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Perspective

Ensuring the climate benefits of the Montreal Protocol: Global governance architecture for cooling efficiency and alternative refrigerants

Won Young Park [a,*], Nihar Shah [a], Edward Vine [a], Patrick Blake [b], Brian Holuj [b], James Hyungkwan Kim [a], Dae Hoon Kim [c]

[a] Lawrence Berkeley National Laboratory, United States
[b] United Nations Environment Programme, France
[c] Korea Refrigeration and Air Conditioning Assessment Center, Republic of Korea

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ABSTRACT

The Montreal Protocol has evolved from focusing primarily on ozone layer protection to addressing climate change mitigation, particularly with the 2016 Kigali Amendment establishing a framework for reducing global hydrofluorocarbon (HFC) use. This shift presents an opportunity to link the HFC phasedown with deployment of energy-efficient cooling equipment and thus provide benefits in terms of greenhouse gas reductions, technical and economic synergies, and reduced dumping of environmentally harmful products in developing countries. Although energy-efficiency and refrigerant considerations are still separate in most regions and under most regulatory systems, multilateral agencies can work to couple the financial assistance provided by the Multilateral Fund to Article 5 countries for refrigerant transition under the Montreal Protocol with finance to improve cooling equipment efficiency. In this perspective, we recommend a global governance architecture for the simultaneous transition to efficient cooling equipment and refrigerants with low global warming potential. Our recommendations leverage decades of experience from national energy-efficiency programs along with the Montreal Protocol's refrigerant assistance program. Major elements of the recommended energy-efficiency governance architecture include an internationally harmonized energy-efficiency standards program, product certification and registration, infrastructure for testing energy-efficiency performance, and an evaluation, measurement, and verification strategy. The goal is to optimize investments by national, regional, and international communities that are establishing or improving energy-efficiency standards and compliance infrastructures in tandem with the refrigerant transition. Ultimately, these efforts should help unlock the potential for climate change mitigation under the Kigali Amendment through harmonization of domestic practices and international obligations.

1. Background and motivation

The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in 1987 to regulate the production and consumption of nearly 100 ozone-depleting substances (ODS), and it remains the only United Nations (UN) treaty ratified by all UN Member States. Between 1987 and 2010, the Montreal Protocol led to the phaseout of 98% of historical levels of ODS production and consumption [1,2].

While the Montreal Protocol originally focused on ozone layer protection, it also contributed to climate change mitigation by phasing out use of ODS such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)—which are potent greenhouse gases (GHGs) [2–4] – and encouraging parties to promote "the selection of alternatives to HCFCs that minimize environmental impacts, in particular impacts on climate, as well as meeting other health, safety and economic considerations," as recognized in Decision XIX/6 [5]. After the original treaty was enacted, hydrofluorocarbon (HFC) use helped fill the need for non-ODS refrigerants. However, HFCs have an extremely high global warming potential (GWP) and represent the fastest-growing type of GHG emissions, increasing at an annual rate of about 10%–15% or more, depending on specific HFCs and regions [6–8]. For this reason, in 2016 the Parties to the Montreal Protocol adopted the Kigali Amendment, which establishes a framework for reducing global HFC use. As of January 2021, 112 parties had ratified the amendment [9].

The Montreal Protocol's shift toward climate protection through the Kigali Amendment (Decisions XVIII/2 and XVIII/3) presents an

* Corresponding author.
E-mail address: wypark@lbl.gov (W.Y. Park).

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opportunity to link the HFC phasedown with deployment of energy-efficient cooling equipment—and thus greatly amplify the GHG-reduction benefits of either strategy alone. In fact, energy efficiency has a larger impact on GHG emissions than refrigerant choice does [10]. Recent studies find that implementing the HFC refrigerant transition and energy-efficiency improvement policies in parallel for air conditioners (ACs) significantly improves the benefit of either policy implemented separately, in terms of GHG reductions and electricity savings [11,12]. Reduced electricity-sector emissions due to higher energy efficiency provide two thirds of the GHG reductions, with low-GWP refrigerants providing the other third [13]. Further, energy-efficiency improvement can maximize climate and health benefits by minimizing emissions and air pollution associated with fossil fuel-based electricity generation, even while AC use is expected to increase [14]. One comprehensive review study for climate change and fluorinated gases (F-gases) highlights "low-GWP, no-GWP, and natural substitute gases" and "energy efficiency and design improvement" as promising cross-cutting options that can help mitigate the effects of potent F-gases that include HFCs [15].

