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RESILIENCE by design: ten principles to guide chemistry in a volatile world

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The unexpected large-scale electrical blackout across the Iberian Peninsula in April 2025 served as a stark reminder of our growing dependency on a stable electricity supply and the inherent vulnerability of electrified systems—including chemical manufacturing, scientific research, and education. Scientists working in green and sustainable chemistry are increasingly committed to electrification and net-zero industrial practices. However, we must also ensure that these processes are resilient to disruption. In this article, we propose ten principles for more resilient chemistry, designed to add to the discussion and to stimulate further research into how chemistry can remain both sustainable and robust in the face of volatility in energy supply, resource constraints, and geopolitical instability. We call on the global chemical community to reflect on the implications of such disruptions—not only for industrial production, but also for scientific gatherings, laboratory research, and the future of chemistry education.

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Introduction

On April 28th, 2025, there was a sudden and near total failure of electrical power across Portugal, Spain and some areas of adjoining countries.[1] At the time, all of the authors were attending the opening day of the 9th Portuguese Young Chemists Meeting (9PYCheM) in Faro, Portugal.[2] The meeting had to be abandoned for that day and power was only restored in Faro ten hours later. This power cut highlighted how reliant we have all become on a stable electricity supply. Traffic lights stopped working, cars could not refuel, people could not access cash from ATMs and cafes and restaurants closed. In short, people's daily lives were totally disrupted.

Spain's chemical industry was significantly affected by the blackout, with facilities restarting at an uneven pace due to their high technical complexity and interdependence. Although critical processes such as production of oxygen and chlorine were swiftly restored, most plants were still operating below full capacity as safety protocols and process reintegration continue with a full return to normalcy taking up to a week. The true economic impact—anticipated to be substantial—will only become clear once all operations are fully re-established and stabilized.[3]

The electricity blackout also dealt a significant blow to scientific research across Spain, temporarily paralyzing activity at numerous laboratories, universities, and research centres. Sensitive experiments were interrupted, some irreversibly, due to the sudden loss of power and the failure of backup systems in several institutions. Data collection was halted, and costly research infrastructure and on-going reactions were compromised.[4] Tragically, at least three people died as a consequence of the blackout.[5]

In Portugal, the scenario was similar. The power cut had a major impact on the industrial chemical sector, which accounts for 12% of Portuguese exports and supports 52 000 jobs. A return to normal operations was expected to occur only gradually over several weeks. In academia, the disruption was also severe, with several critical facilities across various institutions identified as being at risk should similar incidents occur again. Importantly, for those of us com-

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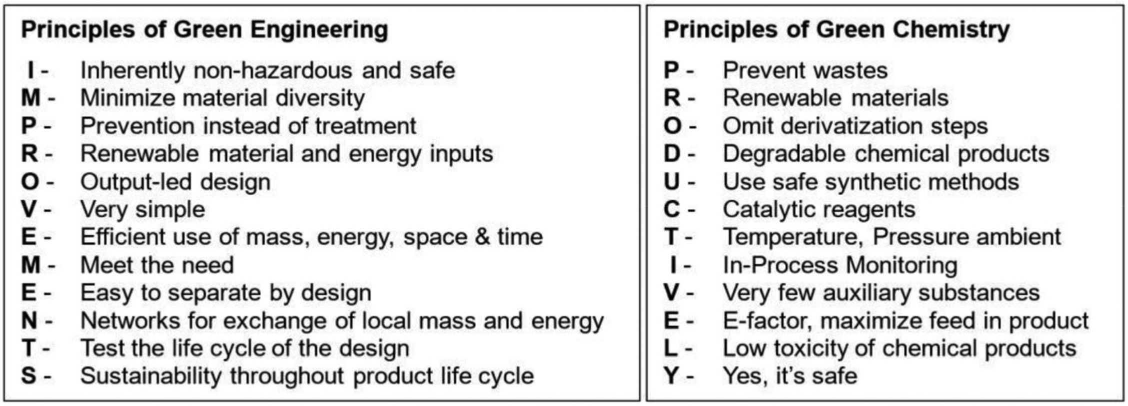

