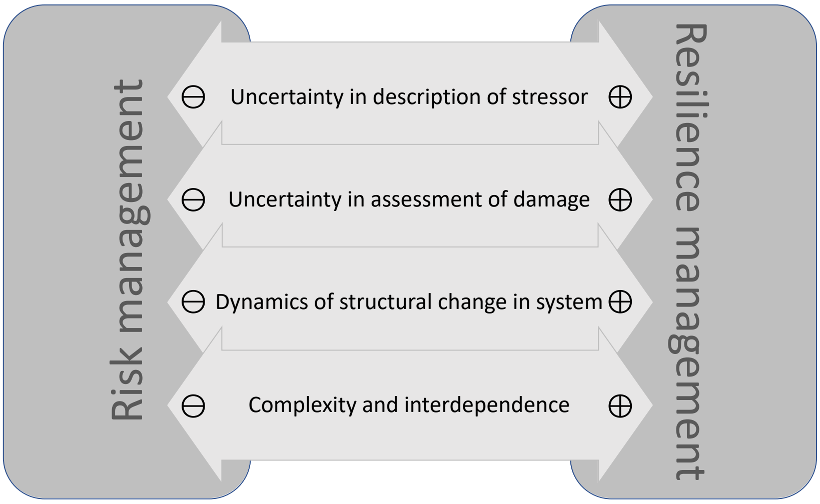

Figure 2: Factors for choosing resilience management as a complementary approach to risk management

3.1 Resilience management cycle

In order to increase a system's resilience, certain steps of analysis and systematic change must be implemented and repeated, not entirely different from risk management. There exist several descriptions of such management cycles (Häring et al. 2017), here we only present two of such approaches.

Based on an analysis of future stressors and ways of preparing the German energy system for these stressors, a group of German scholars developed a set of design elements for resilient energy systems and an accompanying management cycle (Renn et al. 2017), see Figure 3.

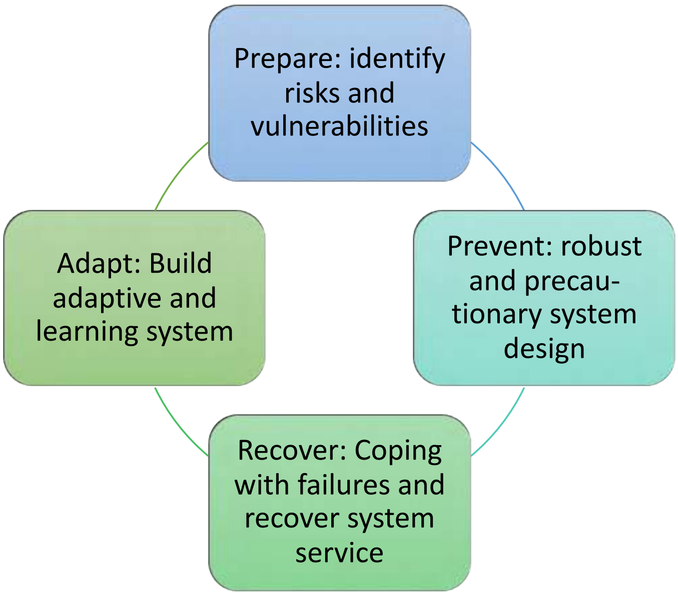

Figure 3: Resilience management cycle based on (Renn et al. 2017)

Based on the well-developed risk management standard (ISO 31000), Heinimann and Hatfield developed a complementary resilience management cycle which has a stronger focus on analysis and evaluation, but is less concrete about measures for building resilience (Heinimann and Hatfield 2017).

