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THE 2025 IBERIAN BLACKOUT COLD CHAIN STRESS TEST

Operational lessons from HFO and $C0_2$ refrigeration systems

Mohammed Youbi Idrissi
Technical Leader Europe and MEA,
Solstice Advanced Materials

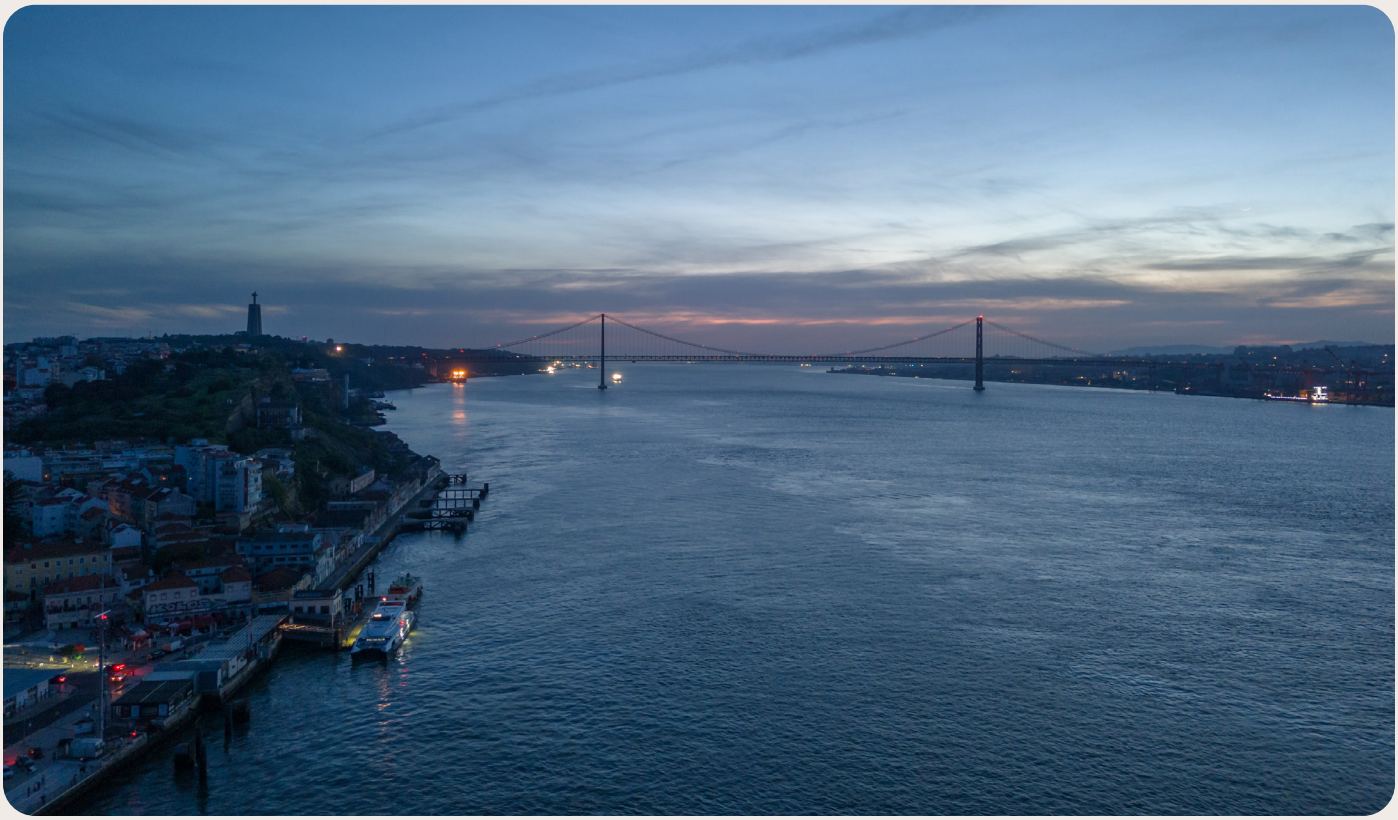


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INTRODUCTION

On April 28, 2025, at precisely 12:33 p.m. CEST, the Iberian Peninsula was plunged into darkness because of a power outage extending into parts of south-western France. Depending on the region, more than 60 million people were left without electricity. Outages lasted between 8 and 20 hours, exposing the fragility of critical infrastructure including food and pharmaceutical cold chains.