Principles of Green Engineering	
I -	Inherently non-hazardous and safe
M -	Minimize material diversity
P -	Prevention instead of treatment
R -	Renewable material and energy inputs
O -	Output-led design
V -	Very simple
E -	Efficient use of mass, energy, space & time
M -	Meet the need
E -	Easy to separate by design
N -	Networks for exchange of local mass and energy
T -	Test the life cycle of the design
S -	Sustainability throughout product life cycle

Principles of Green Chemistry	
P -	Prevent wastes
R -	Renewable materials
O -	Omit derivatization steps
D -	Degradable chemical products
U -	Use safe synthetic methods
C -	Catalytic reagents
T -	Temperature, Pressure ambient
I -	In-Process Monitoring
V -	Very few auxiliary substances
E -	E-factor, maximize feed in product
L -	Low toxicity of chemical products
Y -	Yes, it's safe

Fig. 1 The 24 abbreviated principles of Green Engineering and Green Chemistry.[12]

mitted to advancing sustainable chemistry, the event posed an urgent and previously underexplored question: can our increasingly electrified and decentralized chemical enterprise also be resilient?

The field of Green and Sustainable Chemistry has been characterised by sets of principles beginning with the 12 principles of green chemistry,[6] closely followed by Green Engineering,[7] as well as CO_2 Chemistry,[8] Circular Chemistry,[9] Greener Africa[10] and Greener Analytical Chemistry.[11] In particular, the principles for Analytical Chemistry have been summarised by the acronym SIGNIFICANCE[8] and those of Green Engineering and Chemistry, respectively by the acronyms IMPROVEMENTS and PRODUCTIVELY[12] (Fig. 1).

A call for resilience: implications for industry, research, and education

As we strive towards a net-zero, electrified chemical industry, resilience must be recognized as a core component of sustainability. The Iberian blackout revealed key vulnerabilities across the chemical ecosystem:

1. Scientific meetings were suspended mid-session, and the flow of knowledge was temporarily paralyzed.

2. Laboratory research, dependent on precise environmental controls and continuous power, was interrupted. Many experiments were irreversibly ruined.

3. Educational activities, both in universities and public outreach, were suspended—underscoring the fragile infrastructure supporting the training of future chemists.

If we are to electrify chemistry,[13] we must also build systems that can withstand energy shocks. But the need to build more resilient chemistry goes beyond our ability to withstand power outages. It extends from supply chains to pilot plants, and from classrooms to computational modelling clusters. The need to embed resilience into the practice of chemistry has never been more urgent. Advancing a more resilient chemical enterprise requires a clearly defined framework that articulates its core values and operational priorities. In this context, the establishment of resilient chemistry represents a critical step toward guiding research, education, and policy efforts that promote adaptability, sustainability, and relevance to societal needs. Already, resilient chemistry is becoming a major theme of sustainable chemistry[14] and is being incorporated into innovative curriculum tools.[15] This editorial seeks to initiate the possible formulation of a set of principles which might help accelerate the development of this theme. To stimulate this discussion, we propose an initial set of ten principles with the acronym RESILIENCE, Fig. 2.

Range of suitable renewable feedstocks

There is a move for sustainable chemicals to be made from bio-derived feedstocks (*e.g.* limonene from citrus fruit waste) but plants are vulnerable to diseases such as citrus greening disease.[16] Therefore, a resilient chemical industry must rely on a diversified portfolio of renewable feedstocks, not only to reduce dependency on fossil resources but also to safeguard against single-point failures. While bio-based chemicals offer promising alternatives, their dependence on agricultural outputs introduces new vulnerabilities. The Braskem process for bio-derived poly-ethene using ethene from sucrose is a good example of potential diversification,[17] because that sucrose could be derived from sugar cane or equally from sugar beet which grows in totally different climates from sugar cane. Of course, sucrose is a foodstuff but there are numerous non-food bio-wastes that can also be fermented into bioethanol.