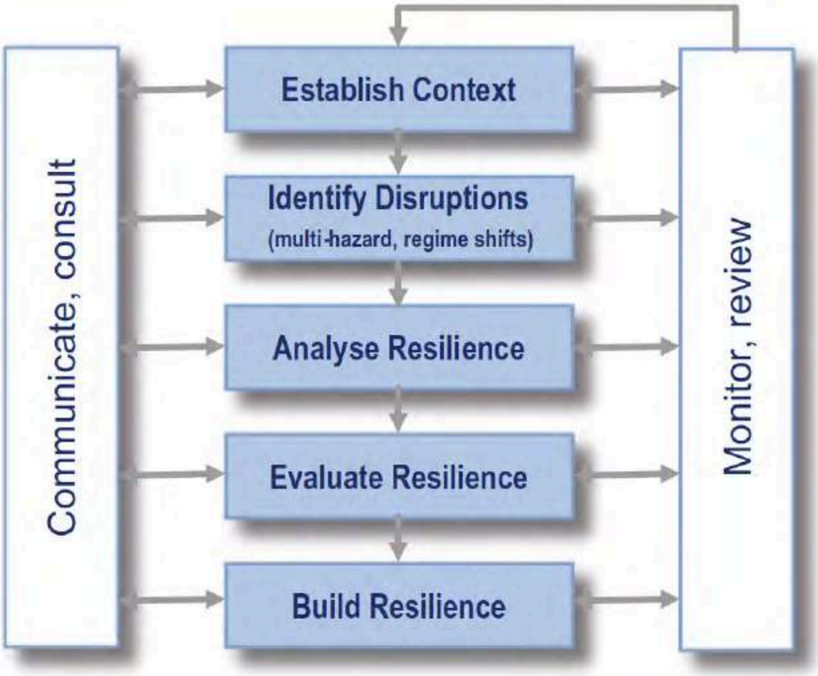

Figure 4: Resilience management cycle according to (Heinimann and Hatfield 2017)

The two examples point towards a common deficiency in the resilience research: all suggestions for resilience management have a common step, where recommendations for resilience improvements follow from analysis. There is, however, a major discrepancy between the claim of resilience management to be able to prepare the system for “surprises” (Sansavini 2017) (Seager et al. 2017) or “unknown unknowns” (Aven 2015) and the actual derivation of resilience measures from analysis: you cannot analyse the impact of “unknown unknowns” on any system, so how can you derive measures from this (non-existing) analysis? As a result of this most resilience management proposals remain rather vague on the actual design elements needed to build resilience.

3.2 Building resilience[1]

‘Resilience-building, in the above sense of resilience, can be understood as a strategy to deal with deep uncertainty, i.e. uncertainty that cannot be reduced by statistics or predictive modeling. Resilience-building and other risk management strategies are thus not to be seen as mutually exclusive, they rather complement each other. Resilience-building can help find answers to stressors that cover a wide range of characteristics, and as a strategy has its comparative strengths where the stressors are unknown with respect to their likelihood of occurrence, their potential impact, or even the nature of their impact on the respective system.

We propose to distinguish certain characteristics of stressors and the capabilities a resilient system should possess in order to deal with them. Stressors are characterized by their dynamics and the state of knowledge about their nature, as follows:

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[1] The following section has been taken from (Goessling-Reisemann 2016)

- **Known/expected**: stressors that the system has already experienced in the past and where predictions of future occurrence exist
- **Unknown/unexpected**: stressors that the system has never or only very rarely been exposed to and where predictions for future occurrences do not exist
- **Gradual/creeping**: stressors that develop slowly and possibly undetected for some time
- **Abrupt/sudden**: stressors that develop suddenly or abruptly without warning

A system that is capable of preparing for, coping with and recover from stressors with an arbitrary combination of the above attributes needs a diverse set of capabilities. For example, when the stressor develops gradually and is already known to the system or can be expected to occur in the near future, an adaptation of existing structures, components and organizations can be initiated to better cope with and recover from occurrences of this stressor. On the other extreme, when the stressor is unknown and develops abruptly, the system will not have time to find innovative solutions or build up resistance, so that it has to use existing resources in the most appropriate form possible to deal with the situation, i.e. it needs to improvise. The needed capabilities for a system to cope with these stressors can thus be summarized as robustness, adaptive capacity, innovation capacity and improvisation capacity, see Table 1 (cf. Goessling-Reisemann et al. 2013)).

Table 1: Characteristics of stressors and needed capabilities

Stressor	**known**	**unknown**
gradual / creeping	adaptive capacity	innovation capacity
abrupt / sudden	robustness	Improvisation capacity

The building up of these capabilities will improve any system’s ability to deal with stressors of many kinds. However, these capabilities are also rather abstract and need “spelling out” for specific systems. Some of the capabilities will require similar structure and processes as traditional risk management: monitoring, predictive modeling, system simulation, crisis management, etc. However, with the additional focus on the “unknown” stressors, it will require new mechanisms and processes to deal with surprises and deep uncertainty.’

In order to build resilience, we suggest a four-step approach. The instruments for resilience management, which should be based on the above derived general capabilities, can be grouped into four main phases or managing resilience: prepare and prevent, implement robust and precautionary design, manage and recover from crises, learn for the future. Here, the instruments are exemplified for energy systems.