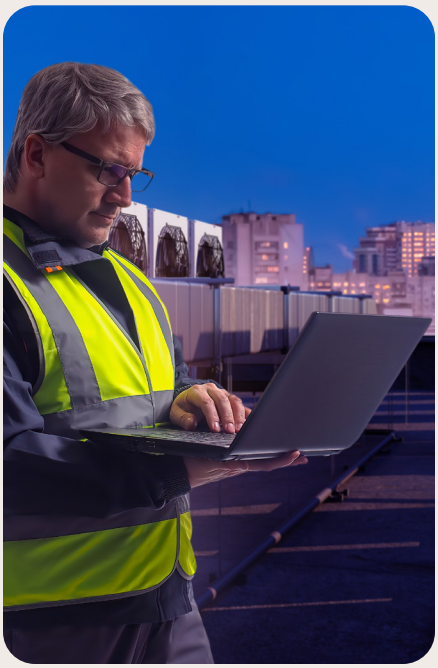
Described by ENTSO-E as "the most severe power outage Europe has experienced in the past twenty years,"[1] the incident exposed key technical challenges related to ensuring that critical cold chain infrastructure remains resilient in an era of increasingly consequential grid disruptions.

Beyond the estimated €1.6 billion in economic losses, it also places the resilience of refrigeration systems firmly in the spotlight.

However, this was not an isolated European event. Only weeks earlier, a nationwide power outage in Chile[2] had demonstrated similar vulnerabilities, disrupting essential services and temperature-controlled logistics across the country. These incidents, occurring on opposite sides of the globe within the same year, highlight an emerging challenge for governments, utilities, and supply chain operators alike: ensuring that critical cold chain infrastructure remains resilient in an era of increasingly consequential grid disruptions.

Amid the wider context of the energy transition and regulatory pressure for the refrigeration sector to decarbonize and adopt sustainable solutions, the April 2025 blackout revealed a crucial insight: t**hat the environmental performance of a refrigeration system should not be judged solely by the global warming potential (GWP)**. Especially for critical cold chains in food and pharmaceutical industries, refrigerant systems' ability to maintain the cold chain during a crisis, to restart safely and swiftly, and to exhibit resilience in unpredictable circumstances is a critical factor that is often overlooked in traditional assessments.

This whitepaper examines key lessons from this unprecedented event, highlighting the **resilience of refrigeration systems operating with low-GWP, HFO-based refrigerants** in the face of extended power outages.



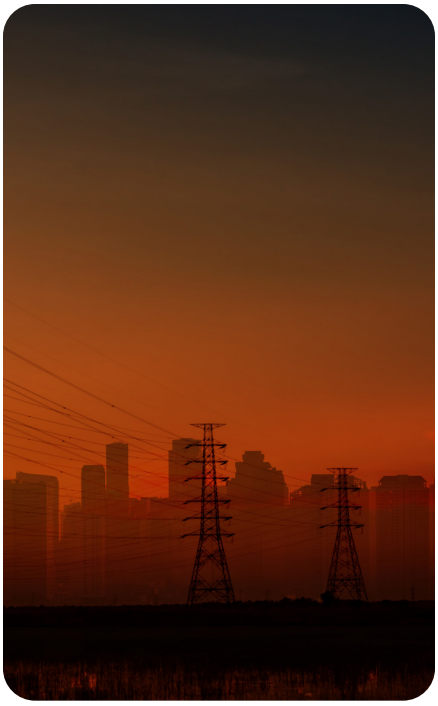
[1] Grid Incident in Spain and Portugal on 28 April 2025, ICS Investigation Expert Panel, Final Report of Marsh 20th, 2026: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/iberian-blackout/Final%20Report%20on%20the%20Grid%20Incident%20in%20Spain%20and%20Portugal%20on%2028%20April%202025.pdf