However, resilience also demands that we look beyond bio-based inputs. Many emerging sustainable technologies, such as batteries, catalysts, or photovoltaic materials, depend on scarce or geopolitically sensitive elements (*e.g.*, cobalt, rare earths, and platinum group metals). A resilient chemical enterprise cannot be built on materials that are both finite and unevenly distributed. We must, therefore, accelerate the development of earth-abundant chemistry: processes and products that rely on elements plentiful in the Earth's crust (*e.g.*, iron, carbon, nitrogen, silicon). Such a shift not only enhances resilience but also aligns with long-term sustainability and geopolitical stability. In

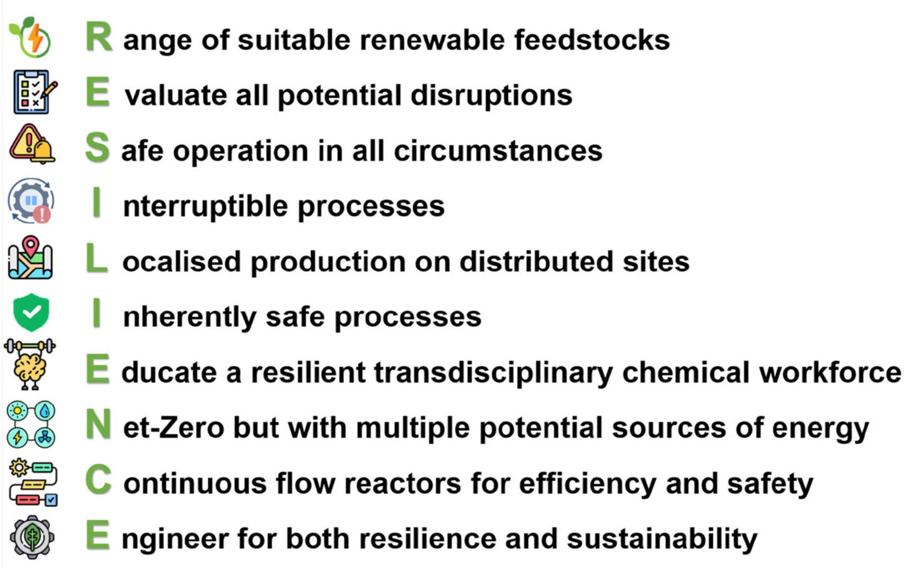

Fig. 2 The proposed ten principles for more resilient chemistry (RESILIENCE).

short, resilient chemistry is not merely renewable—it must also be robustly diversified and materially democratic.

Evaluate all potential disruptions

For resilience, chemists need to take a wide systems view of how their scaled-up process might be disrupted, including disruptions in supply chains, failure of services (electricity, water, *etc.*), natural disasters (wind, flood, wildfires, earthquakes, and so on) and climate change which might affect the use of volatile solvents and feedstocks. To design resilient chemical processes, both academic and industrial chemists must move beyond general risk awareness and implement concrete tools to identify and mitigate vulnerabilities. This involves performing HAZard and OPerability studies (HAZOP),[18] carrying out Failure Mode and Effect Analysis (FMEA)[19] and life cycle risk assessments (LCRA), tailored not just to safety but also to energy security, logistics, and climate risks. For instance, digital process twins and predictive simulation software (*e.g.* software like Aspen Plus, COMSOL, *etc.*) can model how a system responds under stress conditions like power failure, raw material variability, or temperature extremes. Clearly, AI has much to offer when adding to the resilience of chemical activities. However, the energy intensiveness of AI and issues of cyber-security also add vulnerabilities to the chemical enterprise. Indeed, in the early stages of the Iberian power cut, much of the conversation amongst us was over the possibility of a cyber-attack.

Safe operation in all circumstances

We should design our processes with as wide a range of safe operating conditions as possible so that only the largest changes in conditions would force operations to cease. For every shutdown, the first priority must be "fail safe"; the process must stop in a safe condition. Several well-defined guidelines exist to help ensure that chemical processes remain safe and operable across a broad range of conditions. One such approach is to define a Safe Operating Envelope (SOE), specifying the permissible limits of pressure, temperature, composition, and flow regime to avoid unsafe or unstable operation. In addition, chemists and engineers should integrate Inherently Safer Design (ISD) principles.[20]