Linking the HFC phasedown with energy-efficiency improvements offers technical and economic synergies as well. High-efficiency products may entail a temporary increase in upfront prices, compared with the upfront prices of low-efficiency products. However, the price of high-efficiency room ACs varies owing to multiple factors, including premium features beyond energy efficiency and manufacturers' pricing strategies across their product lineups. Several studies find that AC energy efficiency can be further improved cost-effectively [16–23]. Transitioning to low-GWP refrigerants also entails upfront costs to manufacturers, including costs associated with system redesign, research and development, and retooled manufacturing lines. Hence, coordinating efficiency improvements with replacement of high-GWP refrigerants—rather than making two separate technological transitions—can keep costs lower for consumers, manufacturers, and utilities. In fact, highly efficient room ACs using low-GWP refrigerants (e.g., R-32 and R-290) are commercially available today in some well-developed markets at prices comparable to similar room ACs using high-GWP R-22 or high-GWP R-410A refrigerant [24]. Still, inefficient room ACs using high-GWP and ozone-depleting R-22 refrigerant continue to dominate markets in many developing countries [24]. As high-efficiency cooling equipment that uses low-GWP refrigerants is adopted more widely, the increased manufacturing scale will make these products even more cost-effective. Although changing refrigerants poses technical challenges to AC manufacturers with regard to redesigning systems and retrofitting facilities to address thermodynamic and safety issues associated with alternative refrigerants, it also presents an opportunity to redesign ACs for higher efficiency or lower cost [25].

Strengthening refrigerant and efficiency standards could also mitigate dumping of environmentally harmful products. Although more than 30 economies[1] have implemented efficiency standards for cooling equipment, many countries lack meaningful standards and compliance mechanisms (Fig. 1) [26–29]. Inadequate efficiency programs can allow countries to become dumping grounds for products that cannot be sold elsewhere, hindering control of harmful substances and promoting wasteful energy consumption [30]. Importation of used ACs and refrigerating appliances is a major issue in Africa, where imported units often use two to three times as much electricity as new products that comply with minimum energy performance standards (MEPS) in their countries of origin [31–33]. Of the room ACs sold in 10 African countries, 35% do not meet MEPS in their countries of origin and contain refrigerants that exacerbate global warming [34]. Used imports also entail safety concerns, because the contents may include a mix of replacement parts, improper servicing in the past may lead to early failures and risk of electric shock or refrigerant leaks, and so forth.

Despite the benefits of linking energy-efficiency and refrigerant considerations, they are still separate in most regions and under most regulatory systems. The Multilateral Fund (MLF) provided financial and technical assistance toward treaty compliance among developing (or "Article 5") countries that consume and produce less than 0.3 kg per year of ODS per capita on the date of entry into force of the Montreal Protocol or any time thereafter until January 1, 1999. MLF activities are implemented by four international agencies—the UN Environment Programme (UNEP), UN Development Programme, UN Industrial Development Organisation, and World Bank—and through bilateral arrangements between Article 5 and non-Article 5 countries. In 2019, OzonAction's Compliance Assistance Programme conducted regional workshops with national ozone officers on enabling activities for the HFC phasedown. In February 2020, guidance was updated on the submission of standalone HFC investment projects, outlining available resources – such as 30,000 U.S. dollars (USD) for the preparation of such projects – and noting that project impact could be estimated in terms of HFC phasedown as well as other environmental or energy-efficiency related impacts [35]. The MLF for the implementation of the Montreal Protocol will likely begin providing financial assistance to Article 5 countries to implement the Kigali Amendment starting in 2023.

These efforts are still in early stages and have not been linked with energy-efficiency considerations. Although the Kigali Amendment encourages countries to "maintain or enhance" equipment efficiency while transitioning to low-GWP refrigerants, it does not require higher-efficiency cooling equipment. This broad objective could be strengthened through the mechanism of the MLF for the Implementation of the Montreal Protocol, as well as coordinated assistance for improving cooling equipment efficiency through other bilateral or multilateral agencies. Recently, the MLF Executive Committee asked the MLF Secretariat to provide a framework for mobilizing resources to improve energy efficiency when phasing down HFCs [36].[2] Additionally, we understand that funding agencies such as the Green Climate Fund or other multilateral agencies are in discussions with the MLF Secretariat and the Ozone Secretariat[3] to couple financial assistance for improving cooling equipment efficiency with financial assistance provided by the MLF to Article 5 countries for the refrigerant transition [37,38].[4]

