

WHITE PAPER

REFRIGERANT SENSING IN THE LOW-GWP TRANSITION

Environmental drivers, refrigerant evolution, detection requirements, and sensor principles and performance challenges all play a role in the low-GWP transition.



Our planet is warming. While various geopolitical forces differ on climate policy, environmental regulations are accelerating the movement away from high-GWP hydrofluorocarbon refrigerants toward low-GWP alternatives.

This transition reduces climate impact, but it changes safety requirements because many next-generation refrigerants are either mildly or highly flammable. In HVAC/R systems, refrigerant sensing becomes a safety and compliance function rather than a diagnostic accessory.

A series of market issues is driving this transition, while design approaches are facilitating the development of complex solutions. Together, these factors aim to deliver refrigerant sensing solutions that ensure climate protection while providing adequate safety measures.

Environmental Protection is the Macro Driver

The evidence is clear that extreme-heat events are endangering our world. As recently as June 2026, western Europe experienced its hottest June on record, following intense heat in May and raging wildfires in July. The same pattern is visible globally. NASA reported that 2024 was the warmest year on record, following an unprecedented sequence of monthly temperature records from June 2023 through August 2024. The World Meteorological Organization (WMO) later confirmed that 2015–2025 were the hottest 11 years on record, with high land and ocean temperatures helping fuel extreme weather, including heatwaves.

These conditions make a transition to combined ozone and climate protection that much more urgent. Major economies are responding by reducing permitted hydrofluorocarbon (HFC) consumption, all at different timelines (see Figure I), due to their high global warming potential. These policy shifts include phase-down schedules, GWP limits, taxes, incentives, and product-specific adoption dates.

The result: HVAC/R innovations

The HVAC/R industry faces a dual responsibility. On one hand, more people will need reliable cooling to protect their health, productivity, food storage, and basic living conditions during hotter summers. At the same time, expanding air conditioning and heat pump deployment must not deepen the climate problem.

The practical consequence is that HVAC/R platforms cannot merely switch chemical substances. Rather, they must be redesigned around new refrigerant properties, safety classifications, charge limits, control logic, detection architectures, and certification requirements.

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THE HVAC/R INDUSTRY FACES A DUAL RESPONSIBILITY. IT MUST DEVELOP INNOVATIVE COOLING SOLUTIONS WHILE ENSURING ENVIRONMENTAL RESPONSIBILITY.

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The European Union has adopted one of the steepest HFC reduction pathways, while the United States, Japan, China, India, and other economies are following phase-down schedules shaped by national regulation.

Major economies are phasing down HFC refrigerants on differing timelines

Share of each schedule's baseline HFC consumption still permitted, by regulatory phase-down step (2019-2045)