[2] Zero Energy Day: How Nationwide Blackouts Affect the Economy, Luis E. Gonzales, Koichiro Ito & Mar Reguant, 2026

CHRONOLOGY OF A SYSTEMIC FAILURE

Blackout Timeline on April 28, 2025

The April 28 blackout was triggered by a rapid chain of events. At 12:33 p.m., a major loss of synchronization occurred within the Spanish grid, resulting in the near-total disconnection of Spain and Portugal from the rest of the European power network. In France, protection systems managed by Réseau de Transport d'Électricité (RTE) responded instantly by isolating interconnections with Spain to prevent the fault from spreading[3].



The precise origin of the overvoltage remains under investigation. However, authorities ruled out cyberattacks and extreme weather events as potential causes.

Initial investigations by Red Eléctrica de España (REE) and European experts identified an unprecedented phenomenon known as "cascading overvoltages." The overvoltages set off a catastrophic chain reaction: In less than five minutes, a sudden loss of approximately 15 GW of generation capacity was recorded from the automatic disconnection of multiple generation sites, including renewable installations such as wind and solar farms[4].

GEOGRAPHICALLY DIFFERENTIATED IMPACTS

In Spain and Portugal, the outage was both total and prolonged. The regions of Murcia, Valencia, and Andalusia, together with the metropolitan areas of Madrid, Barcelona, Lisbon, and Porto, were among the most severely affected. The average duration of the blackout ranged from 12 to 18 hours, some rural zones waited up to 22 hours for full power restoration.

In France, the impact was more limited but still significant. RTE's protection systems operated effectively, preserving most of the national grid , but the southwest experienced:

- The automatic shutdown of a reactor at the Golfech Nuclear Power Plant.
- Localized outages in the Landes, Pyrénées-Atlantiques, Hautes-Pyrénées, and parts of the Gironde.
- Serious disruption for industrial users, particularly to logistics platforms and cold storage facilities.
- Partial paralysis of cross-border supply chains.

[3] RTE France: https://www.rte-france.com/actualites/mise-jour-25-mars-2026-foire-questions-black-out-28-avril-2025-sur-peninsule-iberique

[4] Flash Énergie: https://www.flash-consulting.fr/2025/04/30/blackout-historique-en-espagne-et-au-portugal-ce-que-lon-sait/

GENERAL INFRASTRUCTURE CONSEQUENCES

The sudden loss of power set off a domino effect across critical infrastructure sectors:

Transport
Total paralysis of trains, metro systems, trams, railway signaling systems, and traffic lights.

Healthcare
Hospitals were forced to operate in degraded mode using emergency generators.

Water distribution
Failure of multiple pumping stations.

Telecommunications
Major disruption to mobile and landline networks, except for Vodafone Spain, which maintained approximately 70% of its service thanks to battery backup systems.

Security
Temporary deactivation of alarms and video surveillance systems.

Banking
Interruption of electronic payment systems and transactions.



This systemic breakdown revealed the deep interdependence of modern infrastructure and the need for resilient systems capable of withstanding and recovering rapidly from widespread disturbances.

CRITICAL IMPACT ON THE COLD CHAIN

A narrowly avoided food and health disaster

The following table summarizes economic losses per sector based on reports and estimates from professional federations:

Sector	Losses (millions €)	Source
Agri-food	400 – 600	FIAB via Agrycomag[5]
Retail	150 – 200	FIAB et Agropopular[6]
Logistics	100 – 150	Flash Énergie[7]
Healthcare	50 – 80	Ouest-France[8]
Transport	200 – 300	RTE[9]
Commerce	250 – 350	Planète CSCA[10]
Telecommunications	80 – 120	Transitions Énergies[11]
Energy	50-60	Inteligenia[12]
TOTAL	**≈ 1,6 B€**	**Average of multiple sources**

The maintenance of the cold chain is a fundamental pillar of modern food safety and public health. Any prolonged interruption exposes millions of tons of perishable goods to spoilage, leading to significant health, economic, and environmental consequences. The April 2025 power outage illustrated the fragility of this essential link in our society.