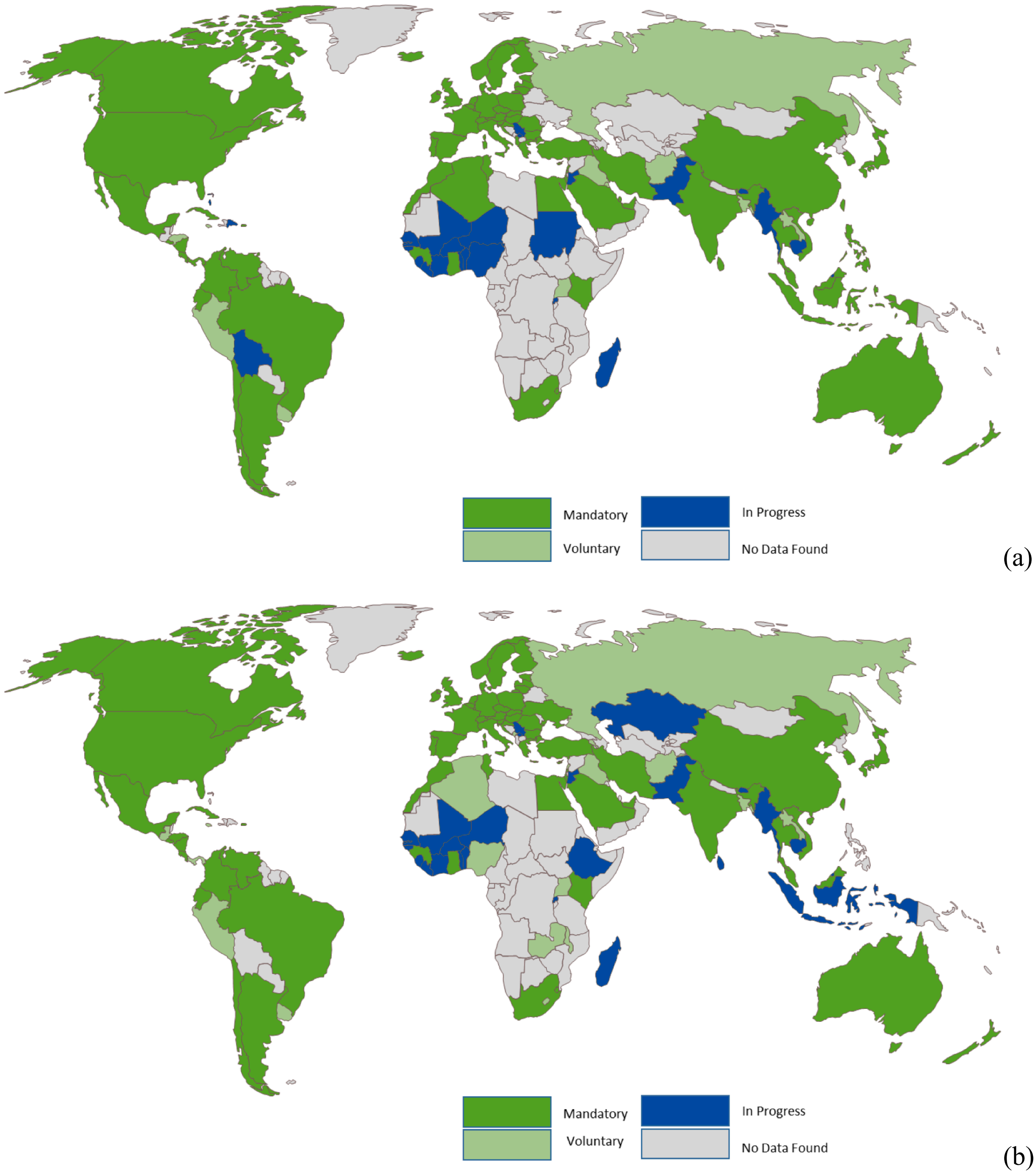
In this perspective, we aim to inform national governments and relevant regional entities by recommending a global compliance infrastructure for the simultaneous transition to efficient cooling equipment and low-GWP refrigerants. In general, countries develop and amend energy-efficiency standards to achieve the maximum efficiency that is technologically feasible and economically justified. For example, in the United States, standards are developed and amended through a formal rulemaking process with impact analyses, stakeholder engagement via public meetings and comment periods, and consensus agreements when petitioned by manufacturers and advocates [39]. Fig. 2 illustrates a

[1] EU member states are counted as a single economy.