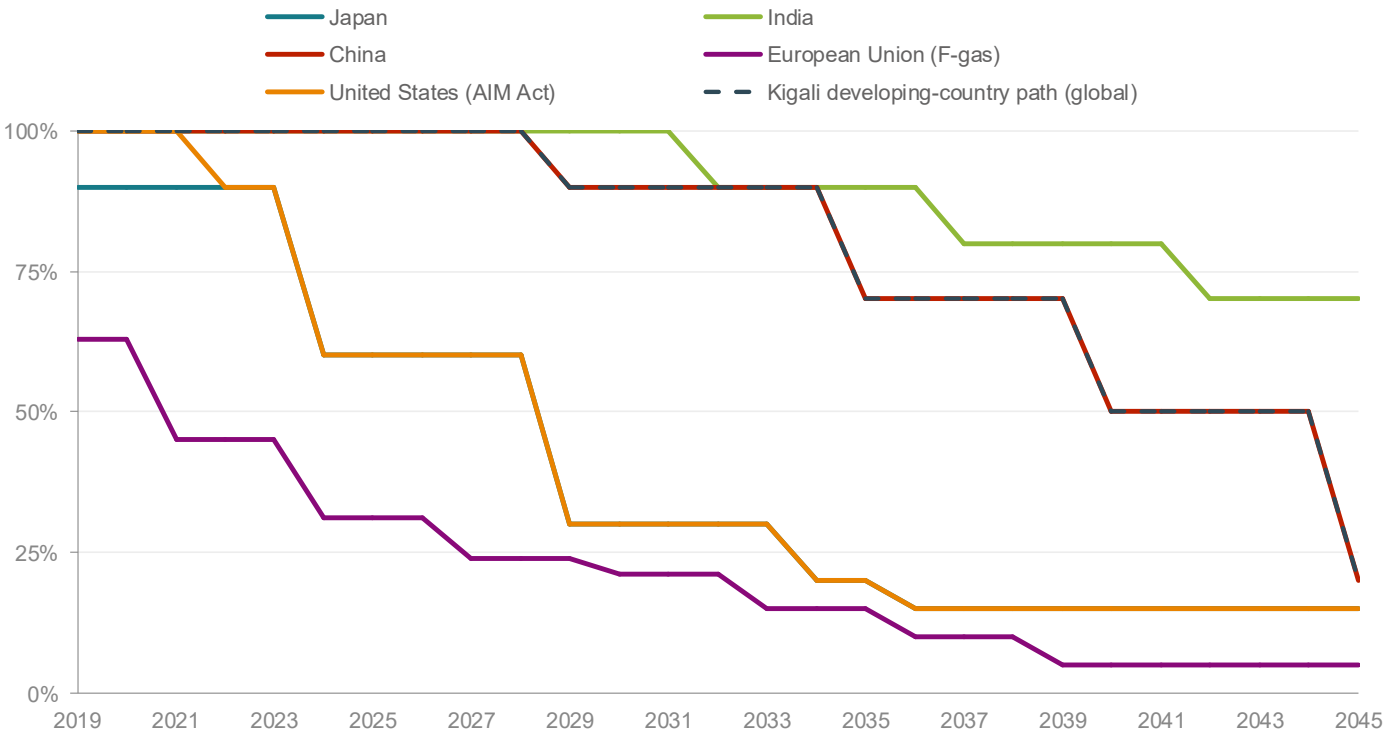


Figure 1. HFC phase-down schedules across major economies, 2019-2045.

Sources: UNEP Ozone Secretariat, Kigali Amendment overview, U.S. EPA, HFC phasedown under the AIM Act, 40 CFR Part 84, EU F-gas Regulation (EU) 2024/573 — European Environment Agency, Japan METI / Ozone Layer Protection Act, China draft National Plan 2024-2030 — IGSD. Lines show the share of each schedule's baseline consumption still permitted; illustrative step schedules.

EU moves fastest	Developed economies converge	Developing economies follow later	China likely to move faster
The F-gas Regulation cuts to about 5% of baseline by 2039 — the steepest schedule.	The US (AIM Act) and Japan track the Kigali Amendment developed country mandate: 85% by 2036.	China freezes in 2024 (~80% by 2045); India freezes in 2028 under the Kigali Amendment.	Chinese manufacturers are expected to adopt A3 (propane-based, ultra-low-GWP) refrigerants around 2030 — ahead of the Kigali developing country mandate.

The Refrigerant Transition: A Look at Refrigerant Generations

One of the most concrete examples of climate policy impacting changes in equipment architecture is the ongoing refrigerant transition. Refrigerant selection has progressed through several generations, each resolving one problem while creating another.

Early refrigeration used natural and inorganic working fluids, such as ammonia, carbon dioxide, sulfur dioxide, methyl chloride, and hydrocarbons. These fluids moved heat effectively, but many were toxic, flammable, corrosive, or operated at pressures that were difficult for early equipment to manage.

Alternatively, the first synthetic refrigerants, especially chlorofluorocarbons (CFCs) such as CFC-12, solved many near-term safety and usability concerns because they were stable, non-flammable, and suitable for mass-market refrigeration and air conditioning. However, their negative impact on the environment only became clear later. CFCs and, to a lesser degree, hydrochlorofluorocarbons (HCFCs), contain chlorine that can reach the stratosphere and destroy ozone.

In turn, the refrigerant industry moved away from CFCs and HCFCs toward HFCs. To be clear, this was not a failure of refrigerant policy but rather a major ozone-protection success story. HFCs have proven essential to progress by eliminating ozone-depleting chlorine from many refrigerant applications. Data support this. Assuming continued compliance, UN-backed assessments indicate that globally, the ozone layer is on track to recover to 1980 values around 2040.