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These losses represent only a portion of the true cost. Indirect effects—logistical disruption, reputational damage, loss of customer confidence, and restart costs—total several hundred million euros more.

[5] FIAB via Agrycomag: https://www.agryco.com/blog/actualites/panne-espagne-agriculture-agroalimentaire-impact

[6] FIAB and Agropopular: https://www.agropopular.com/fiab-apagon-290425/

[7] Flash Énergie: https://www.flash-consulting.fr/2025/04/30/blackout-historique-en-espagne-et-au-portugal-ce-que-lon-sait/

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MASSIVE FOOD LOSSES ON THE IBERIAN PENINSULA

MEAT INDUSTRY

The Spanish Federation of Food and Beverage Industries (FIAB) estimated total losses at between €400 million and €600 million.[13]

DAIRY AND SEAFOOD

Cold storage centers in Murcia, Valencia, and Andalusia were forced to discard entire batches for sanitary reasons. With traceability systems also out of service, the inability to guarantee cold chain integrity led to the widespread preventive destruction of goods.[14]

FOOD RETAILERS

Major supermarket chains such as Mercadona, Carrefour, Dia, Continente, and Lidl faced varying degrees of disruption. Stores equipped with backup generators were able to partially maintain their refrigeration systems, but many outlets had to close as a precaution. Fresh and frozen food sections suffered significant losses, particularly in densely populated areas.[15]

AGRICULTURE

Producers of fruit, vegetables, and seafood in southern Spain and Portugal reported millions of euros in losses[16]. Rural cold storage facilities, which are rarely equipped with autonomous generators, were among the most affected.



PHARMACEUTICAL THREAT

Temperature-sensitive vaccines and medicines

The pharmaceutical sector faced an equally critical situation. Although hospitals and pharmacies typically have emergency generators, they encountered severe challenges in maintaining precise temperature control for vaccines and medicines requiring strict conditions (+2°C / 35°F to +8°C/ 47°F).

According to the newspaper Ouest France[17], estimated losses in the healthcare sector reached between €50 million and €80 million, including precautionary destruction of vaccine stocks whose temperature stability could not be guaranteed.

[13] FIAB via Agrycomag: https://www.agryco.com/blog/actualites/panne-espagne-agriculture-agroalimentaire-impact

[14] FIAB and Agropopular: https://www.agropopular.com/fiab-apagon-290425/

[15] Flash Énergie: https://www.flash-consulting.fr/2025/04/30/blackout-historique-en-espagne-et-au-portugal-ce-que-lon-sait/

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COMPARATIVE PERFORMANCE OF REFRIGERATION TECHNOLOGIES

The reality test

The April 2025 blackout delivered a revealing test of the resilience of various refrigeration technologies during a prolonged power outage. Beyond theoretical energy performance and the usual environmental considerations, **a system's ability to withstand a sudden shutdown, maintain temperatures in passive mode, and restart safely that proved decisive.**



LOW-GWP HFC/HFO REFRIGERANTS: DEMONSTRATED RESILIENCE

Installations operating with next-generation synthetic refrigerants—particularly low-GWP HFO blends such as R-454C (GWP 146) and R-455A (GWP 148)—demonstrated exceptional resilience. These ASHRAE A2L-classified refrigerants possess technical characteristics that make them well-suited to emergency scenarios.

PRESSURE SAFETY IN PASSIVE MODE

Unlike systems that operate under extreme pressure (such as CO_2 refrigeration), HFO installations experience small, predictable pressure increases during extended shutdowns. Safety valves, implemented in accordance with EN 378 and the Pressure Equipment Directive (PED), remain inactive and minimize the risk of leaks and refrigerant loss.