[2] The report of the Executive Committee states [36], "To request the Secretariat:To prepare, in consultation with implementing agencies, a document for the 85th meeting that could provide a framework for consultations with relevant funds and financial institutions to explore, at both the governing and operational levels, the mobilization of financial resources, additional to those provided by the Multilateral Fund, for maintaining or enhancing energy efficiency when replacing HFCs with low global-warming-potential refrigerants in the refrigeration and air-conditioning sector; andTo continue the informal exchange of information with relevant funds and financial institutions, including for the preparation of the document referred to in sub-paragraph (b)(i) above."

[3] The Ozone Secretariat (based at UNEP headquarters in Nairobi, Kenya) provides technical support to the Meeting of the Parties, which is the treaty's governing body.

[4] "Parties inter alia requested the Executive Committee, in dialogue with the Ozone Secretariat, to liaise with other funds and financial institutions to explore mobilizing additional resources and, as appropriate, set up modalities for cooperation, such as co-funding arrangements, to maintain or enhance EE when phasing down HFCs." [37].



Source: UNEP United for Efficiency (U4E) Initiative

Fig. 1. Status of MEPS and efficiency labels for (a) room ACs and (b) refrigerating appliances.

model framework for establishing appliance and equipment standards programs.

The four steps outlined by the dotted box in Fig. 2 are the focus of our recommendations, which leverage decades of experience from national energy-efficiency programs along with the Montreal Protocol's refrigerant assistance program. The recommendations cover a broad compliance infrastructure, and they apply to residential, commercial, and