However, as noted earlier, the same chemical stability that made many HFCs useful also made them powerful greenhouse gases when released. In other words, HFCs helped solve the ozone crisis but created a new climate-management challenge.

Moving to the next generation of refrigerants (see Figure II) will require building on the success of HFCs. This includes constraining high-Global Warming Potential (GWP) refrigerants by adapting equipment platforms in legacy A1 systems.

More specifically, it means focusing on low-GWP refrigerants — new A2L and A3 alternatives offering more favorable climate profiles — that are designed with efficient equipment and dependable leak detection. The clear objective is to both expand cooling access while reducing the risk of cooling demand that forces and accelerates greenhouse gas production.

REFRIGERANT GROUP	ENVIRONMENTAL PROFILE	SAFETY/SYSTEM PROFILE	EXAMPLES AND COMMON USES
A1 legacy / conventional	Typically high GWP in the strategy material; being reduced by regulation.	Non-flammable or low flammability, which simplified historical HVAC/R safety design.	R-134a, R-22, R-410A and blends; traditional AC and refrigeration.
A2L lower-GWP alternatives	Lower GWP range in the strategy material, typically ~1 to ~700.	Mild flammability; requires controls and leak mitigation when charge and application conditions trigger standards.	R-32 and R-454 blends; AC and heat pump platforms.
A3 natural / hydrocarbon alternatives	Very low GWP range in the strategy material, typically below ~10.	Highly flammable; system architecture and location of refrigerant circuit become central design constraints.	R-290 propane, R-600a isobutane; heat pumps and small refrigeration.
CO ₂ and ammonia	CO ₂ has GWP of 1; ammonia is noted as below 1 in the source material.	CO ₂ is non-flammable but high-pressure and can be an asphyxiant; ammonia has toxicity concerns.	Larger refrigeration and industrial systems where pressure/toxicity controls are engineered into the platform.

Figure II: Various refrigerants and their environmental and safety profiles.

System development: The Importance of A2L and A3 Leak Detection

The focus on developing low-GWP refrigerants, such as A2L and A3 alternatives, can be best understood as a sequence of optimized compromises that create an engineering tradeoff: to lower climate impact requires increasing the importance of designing active safety systems.

For example, in lower-capacity HVAC/R equipment, A2L and A3 refrigerants are especially relevant in satisfying lower-GWP targets while maintaining system efficiency. Gas detection, however, is essential because the risk mechanism changes when flammable refrigerants become mainstream. An A2L or A3 leakage event can create a flammability hazard if the concentration in air approaches a defined lower flammability limit. The severity of the hazard depends on the refrigerant, quantity, enclosure, ventilation, ignition sources, and control response.

As a result, gas sensing is emerging as a regulatory requirement, safety necessity, and mission-critical component for next-generation HVAC platforms. Low-GWP application requirements vary based on regulatory frameworks (see Figure III.) For example, A2L usage is more prominent in North America for air conditioners and heat pumps, while A3 adoption is accelerated in Europe and for selected niche applications. The effect is that OEMs may need various sensing architectures to support different future refrigerant pathways.

Regulations, taxes and incentives are adoption drivers of low-GWP refrigerants globally to replace high-GWP refrigerants