3.2.1 Prepare and prevent

As a first measure, past crises and near accidents should be transparently documented and examined to learn about the stressors that caused them and the context in which they occurred, or in which they were avoided, respectively. The latter is especially important as a learning tool for resilience engineering (Hollnagel et al. 2007). Further analysis should be directed at stressors that have not yet occurred, but are likely to occur in the near future, e.g. known from trend extrapolation. For the energy system this would include using climate change trends, like trends for extreme weather conditions, in system simulations and planning. The observed trends of converging and coupling of infrastructures (electricity, gas, heat, fuels, IT) in the course of a transition to high shares of renewable energies should also be observed for new threats and vulnerabilities, like hacker attacks, data privacy issues or cascading failures across infrastructures. Furthermore, new threats can stem from social processes, for example increasing non-acceptance of certain technologies or unfair cost-benefit distributions in the context of energy transitions leading to protests and delays or halts in necessary system changes. Newly developing stressors can be analyzed by vulnerability assessment methodologies. Results from theses analyses should then be used to adjust the design parameters of energy system components (technology level), develop testing scenarios and design guidelines for coupled infrastructures (system level) and monitor social impacts and responses to technological change with feedback to governance processes (governance level).

3.2.2 Implement robust and precautionary design

In line with the above detailed characteristic capabilities of resilient systems, the central design elements of resilient energy systems must comprise robustness, adaptive capacity, innovation capacity and improvisation capacity. On the design level of components and systems the resilience-enhancing capabilities can be achieved by first strengthening the identified vulnerable elements (see above) by increasing redundancy, buffer capacity and energy storage. This will reduce the stress on vulnerable elements in the system and will also act as a precautionary measure for further and yet unknown stressors. In order to prepare for unknown future stressors, it is also advisable to check existing technologies in the energy system for alternative solutions in order to enhance the diversity. Diversity should encompass notions of variety, disparity and balance (cf. (Stirling 2007) and (Stirling 2010)). Additional analyses should also be directed at components and structures that have not yet been affected by known stressors but are otherwise crucial to the system. As a precautionary measure, they should also be strengthened by increased diversity, redundancy, and buffer and storage capacity. Especially for new couplings between systems (e.g. between electricity and mobility sector) and newly developing technologies (e.g. smart grid and cyber-physical energy systems) special attention on new potential vulnerabilities is needed, since integrating different systems into one also imports the respective vulnerabilities. Resilient coupling of systems should yield additional flexibilities to buffer imbalances in each sub-system, while minimizing the potential for cascading failures (loose or flexible coupling, cf. (Perrow 2011)(Orton and Weick 1990), (Beekun and Glick 2001) for loosely coupled organization). It should be obvious that these resilience design measures will cause conflict with other design goals of energy systems, most prominently with technical efficiency and (at least short-term) economic competitiveness. Some conflicts with the ecological sustainability might also be possible, especially in terms of additional equipment and possibly reduced efficiency. These conflicts need to be addressed systematically by cost-benefit analyses that include long-term effects and an evaluation of costs due to rare but possibly extremely damaging events.

3.2.3 Manage and recover from crises

If failures of the energy system lead to crises, they should be restricted to the smallest possible area or subsystem and be overcome as quickly as possible. In order to reduce the extent of such crises, emergency planning and respective measures must be implemented on the regional or local level. With the increasing share of renewable energies comes a trend towards decentralization of energy systems, which can be utilized for increased resilience. Currently, the restoration of the electricity supply after blackouts in most industrialized countries is organized in a rather central fashion and dependent on large thermal power plants. A decentral design more in line with increasing decentral renewables and the advent of smart grids would be to organize the energy system in a cellular structure where each cell has the potential to run autonomously for a limited time and inter-cellular synchronization is used to restore overall system performance after blackouts. The adequate size of these cells has still to be determined and will also be dependent on the respective investments necessary to equip cells with restorative functions in relation to the added resilience of the overall system. Flexible coupling between the electricity system and other energy subsystems (especially gas, heat and fuel networks) will increase the restorative capacity and decrease the need for regional storage capacity.