Interruptible processes

Such processes are a cornerstone of resilient chemistry, allowing operations to pause and resume without incurring damage, safety risks, or prohibitive restart costs. Many traditional chemical processes, especially those involving high temperatures or continuous reactions, are inherently inflexible—once stopped, restarting may be technically unfeasible or economically unjustifiable. A stark example is the threatened catastrophic shutdown of the blast furnaces at British Steel Scunthorpe during a coking coal shortage; had the furnaces fully cooled, they would have been permanently damaged, threatening not only production continuity but also asset integrity.[21] In addition, there are examples of accidents caused by shutdown and subsequent restarting of reactors, *e.g.* in the early development of continuous supercritical water oxidation of organic compounds with oxygen, there were serious accidents caused by unanticipated shutdowns. As the reactors cooled, there were phase separations of the oxygen, the substrate and water, leaving a pure organic layer in direct contact with gaseous oxygen. When the systems were re-pressurised, there were explosions caused by reaction of the organic compound with high-pressure oxygen. Therefore, there is a strong need to design processes that can be restarted safely under a wide range of operational conditions and user expertise levels.

Designing chemical processes with interruptibility in mind is a multidisciplinary challenge which should begin with the fundamental chemistry. Then, chemical engineering techniques such as modular or batch-based operations, integrated thermal management systems, and robust process controls can be implemented to significantly reduce vulnerability to disruptions in feedstock, utilities, or external supply chains. Moreover, digital twins, advanced process control, and predictive maintenance tools can help identify safe pause points and optimize restart protocols, making flexible operations more achievable.

Localised production on distributed sites

Economies of scale have dictated that chemical production has moved to increasingly large, centralised manufacturing sites, which increases the vulnerability and security of supply. This was demonstrated by the shortages of generic medicines in Europe during the COVID-19 pandemic because of disruption to supply chains from the Asian countries where most of these medicines are currently manufactured. Furthermore, the recent political upheavals in international trade have revealed quite how vulnerable is the current system of centralised manufacturing. Many of these risks would be mitigated by having a larger number of smaller manufacturing centres distributed across the globe. The extra capital costs of having multiple manufacturing centres could perhaps be partially offset by co-locating several plants for manufacturing different products in the same place. Of course, localised manufacturing will also provide greater security of supply.

Inherently safe processes

The chemical safety pioneer Trevor Kletz gave a revolutionary lecture in 1978, "*What you don't have, Can't leak*",[22] in which he introduced the idea of inherent safety,[20] anticipating some of the ideas of Green Chemistry by more than a decade. Kletz challenged chemists to try to design chemistries where the chemicals would pose no hazard if they were to be released. Now we need to go to the next level, namely, to create processes where disruptions of the process will not lead to release of those, albeit safe chemicals, so that there is minimal loss of production. This line of thinking aligns with the broader systemic changes outlined in the SIDE vision (Sustainability, Innovation, Diversity and Education) for Chemistry 2030, which provides a roadmap to tackle increasingly complex and interconnected challenges. As emphasized in our recent perspective,[23] the next decade demands bold innovation to ensure that chemistry contributes to a safer, more resilient, and circular society.

Educate a resilient transdisciplinary chemical workforce

Universities and other tertiary educational organisations are training the next generation of scientists, engineers and technicians, who may well be working in much more challenging circumstances than those of today. It is therefore essential that we train them to approach future challenges in a very flexible manner. They must be prepared to cross the current boundaries between disciplines, to acquire new skills through lifelong learning, and to take a more holistic approach to problem solving. They will be faced with rapidly changing conditions both on a local and a global scale and must not be daunted by the need to respond to evolving situations. They need to balance optimism and despair so as to have a constructive view of events, a situation sometimes called the Stockdale Paradox.[24] Our chemical workforce is a valuable resource, and it will be impossible to deliver resilient chemical-using industries without their skills and knowledge. Educating the workforce is a real opportunity for collaboration between Chemical Societies and Institutions of Chemical Engineers. Resilience is not only a matter of infrastructure and technology, but also of cultivating a community capable of adapting, responding, and innovating in the face of disruption. For example, the two universities in Nottingham have set up a transdisciplinary Centre for Doctoral Training in Resilient Chemistry for precisely this purpose[25] and the Royal Society of Chemistry has highlighted the importance of developing resilience in our students.[26] The fact that young chemists can have both the power and responsibility to shape things was clearly demonstrated during the 9th PYCheM conference, where they showed remarkable resilience in adapting quickly and maintaining scientific dialogue despite the disruptive power outage.