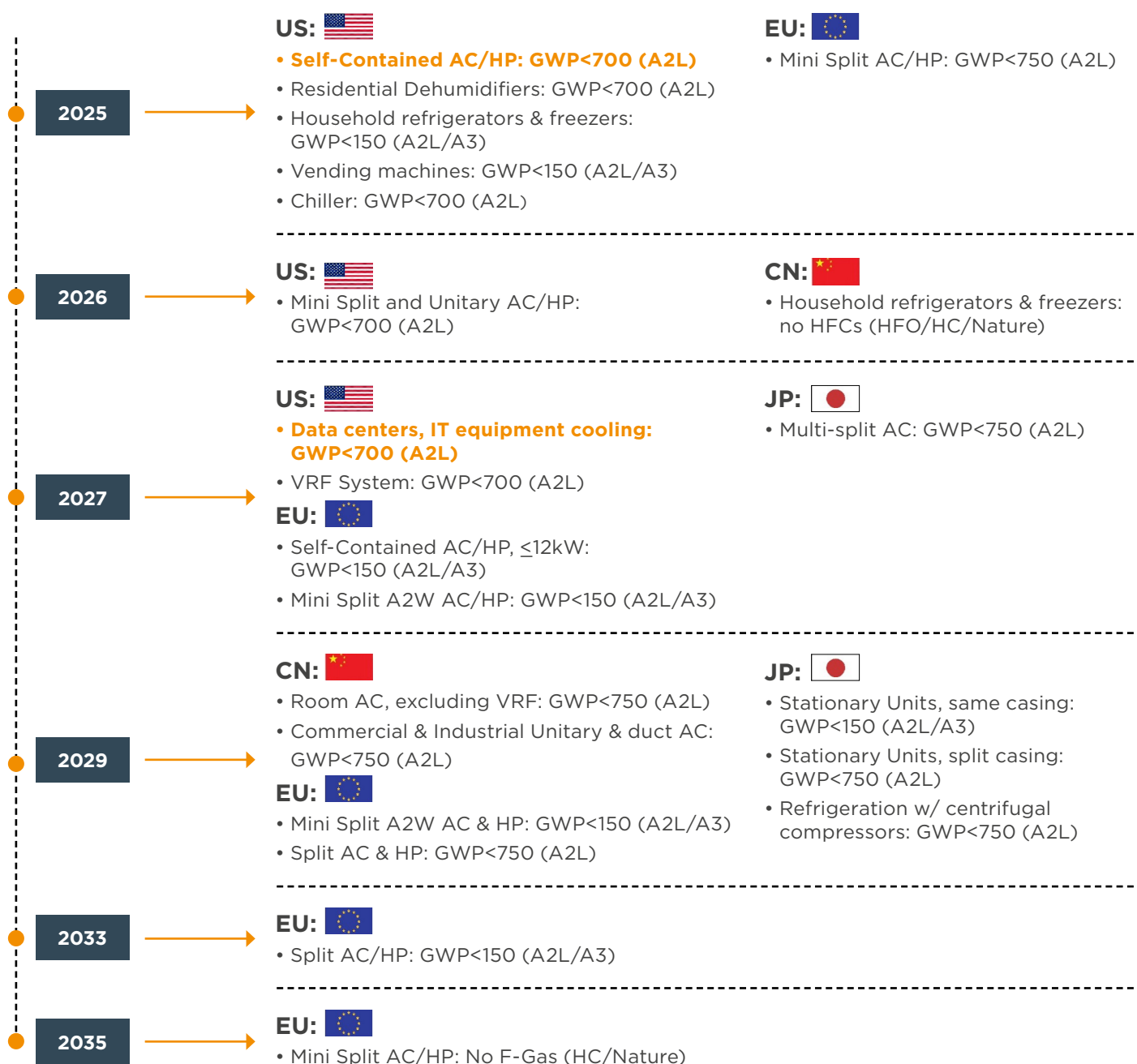


Figure III. Regulatory inflection points driving adoption of low-GWP refrigerants.

Refrigerant Sensors: Performance Challenges

As part of an optimal architectural system, a refrigerant sensor is a critical component for detection and mitigation. The sensor output must be integrated with controls that can initiate alarms, ventilation, compressor shutdown, or other mitigation actions in accordance with equipment design and applicable standards.

Refrigerant sensing is technically demanding because it does not function in a laboratory environment. Rather, HVAC/R modules may be exposed to temperature swings, high humidity, condensation, dust, oil mist, vibration, electromagnetic noise, and installation variability. The same sensor must support a myriad of performance issues:

- **Detection threshold and accuracy are paramount.**

A2L and A3 systems require detection before a leak reaches an unsafe concentration. The sensor must distinguish the refrigerant from background environmental changes and maintain accuracy across temperature, humidity, and pressure variation.

- **Response time is equally important.** Fast detection reduces the delay between leak formation and mitigation action. From an overall architectural perspective, the response is influenced by packaging, diffusion path, signal processing, and environmental compensation.