3.2.4 Learn for the future

Mastered or averted crises should be used to learn and increase the adaptive capacity of the system. This can be achieved by documenting and analyzing these crises and events thereby identifying the weaknesses that led to their occurrence (vulnerability store), or, respectively, identify the strengths that led to their avoidance or recovery (solution store). Knowledge about crises and potential solutions should then be used to create simulations and business games for system actors on all levels. Improvisation capacity can be increased by confronting actors in these simulations with unforeseen and unlikely developments, like combined external threats and internal failures of equipment. In the actual operation of the energy system, improvisation capacity can also be improved by allowing a certain amount of unused resources to be maintained in the system, comparable to a strategy called “organizational slack” in business organizations (cf. (Cyert and March 1963), (Linnenluecke and Griffiths 2010))

3.3 Design principles for resilient systems

As should be obvious from our discussion above, the unknown nature of stressors to which the system could be exposed makes it difficult to develop design principles for resilient systems. The design must thus be focused on the implementation of a robust and precautionary system design, taking into account as many stressors as possible. In the previous section, we have identified basic capabilities of resilient systems, especially critical infrastructures, that must be fulfilled for the system to be resilient against a wide array of possible stressors. One can then look towards systems in nature and technology where resilience against unknown stressors plays an important role for survival or system performance and collect design principles that improve these system's ability to withstand such stressors.

The following principles and elements that are summarized in Table 2 are derived from a search on design principles and elements with known resilience-enhancing features, e.g. taken from the knowledge of evolutionary processes in ecosystems or socio-technical resilience in energy systems, organizations and other application fields. A more detailed analysis can be found in (Brand et al. 2017). The application of these principles follows the aim to increase the resilience of the system against all kind of unknown stressors ("no matter what"). It should be noted that the principles and elements provide useful hints for the design of resilient systems from a general point of view. However, implementation in a specific context requires further analysis of the system under evaluation and its boundary conditions.

Table 2: Overview of principles and elements that enhance the resilience of systems.

- Variety / Diversity
- Geographical Dispersion
- Redundancy (num/funct)
- Balance of feedback mechanisms (+/-)
- Flexible / optional coupling
- Buffer and storage
- Subsidiarity
- Modularity / Cellularity
- (unallocated) Resources / slack
- Flexible system requirements (quant/qual)

Diversity contributes positively to the way a system can respond to stressors. In ecosystem theory, the assurance hypothesis states, that a large number and variants of species have a stabilizing effect on the systems. In socio-technical systems, this can be achieved by differing implementations of functions in the systems, e.g. diversifying the electricity generation.

Diversity is also thought to help preventing path dependencies (Farrell et al. 2004). Diversity promises also to enhance the evolutionary innovation capabilities of systems and raises the functional diversity (Peterson et al. 1998) cited in (Molyneaux et al. 2016). In order to make the concept of diversity more operational and potentially measurable, Stirling suggests to specify diversity in terms of disparity, variety and balance (Stirling 2007). Disparity is understood as the differences between system elements. Variety characterises the amount or number of different elements with the same functionality in the system. Balance is given by the distribution (mix) of these different elements.

Redundancy describes the multiple availability of elements in a system, either in number or in functional equivalence. These multiple elements are usually not needed in normal operation. Numerical redundancy is understood as the provision of a number of identical elements with the same function, while functional redundancy refers to the situation where the same function is delivered by distinctly different elements (e.g. by different technologies, operating systems, etc.). The n-1 principle in electrical transmission systems is a good example for numerical redundancy: if one element in the transmission fails, the performance of the system should not be affected. If functionally equivalent elements in the system are also technologically or structurally different, then the system also has functional redundancy, a term borrowed from ecosystem theory.

When we think of larger systems, e.g. electricity supply systems, **geographical dispersion** plays an important role for resilience. By spreading system elements geographically, all localized stressors, from weather related events to terrorist attacks, have a relatively smaller attack surface. Renewable energies need to be geographically spread out by nature, fossil and nuclear energy systems are usually more concentrated, but can be dispersed in principle. For other critical infrastructures geographical dispersion is implemented to a somewhat different degree: water supply is rather broadly distributed, except for regions with water scarcity problems, while there is some regional concentration of critical elements in ICT systems.

Adaptive behaviour in socio-technical systems requires information collection and analysis over different time scales. On short time scales and with regard to technical control, ICT helps with this task by allowing the collection of large amounts of data and automated analysis. On longer time scales and applying also to the social and organizational structure, adaptive behaviour and learning is enabled by having **feedback mechanisms** and active and passive communication structures. A possible realisation of feedback mechanisms are monitoring systems. These enable a status detection and can at the same time deliver important information for the analysis of disruptions, hazards and near-accidents. Designing feeback mechanisms with low complexity makes them more robust against failures (Lovins and Lovins 1982). In general, it can be highlighted that open communication structures enhance the transfer of knowledge und lay the foundation for trust and learning capabilities (Carpenter et al. 2012; Crona and Parker 2012).