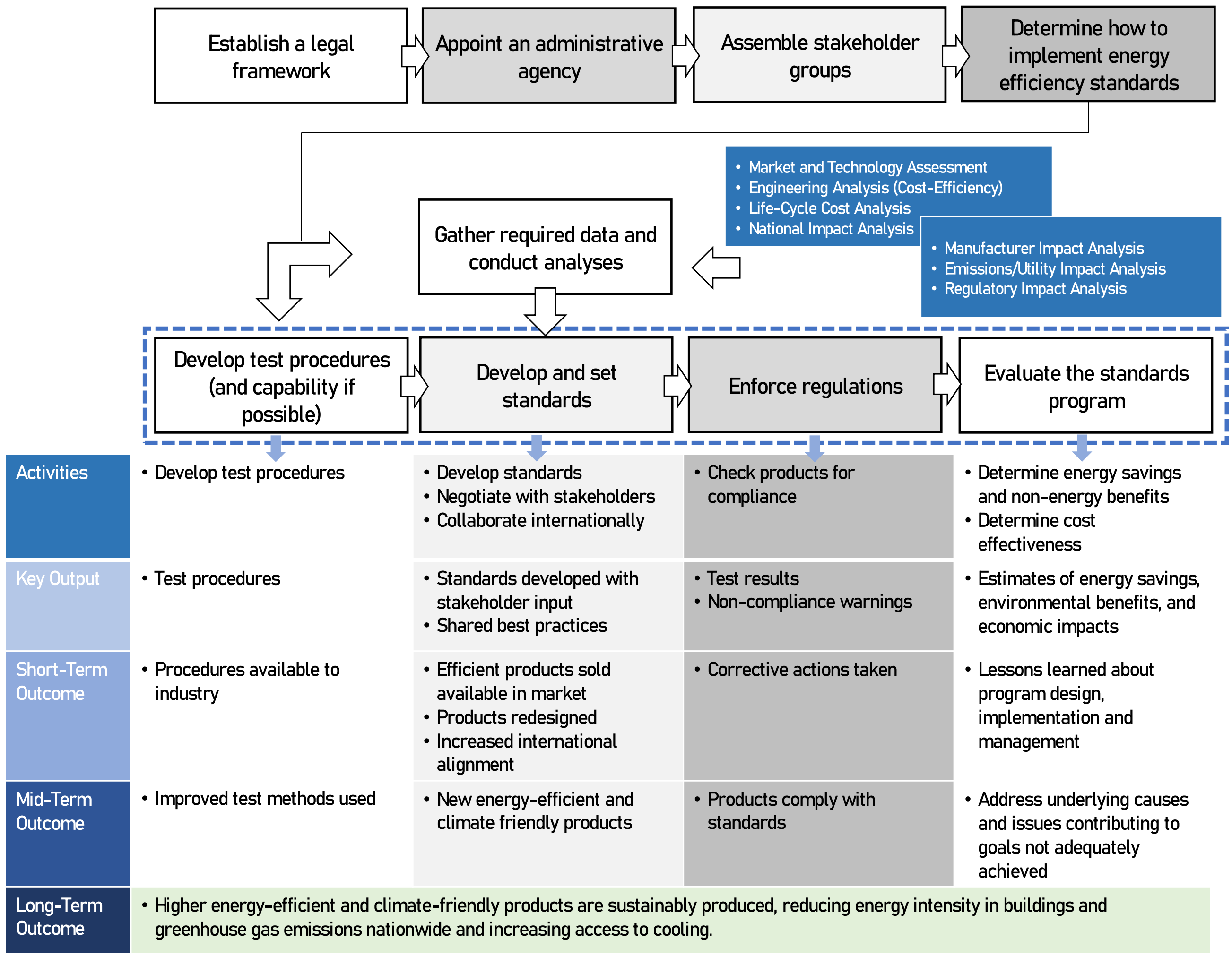


Fig. 2. Authors' work based on several sources [27,40,41].
Appliance and equipment standards program framework.

industrial cooling equipment.[5] The following are the major elements of the recommended compliance infrastructure, which are described in the remainder of the perspective:

1) Internationally harmonized energy-efficiency standards program
2) Product certification and registration
3) Infrastructure for testing energy-efficiency performance
4) Evaluation, measurement, and verification (EM&V) strategy

The goal is to optimize investments by national, regional, and international communities that are establishing or improving energy-efficiency compliance infrastructures in tandem with the refrigerant transition. Ultimately, these efforts should help unlock the potential for climate change mitigation under the Kigali Amendment through harmonization of domestic practices and international obligations.

2. Internationally harmonized energy-efficiency standards

The following are our recommendations related to internationally harmonized energy-efficiency standards.

i. Implement energy-efficiency standards that consider low-GWP refrigerants along with improvement of safety standards.

In the context of the Kigali Amendment, especially for countries that have nonexistent or outdated energy-efficiency standards for cooling equipment, policy action can be accelerated by advancing the refrigerant transition and efficiency improvements simultaneously. Jurisdictions that already have advanced energy-efficiency standards may add the refrigerant transition to the market transformation. For example, in the European Union (EU), Regulation (EU) No. 517/2014 requires an HFC phasedown. Effective January 2025, the European Commission will ban refrigerants with GWP greater than 750 for residential split ACs that contain less than 3 kg of refrigerant charge [42]. In the United States, the California Air Resources Board (CARB) approved a new regulation to

[5] Our recommendations complement the UNEP U4E Model Regulation Guidelines for ACs and refrigerating appliances, which address core requirements and test methods related to energy efficiency and refrigerants, and the U4E Guidance Notes on i) Protocols to Conduct Market and Impact Assessments, ii) Energy Labeling, and iii) Ensuring Compliance with MEPS and Energy Labels.

limit GWP for new stationary refrigeration and AC systems: a GWP limit of 150 on new stationary refrigeration systems containing more than 50 lb of refrigerant starting January 1, 2022, and a GWP limit of 750 for stationary AC systems starting January 1, 2025 [43]. Government officials that have jurisdiction over both types of policy should maximize coordination by implementing low-GWP criteria when establishing or revising efficiency-improvement policies. For example, Rwanda's National Cooling Strategy established MEPS and energy labels for room ACs and refrigerating appliances with energy-efficiency requirements and refrigerant GWP limits based on the U4E Model Regulation Guidelines [44]. In this effort, the thermodynamic properties – including flammability risks – of alternative refrigerants must satisfy national safety standards. Hence, in-depth understanding of the product- and building-level risks and risk-mitigation strategies are also key to accelerating the market transition to low-GWP refrigerants [25].