Net-zero but with multiple potential sources of energy

Some use of electricity is likely to be unavoidable in any process, but direct electrical heating could be replaced by use of steam to heat. The steam could be produced by electrical heating but also by burning waste biomass or even from small modular nuclear reactors.[27] More generally, vulnerability of chemical processes could be reduced by ensuring access to off-grid energy supplies as an additional "safety" measure.

Continuous flow reactors for efficiency and safety

Flow reactors have twin advantages. They open up new technologies such as photochemistry and electrosynthesis, which are hard to scale-up in batch reactors,[28,29] with the added advantage that these reactions can be instantly stopped merely by switching off the light or power. Furthermore, photochemistry can be powered by solar energy,[30] which is the ultimate renewable power source, either by direct solar radiation or by use of LED lights powered by photovoltaic (PV) solar panels. From the point of view of safety, flow reactors have only a small volume of reaction mixture being processed at any one time, thereby minimising the amount of chemicals that could be involved in a safety incident.

Engineer for both resilience and sustainability

This principle encapsulates the whole aim of resilient chemistry, when modifying existing processes or designing new ones, we must bear in mind the need to manufacture chemicals reliably for the present generation while ensuring that our design will also deliver those chemicals sustainably to future generations. In fact, the Iberian power cut turned out to be more effective in making us think differently about resilience in chemistry production than all of the excellent lectures and posters at our conference.

The widespread blackout that paralyzed Spain's chemical and refining sectors, and disrupted research institutions and universities across the Iberian Peninsula is a stark reminder of how vulnerable our interconnected systems remain. Building a more resilient chemistry must go beyond safeguarding industrial continuity—it must encompass the infrastructures of research and education that drive innovation and knowledge.

Laboratories were left inoperative, experimental data lost, and learning halted, revealing a fragility that we can no longer afford. Addressing this challenge requires a collective and systemic response that reaches beyond the chemical sciences. The resilience of chemistry is inseparable from that of our energy, digital, and educational systems. It is time to reimagine our preparedness through collaborative strategies that span disciplines and sectors. The broader systemic transformation called for in the SIDE vision for Chemistry 2030 offers such a framework—a roadmap to confront increasingly complex and intertwined global challenges. As we have argued,[23] this current decade demands bold innovation to ensure chemistry becomes a cornerstone of a safer, more resilient, and circular economy.[31] This vision needs to be underpinned by governmental regulation and legislation to provide a framework for industrial development. Thus, it is our role as experts to go beyond scientific knowledge so that we can provide politicians and policymakers with the necessary data to support future changes in legislation.

Conclusion: a chemistry that endures

The recent blackout in the Iberian Peninsula was not just a technological failure; it was a warning. As the chemical sciences move towards net-zero goals and increasing electrification, we must ensure that our processes, infrastructures, and institutions can withstand real-world stressors. Therefore, we propose these ten principles not as a fixed doctrine but as an invitation to scientists, engineers, educators, and policymakers. Let us begin a conversation, across disciplines and sectors, about how to build a **more resilient chemistry for a volatile world**.

Fortuitously, the revision of this Editorial coincided with the launch of the Stockholm Declaration on Chemistry for the Future[32] at the Nobel Prize Museum on May 23rd 2025. This declaration represents a collective call to reimagine chemistry from the ground up, placing sustainability, safety, resilience and equity at its core. It emerged from the deliberations of green chemistry experts who convened at the Nobel Symposium on Sustainable Chemistry. The declaration sets out five key commitments, including developing materials that are benign by design, chemical processes that minimise waste and energy use, and products that are engineered to be durable, degradable, or circular. It also emphasises the critical role of chemistry in enabling renewable systems, most relevantly here, highlighting the need for solutions that are not only efficient but also resilient. Our principles were briefly presented at the prelaunch conference in Stockholm (by JGM) and, hopefully, the principles will contribute to future discussions as this landmark declaration is developed further.

Author contributions

C. S. P. V., D. M., D. R. C, J. F. L., and J. P. M. A. were the organizers of 9PYCheM 2025, who successfully addressed the challenges to the conference posed by the power cut, P. M. P. G. was the representative of the Portuguese Chemical Society and J. G. M., T. N. and M. P. were the international plenary speakers at the conference. M. P. coordinated the writing of this paper, and all authors contributed to the writing.

Conflicts of interest

The authors declare no conflicts.

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