All elements in a system are connected to each other in various ways and to different degrees. Here, we distinguish between tight coupling and **flexible / optional coupling,** or lose coupling as introduced by Perrow (Perrow 2011)**.** Tight coupling between elements or between systems, as e.g. in interdependent critical infrastructures, lead to the possibility of cascading failures: if one element or sub-system fails, and others are dependent on this element, they too will fail. Flexible or optional coupling enables the functioning, or partial functioning, of elements and sub-systems without connection to other elements, so that cascades are prevented from spreading out. Buffers and storage of material, decentral organization and polycentric governance can all contribute to optional coupling. The strategy of uncoupling contributes to a fast isolation in case of a damage (Gershenson et al. 2003; Lovins and Lovins 1982).

A system that can be divided and split into sub-segments is called **modular/cellular**, if the aggregated elements provide full system function in the sub-segments**.** Modularity is considered to enhance reparability and lower outage times in technical systems, but also allows for an enhanced diversity, if modules are equipped with well-defined interfaces so as to ease swapping different technological implementations (Huang and Kusiak 1998). In aviation control, for example, modular system design enhances safety but challenges traditional certification schemes, which are currently still based on monolithic systems (Bate und Kelly 2003). Another example is modularity in forest management that helps preventing the spreading of fires (Carpenter et al. 2012).

Subsidiarity describes the approach to solve problems on the lowest level possible, preferably were the perturbation occurs. As a governance paradigm it has been enacted in e.g. federal states, where local and regional decisions are usually separate from federal decisions and there is as little overlap as possible. Elements in lower organizational levels should thus be independent from decisions on higher levels. A polycentric governance, with several small governance entities mostly independent of higher levels of governance, helps implementing the subsidiarity principle and promises to enhance innovation, trust and the achievement of sustainable solutions by incorporating local participants (Ostrom 2010). For social-ecological systems, open communication is seen as a facilitating aspect of polycentric governance forms that also enhances resilience (Biggs et al. 2012).

As should be obvious, the implementation of **buffer and storages** in systems will enable the system to maintain its services in case of internal or external resource restrictions. Buffer and storages provide the system with extra capacities that delay critical systems states after a disrupted supply. These elements thus serve several functions that enhance a system’s resilience: they decouple subs-systems or infrastructures from each other, allowing functioning after connections have been severed; they buy a system extra time for recovery and facilitate the recovery process itself; if implemented locally, they can help maintaining a minimum service in times of crisis to a larger number of system users (see (Lovins and Lovins 1982) for examples in electricity grids). Delivering backup power from batteries in cases of disrupted transmission grids is one example.

In case of unprecedented stressors acting on the system, a stressor-oriented preparation is impossible. In these cases it seems helpful to have **unallocated resources or slack** in the system (cf. (Cyert and March 1963), (Linnenluecke and Griffiths 2010)). These additional resources (personnel, machines, time, etc.) are not dedicated to a certain task, but can be used for whatever the need may be. A historic example are the differing ways Nokia and Ericsson handled a supply chain disruption hitting both companies in 2000. Nokia was able to fend off the disruption by not only being more agile and adaptive, but also by maintaining backup suppliers which were not engaged in routine operations, and by establishing a collaborating relationship with their suppliers, requiring extra personnel (Lee 2004).

A rather trivial strategy to increase a system's resilience is to make **system requirements more flexible (quantitatively / qualitatively).** After all, resilience describes a socio-technical system's ability to deliver its service under stress and in turbulent conditions. The system service is defined by the users or beneficiaries of that system. Thus, if there is flexibility in the service requirements, the definition of resilience can more easily be fulfilled. Instead of asking for a resilient system, in this case the resilience really lies in the user of the system's service. As an example, when the electrical grid stability is high but threatened from increasing shares of renewables and a delay in grid extensions (as is the case in Germany), one could discuss decreasing the expected availability of electricity, at least for a limited time. Of course, this shifts some of the burden of having a resilient power supply to customers, which can only be decided when there is a common agreement between grid operators, regulators, industry and private customers. The example can easily be extended to other critical infrastructures and links the question of resilience to the discussion on sufficiency.