RESTART PERFORMANCE

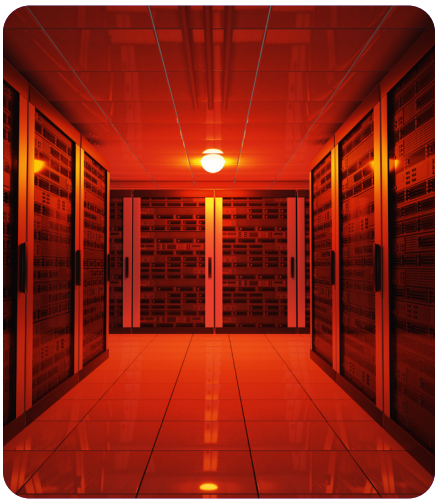
Restarting HFO systems after a prolonged outage follows procedures familiar to most refrigeration technicians. The sequence typically involves:

- Visual inspection of system components.
- Reviewing alarms and fault logs.
- Gradual start-up of compressors.
- Recalibration of electronic expansion valves, if required.
- Monitoring of operational parameters.

This straightforward process enables rapid system recovery once power is restored, reducing additional losses. Technicians can consequently service multiple sites in a single day, optimizing human resources in crisis conditions.

CO_2 SYSTEMS: SIGNIFICANT TECHNICAL VULNERABILITIES

The blackout exposed serious technical vulnerabilities under conditions of prolonged power loss for CO_2 systems in cold chain refrigeration.



THERMODYNAMIC CONSTRAINTS OF CO_2

CO_2 exhibits markedly different thermodynamic properties compared to HFO refrigerants:

- Critical temperature: 31.1°C / 88°F (extremely low).
- Critical pressure: 73.8 bar / 1070 psi (very high).
- Transcritical operation required when ambient temperature exceeds approximately 25–28°C / 77°F–82°F.

Parameter	CO_2 (R744)	HFO based Refrigerants (R-455A, R-454C)	Impact on System Design
Global Warming Potential (GWP)	1	146	Both offer very low environmental impact compliance with F-gas
Critical Temperature	31.1°C (88°F)	Typically 88°C (~190°F)	CO_2 reaches the critical point easily in warm climates
Critical Pressure	73.8 bar (1,070 psi)	Typically 36 bar (435–522 psi)	CO_2 systems require stronger components and piping
Operating Pressure	Very high	Moderate	Higher installation and equipment design requirements for CO_2
Cycle Type in Warm Climates	Transcritical operation required above ~25–28°C (77–82°F)	Conventional subcritical vapor-compression cycle	CO_2 system efficiency becomes more dependent on gas cooler optimization



Low critical temperature poses a major challenge in crisis conditions. During the April 28 blackout, outdoor temperatures in Spain and Portugal ranged from 20°C–28°C / 68°F–82°F[18]. Without active cooling of the gas cooler, the temperature of CO_2 in the high-pressure circuit quickly rose, leading to a rapid and continuous increase in pressure.

[18] Copeland, CO_2 Refrigeration Fundamentals: System Operation: CO_2 Refrigeration Fundamentals: System Operation

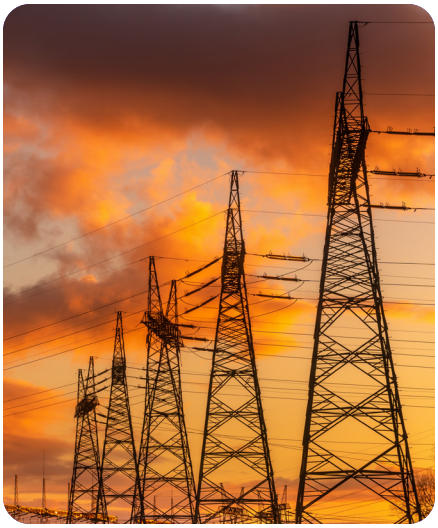
OVERPRESSURE RISKS AND EQUIPMENT FAILURES



CO_2 systems typically operate at very high pressures (90–120 bar / 1305 – 1740 psi on the high-pressure side for transcritical systems). During extended shutdowns without heat rejection, pressure can reach critical levels, triggering safety valves. Field reports indicate that several CO_2 installations without backup generators experienced[19,20,21]:

- Activation of pressure relief valves.
- Atmospheric releases of CO_2.
- Loss of refrigerant charge requiring recharging.
- Loss of lubrication oil requiring replenishment.
- Damage to compressors and seals.
- Excessive condensation in the circuits.

RESTART COMPLEXITY



Restarting a CO_2 installation after a prolonged shutdown requires specific procedures and heightened precautions, including:

- Waiting for the natural cooling of compressors.
- Thorough pressure checks across various parts of the circuit.
- Inspecting the condition of lubrication oil.
- Recalibration of pressure regulators and electronic valves, if required.
- Close monitoring during initial hours of operation.

Such complexity necessitates the intervention of technicians specifically trained in CO_2 systems, a scarce resource during a crisis in which hundreds of installations had to be brought back online simultaneously.[22]

[19] ACHR News: https://www.achrnews.com/articles/165018-power-outages-pose-risk-for-co2-refrigeration-systems

[20] Natural Refrigerants News: https://naturalrefrigerants.com/news/whats-the-best-way-to-prevent-release-of-co2-refrigerant-in-a-power-outage/

[21] Axiom Cloud: https://www.axiomcloud.ai/post/compressors-don-t-die-they-re-usually-killed

[22] Frigoriste: https://www.frigoristes.fr/article.php?sid=533

BACKUP GENERATORS: A COSTLY AND LIMITED SAFEGUARD

While most large CO_2 installations equipped with backup generators endured the crisis without major issues, this safeguard has some inherent drawbacks:

HIGH CAPITAL COST

A backup generator sized for a supermarket CO_2 refrigeration system represents an investment of €30,000 – €100,000 depending on capacity, plus installation and connection expenses.

MAINTENANCE BURDEN

Generators require regular maintenance, periodic testing, and fueling, resulting in high operating costs.



LIMITED RELIABILITY

Field reports show that some generators failed to start during the blackout due to poor maintenance or mechanical issues.

LOW DEPLOYMENT RATE

The majority of small and medium-sized CO2 installations, including convenience stores, mid-sized warehouses, and restaurants are not equipped with generators for obvious economic reasons. Yet these installations represent a significant share of the refrigeration fleet.



ELECTRICAL SECURITY

Beyond the diesel generator

While installing backup generators provides a degree of reassurance, the blackout exposed limitations:

- Startup time ranging from 30 seconds to 2 minutes.
- Mechanical failure rates of 5–10% during the event.
- Dependence on fuel supply, limiting autonomy to 12–24 hours.
- High maintenance and operational complexity.
- Environmental drawbacks such as local emissions and noise pollution.

Alternative and complementary solutions deserve greater attention, particularly thermal energy storage using phase change materials (PCM) and Battery Energy Storage Systems (BESS). These technologies can provide smoother, cleaner, and faster responses to power interruptions.

Technical and strategic recommendations to strengthen resilience.

Adapting technology choices to operational context.

For temperate and cold climates (e.g. Scandinavia, Northern USA, Canada)

- CO_2 systems can be considered with an acceptable level of risk.
- Energy performance is optimal (outdoor temperatures mostly < 25°C / 77°F).
- Investment in backup generators is strongly recommended to mitigate grid reliability risks.
- A2L's are an alternative for lower CapEx and improved resilience under power loss scenarios.

For warmer climates (e.g. Southern Europe, Southern USA, LATAM, South East Asia)

- Low -GWP A2L systems may offer a decisive technical and economic advantage.
- Such systems exhibit greater natural resilience during power outages.
- Both investment and maintenance costs are optimized.
- Greater availability of qualified technicians.