- **False alarms and selectivity are a major concern.**

False alarms can cause downtime, resulting in service costs and customer distrust. Interference gases, humidity transients, condensation, and contamination can produce non-refrigerant signals that complicate interpretation.

- **Long lifetime and drift must be addressed.** HVAC equipment often requires a long service life and a low maintenance burden. Optical aging, contamination, chemical poisoning, sensor drift, and calibration stability vary by technology and directly affect long-term field reliability.

- **Environmental robustness is critical.** As sensors may be mounted near compressors, coils, or outdoor sections, they must be sufficiently durable to handle harsh conditions. Thermal cycling, vibration, water ingress, salt spray, and dust require robust enclosure and connector design.

- **Integration flexibility is also important.** OEMs may need different mounting, harness, signal, and protocol options. Customization, however, must not undermine certification, cost, manufacturability, or reliability.

- **System ownership, rather than sensor unit price, determines cost.** The economic value of a sensing approach is determined by a variety of factors: recalibration, warranty exposure, false-alarm service calls, replacement intervals, qualification costs, installation time, and system downtime. This is why low-drift, no-field-calibration architectures can be valuable, even when the sensor module price is not the lowest bill of material option.



REFRIGERANT SENSING IS TECHNICALLY DEMANDING, AS THE SAME SENSOR NEEDS TO SUPPORT A MULTITUDE OF PERFORMANCE ISSUES.



Refrigerant Sensing Principles: Strengths and Constraints

As sensors are critical system components, multiple sensing principles are critical to refrigerant detection in A2L and A3 applications. The appropriate sensing choice depends on target gas, environmental exposure, lifecycle expectations, certification needs, and system-level mitigation strategy. For each sensing principle, consider the following:

- **Thermal conductivity:** measures heat-transfer differences between clean air and refrigerant-containing air. For A2L and potentially A3 applications, this offers an attractive cost/performance balance, with strong potential for compact modules and cost reduction when implemented with MEMS processes.
- **Non-dispersive infrared:** measures the absorption of infrared light by the target gas. It is widely used and mature, but optical path contamination, condensation, and package constraints can affect long-term maintenance and miniaturization.
- **Photoacoustic spectroscopy:** measures acoustic pressure waves generated by light absorption. It is promising for selectivity and mission-critical applications, although cost, maturity, and environmental vibration sensitivity remain important considerations, justified by the added complexity.

- **Metal oxide semiconductor:** measures resistance changes from gas reaction on a heated surface. This approach can be low-cost, but chemical sensitivity, humidity effects, and drift or aging can limit suitability for stringent long-life HVAC safety applications.
- **Speed-of-sound or acoustic:** infers gas composition by measuring changes in acoustic propagation through a gas mixture. This can be robust for certain refrigerant mixtures, but may involve technology-specific integration considerations that are potentially sensitive to environmental vibration.

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FOR OEMS, THE BEST TECHNOLOGY IS DEPENDENT ON TARGET GAS, DETECTION RANGE, PERFORMANCE ENVELOPE, COST CURVE, PACKAGE SIZE, RESPONSE TIME, AND THE ABILITY TO MAINTAIN STABILITY OVER THE PRODUCT LIFE.
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Example: Implementing an A2L Refrigerant Sensor

TE Connectivity’s (TE) [A2L refrigerant sensor module](#) for R-454B and R-32 detection provides a useful example of how requirements can be translated into a packaged detection product. Figure IV provides both an image and the details on sensing principles, thresholds, detection, response times, and maintenance model.

This sensor example is significant because it reflects the convergence of four design disciplines: sensing physics, environmental compensation, safety-standard compliance, and electromechanical integration. The connectorized module, integrated compensation sensors, and digital communication interface directly address practical OEM design constraints: wiring architecture, mounting variability, robustness, diagnostics, and manufacturability.

While this example focuses on A2L refrigerants, TE has also developed [sensing solutions for A3 refrigerants](#), where the higher flammability of hydrocarbons such as propane (R-290) places even greater emphasis on reliable leak detection, fast response, environmental robustness, and long-term stability. Together, TE’s A2L and emerging A3 sensing solutions illustrate how refrigerant sensing technology is evolving to support the broader industry transition toward low-GWP refrigerants. By leveraging common sensing, connectivity, and packaging expertise across both A2L and A3 platforms, TE is positioned to support OEMs as regional regulations and refrigerant preferences continue to evolve.