4 Scientific and practical challenges

The analysis and the design of resilient critical infrastructures is very often discussed alongside a certain mental model, where "shocks" (or stressors in our terminology) create a dip in "performance" of the system with subsequent phases of absorption, recovery, adaptation and learning or transformation, cf. Figure 5.

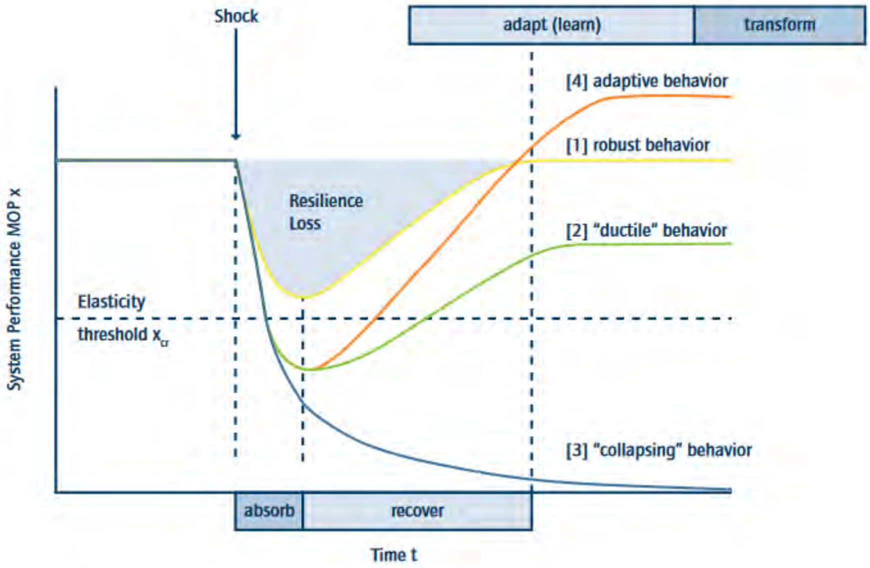

Figure 5: Reaction of resilient and non-resilient System to shocks. Source: (Kröger cited in (Thoma 2014))

This mental model is a good visualization for some aspects of resilience, but it is also misleading in some way and should be interpreted with consideration of real-world complexities. Regarding the current approach towards analysing and designing resilient critical infrastructures, there are a few challenges that we would like to address briefly, without attempting to answer them here.

4.1 What is the system performance?

The assumption in many resilience analyses is that you can adequately define the system’s performance, usually in a quantitative way. However, there are a few caveats that are seldom addressed. Firstly, the definition of the system performance is subjective and different definitions can lead to different answers. For electrical transmission systems, is the number of served customers a good measure? Or the load being served? Or the energy delivered? Is there any consideration of the criticality of the end-consumer being served, e.g. hospitals vs. industrial plants? The resilience loss and, more importantly, the recommendation for enhanced resilience will definitely depend on these choices and thus they should be made transparent and be subject to a sensitivity analysis.

4.2 Is minimizing the “triangle” the best approach?

An often-used measure for system resilience is the area of “performance loss” between the nominal performance value and the actual performance after a shock. The smaller this triangle, the more resilient the system, or is it? Again, this depends on the performance measure chosen. Minimizing the triangle for one measure might lead to non-minimization if another measure was chosen. Would it be preferable to first reconnect critical end-users after an infrastructure fails instead of randomly reconnect users? Again, this choice is subjective but the consequence must be made transparent.

4.3 Can we understand the dynamics of resilience (evolution of systems)?

A challenge for science is the analysis and design of resilience in dynamic systems, especially critical infrastructures. One highly dynamic driving force for all infrastructures is digitalization. How can we analyse systems that are developing faster than our analysis methods can be applied? And how do we develop design guidelines for highly dynamic systems that are not “stale” when they are put into practice? The transitioning energy systems are an especially hard nut in this respect: they are developing technologically, structurally, economically and organizationally at a very fast pace. Additionally, the ever-increasing interdependence of heat, electricity, gas and fuel subsystems, the growing threat from cyber-physical attacks and the large uncertainties of climate change make a sound analysis of future threats to the energy system and the derivation of resilience enhancing measures complex, to say the least. The less we know about the future state of our critical infrastructures and the stress they might be subjected to, the more we should probably focus on adaptive, innovation-capable and flexible systems instead of robust ones.