Recommended decision criteria:

1. Frequency and duration of heatwaves (>30°C / >86°F).
2. Historical reliability of the local power grid.
3. Availability and cost of backup generators.
4. Initial investment budget and debt capacity.
5. Local availability of specialized technicians.
6. Criticality of service continuity (pharmaceutical > food > retail).

CONCLUSION

Toward a pragmatic and resilient refrigeration transition

The April 2025 power outages exposed, in the starkest terms, the vulnerability of our refrigeration systems to prolonged power failures. With total economic losses in Europe estimated at €1.6 billion. These impacts alongside millions of tons of destroyed goods, left our industry with invaluable lessons.



RESILIENCE: A FULL-FLEDGED ENVIRONMENTAL CRITERION

It is an imperative to preserve critical cold chains in food and pharmaceutical industries in increasingly unpredictable circumstances. A detailed analysis of this crisis demonstrates that refrigeration systems should not be evaluated solely based on their GWP. The transition of the refrigeration sector should represent a controlled, evidence-based evolution that embraces innovation while safeguarding operational reliability.

Today, low-GWP HFO refrigerants embody this operational excellence, supporting a refrigeration transition that is responsible, pragmatic, and truly sustainable. Low-GWP HFO refrigerants offer a strong balance between environmental performance (GWP <150 and full F-Gas compliance), energy efficiency, operational resilience, and economic feasibility.

The most effective environmental technology is the one that maintains the cold chain, preserves food and medicine, protects jobs, and withstands crises.

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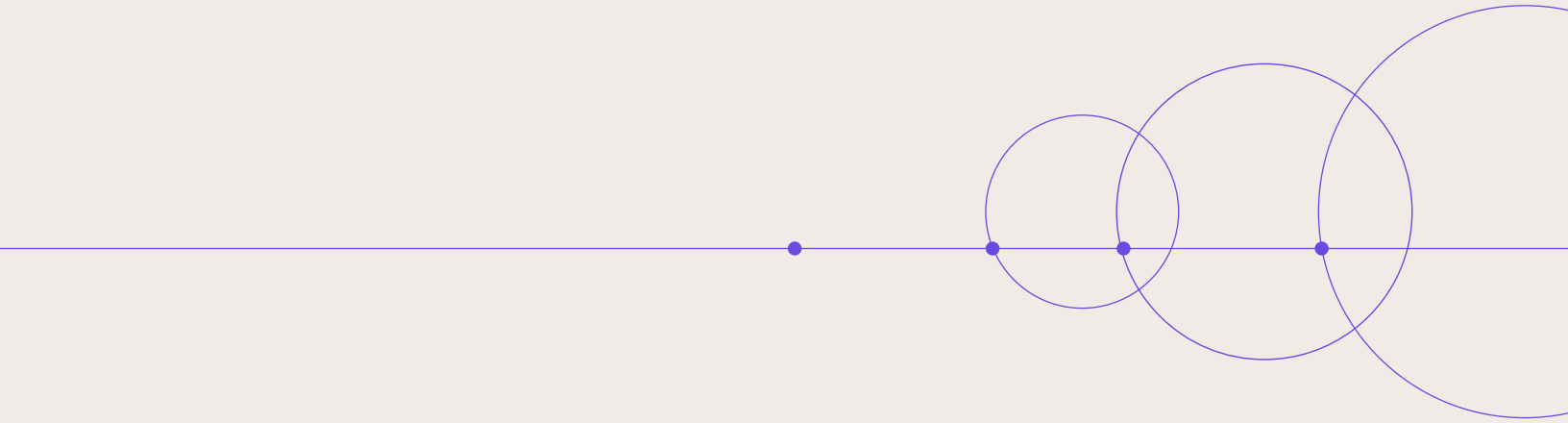
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115 Tabor Rd. | Morris Plains, NJ 07950

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