Regardless, this sensor module should be evaluated against target refrigerants, applicable standards, enclosure design, control strategy, mounting location, environmental exposure, certification plan, and OEM-specific interface requirements.



Figure IV: A2L refrigerant sensor module for R-454B and R-32 leak detection, [2539600-1](#)

SENSOR ATTRIBUTE	PUBLISHED SPECIFICATION/DESCRIPTION
Detected refrigerants	R-454B and R-32
Sensing principle	Thermal conductivity with temperature and humidity compensation
Detection threshold	10% lower flammability limit
Detection accuracy	±2.5% LFL
Response time	15 seconds typical; 30 seconds maximum on flyer
Operating range	-40°C to +95°C and up to 100% relative humidity
Communication	RS485 Modbus RTU, with options noted for PWM or UART
Maintenance model	Automated self-calibration; up to 15 years without field recalibration
Package/integration	Compact enclosure, IP54 sealed version, locking connector interface, mounting bracket options
Compliance statement	ETL certified to conform to UL and CSA 60335-2-40 Annex LL according to published product information

Design implications for OEMs and System Integrators

The low-GWP transition requires OEMs to evaluate refrigerant sensing early in platform development rather than at the end of the compliance process. Sensor choice affects the detection algorithm, wiring, connector selection, controller interface, bracket design, service model, and mitigation response. In addition, the refrigerant transition does not proceed uniformly by region: designs for North America, Europe, China, Japan, and India may require different refrigerant assumptions and certification timelines.

Here are a few guidelines for OEMs to consider in making design decisions:

- **Define which refrigerants the platform must detect.** A2L and A3 refrigerants have different gas properties and safety thresholds. As a result, future multi-gas needs should be considered early rather than treated as a late-stage compliance adjustment.
- **Determine the sensor mounting location.** Leak path, airflow, condensation, dust, vibration, and service access all determine whether a placement is practical and reliable in the field.
- **Design a mitigation strategy together with the sensor.** The sensor output must connect to controls capable of initiating alarms, ventilation, compressor shutdown, or other risk-reduction actions.
- **Decide what lifetime and calibration model is acceptable for the target equipment.** No-field-calibration designs can reduce service burden, but qualification must validate drift behavior and robustness over the required operating life.
- **Determine interface selection.** This has a direct implication for controller design and harness complexity. RS485/Modbus, PWM, UART, relay, and analog approaches each create different integration tradeoffs.
- **Align sensing architecture with the applicable regional roadmap.** The adoption of A2L, A3, CO₂, and NH₃ alternatives differs by region and equipment capacity, making platform flexibility a strategic value as regulations and refrigerant preferences continue to evolve.

Summary

Environmental protection policy is reshaping refrigerant selection. The phase-down of HFCs is driving HVAC/R systems from high-GWP A1 refrigerants toward low-GWP alternatives. This transition delivers climate benefits but changes the safety profile of equipment, as A2L refrigerants are mildly flammable while A3 refrigerants are highly flammable. This makes detection a crucial part of the core system architecture for many applications, particularly where charge levels, installation conditions, and standards require mitigation.

The central technical challenge is that refrigerant sensors must be simultaneously accurate, fast, selective, durable, low-maintenance, compact, and affordable. A sensor that performs well in a controlled environment may still fail to meet field expectations if it drifts, triggers false alarms during humidity transients, requires frequent recalibration, or is difficult to integrate.

Thermal conductivity, PAS, NDIR, MOS, and acoustic methods each offer different tradeoffs. While thermal conductivity is a strong near-term fit for selected A2L applications, PAS and other approaches remain relevant for applications that require different selectivity, robustness, or lifecycle characteristics.

A2L refrigerant sensor modules illustrate how this system need can be implemented through thermal conductivity sensing, environmental compensation, digital communication, connectorized integration, and long-life calibration models. Their relevance should be assessed not as standalone components, but as part of broader refrigerant detection and mitigation systems designed for evolving low-GWP regulations.

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