4.4 Can we assess a system’s resilience ex-ante?

In most analyses guided by the above mental model of resilience, a known shock is assumed that acts on the system and leads to more or less performance loss. This, however, does not capture the real essence of resilience: being prepared for the unknown. If the stressor is fully known, we would speak of a vulnerability analysis when we measure the performance loss under stress. The resilience, on the other hand, as the ability of a system to maintain its service even under unknown stress, cannot be measured in this way. Can it be measured at all, one might ask? A more resilient system should be less vulnerable to (most) known stressors, but this is only a necessary and not sufficient condition. Resilience is more than the absence of vulnerability.

And even when the analysis of real systems under stress has shown differences in the resilience of different system designs, how do we systematically derive the main design elements necessary to build futures systems? In simulations we can use trial-and-error, which, however, might run into computing limits. Is there a more analytic way to get to improved resilience? Since we cannot measure resilience adequately, i.e. including the unknown or insufficiently characterised stressors, we surely can also not know what “optimal” resilience is.

4.5 Who’s resilience anyway?

Resilience is usually attributed to a “system” without mentioning the beneficiaries involved. If the resilience of infrastructures is debated, it is clear that almost everyone in a society benefits from infrastructure resilience and thus it is seen as a “good thing”. However, if one part of an infrastructure, and its operator, are in the way of adaptation, an incumbent in a changing system, then the resilience of this part is actually in conflict with the encompassing system’s resilience. Think of the internet and the many billions of private computers attached to it, together providing communication services. If a large fraction of the attached machines run the same operating system, the attack surface for viruses or other malicious attacks is enormous. A more resilient network would contain a more balanced mix of different operating systems. From the perspective of the company producing the dominant operating system, keeping its market share high even in times of stress is part of its own resilience understanding. For the whole system (internet), however, this leads to the contrary. Other examples could be found in energy systems, where the resilience of sub-grids could come at the cost of the larger grid, e.g. when many sub-grids go into island mode to protect their local system service while simultaneously depriving the rest of the system of their stabilizing capabilities. Resilience can be double-edged sword. It is therefore crucial to discuss the beneficiaries of a resilience strategy when analysing and designing systems and include a broader perspective as not to miss possible negative side-effects.

4.6 How to balance resilience design elements?

Above, we have suggested several design elements for resilient systems. What is lacking, is a recipe for finding the right balance between these elements. There will be conflicts and trade-offs which need to be balanced and there is currently a lack of theory describing how to reach some form of optimality or least regret. Design elements that make a system more robust might make it less adaptive at the same time. Building intelligent feedback loops into a critical infrastructure might lead to more complexity and might open up new vulnerabilities. Connecting infrastructures to increase flexibility, e.g. linking electricity grids more thoroughly to heat networks, might also increase the risk of cascading failures originating in one of the infrastructures. When taking other design objectives into consideration, e.g. environmental sustainability or efficiency, even more trade-offs must be balanced. Redundant elements directly add cost and environmental burden to the system, although in the long-run they might be cost-efficient and eco-efficient, if they should be needed at any time.

4.7 What is the resilience of interdependent systems of systems?

A major challenge for improving the resilience of critical infrastructures is the case of interdependent infrastructures. First of all, the complexity of such combined infrastructures is growing with every connection and feedback loop between the infrastructures, making analysis and prediction of (cascading) failures much harder. Network simulation, stochastic modelling and other computational tools can help address this challenge. On a more fundamental side, one needs to define a combined system service for interdependent infrastructures which captures both individual services and which can be quantified. For the combined systems of energy supply and communication infrastructure, for example, there is no straightforward way of finding such a combined system service. With different beneficiaries of either infrastructure, there is also the need for finding acceptable prioritization of system services when designing a resilient combined system. Is a performance loss in one of the infrastructures acceptable when it helps to stabilize the other infrastructure? This question can only be answered asking the users and through a negotiation process involving all stakeholders and participants in the system with their individual needs.

5 Conclusion

There is a clear distinction between risk management and resilience management and both have their distinct range of application. When uncertainty in stressors and system dynamic increase, the traditional risk analysis becomes more and more inadequate to help preparing the system under analysis for the future. Here, resilience management can play out its strength in bringing the focus back on the system design, not the stressor. There are, however, many challenges, scientifically and practically, which need to be addressed before resilience management as a precautionary strategy achieves the necessary level of maturity to be applicable for a wide range of systems.

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