Integrating policies may not be easy, because regulatory priorities, influence, and budgets are associated with individual government-agency "silos" [45]. It is necessary to discuss the feasibility of integrating energy-efficiency standards programs with emerging needs from different policy arenas, such as refrigerants and renewable energy. Metrics and accounting systems within refrigerant compliance plans must be resolved before ozone officers and energy officials can identify new opportunities for energy-efficiency improvements within refrigerant compliance strategies. However, the urgent need to mitigate climate change may help motivate the efforts needed to develop a cohesive set of energy-efficiency and refrigerant policies and regulatory initiatives [45].

ii. Harmonize national/regional energy-efficiency and test standards with international standards to help the industry accelerate the market transition.

The test procedures and metrics established by different countries often vary, making it difficult to compare the energy performance of cooling equipment across jurisdictions. In particular, seasonal energy efficiency metrics for evaluating AC performance may differ, mainly because they are designed to consider the impact of outdoor temperature variation on AC cooling load and energy consumption, requiring multiple test points to compute a seasonally weighted average efficiency [46]. Table 1 shows a brief comparison of primary test conditions for variable-speed drive (inverter-driven) ACs.

The energy-efficiency standards rulemaking process should include collaboration with other countries to enable international alignment of standards and test procedures. For governments that are considering a regulatory or legislative framework requiring new ACs and refrigerating appliances to be energy efficient and use lower-GWP refrigerants, the U4E Model Regulation Guidelines can be used as a starting point to inform regulatory considerations and collaboration with other entities [28,29,47,48]. Harmonization of standards and test specifications can help accelerate the transition to higher-efficiency, lower-GWP cooling equipment, because it enables manufacturers to sell the same desirable equipment across multiple countries and regions. Currently, regional AC harmonization efforts are ongoing in Southeast Asia, Southern Africa, East Africa, West Africa, the Caribbean, and other regions.

iii. Improve links to other policy programs, such as building codes, incentives, and demand response

Cooling equipment is an important element of energy-efficient buildings, which are meant to reduce energy consumption via integrated design, efficiency measures, reduced plug loads, and so forth. An optimal standards program would include a database of cooling products that comply with regional efficiency standards or labels, and only listed equipment could be installed in the region's buildings. In addition, regulations on refrigerant use, disposal, and replacement could be linked to the energy-efficiency standards and building codes. For example,

Table 1
Comparison of Primary Test Conditions for Variable-Speed Acs.

	ISO[a]		North America			EU[b]			
Part Load	Outdoor DB/WB Temp. (°C)	Indoor DB/WB Temp. (°C)	Required Test – Compressor Speed/ Cooling Air Volume	Outdoor DB/WB Temp. (°C) [°F]	Indoor DB/WB Temp. (°C) [°F]		Part Load Ratio (%)	Outdoor DB Temp. (°C)	Indoor DB/ WB Temp. (°C)
Full Load (required)	35/24	27/19	A_2 – Max/Full (required)	35.0/23.9 [95/75]	26.7/19.4 [80/67]	A	100	35	27/19
Half Load (required)			B_2 – Max/Full (required)	27.8/18.3 [82/65]		B	74	30	
Min Load[c] (optional)			E_v – Intermediate/ Intermediate (required)	30.6/20.6 [87/69]		C	47	25	
Full Load (calculated)	29/19	27/19	B_1 – Min/Min (required)	27.8/18.3 [82/65]		D	21	20	
Half Load (optional)			F_1 – Min/Min (required)	19.4/11.9 [67/53.5]					
Min Load[c] (optional)									

DB = dry bulb, ISO = International Organization for Standardization, WB = wet bulb.
Part-load capacities under these conditions are achieved by fixing the compressor speed of the variable-speed unit.
[a] Standards and/or labels of many countries—including Australia, Japan, India, Indonesia, Malaysia, Myanmar, Philippines, Cambodia, Thailand, Vietnam, Lao People's Democratic Republic, Hong Kong, Brazil, Rwanda, and more—fully or largely refer to the ISO 16358-1:2013 standard.
[b] The four test points (A, B, C, and D) defined in the EU standard are points that manufacturers are supposed to "declare." Each point does not need to be tested; the points could also be calculated based on other tested points or based on the performance of similar units.
[c] According to ISO 16358-1:2013, minimum-load operation is defined as operation of the equipment and controls at minimum continuous capacity; 25% of minimum load is used under the Chinese standard. Source: Park et al. [46].

California's building energy-efficiency standards have minimum efficiency requirements for ACs and condensing units by type and size [49]. However, when linking policy programs, challenges related to the governmental silos discussed in recommendation *i* above must be addressed.

Incentives can also be linked to energy-efficient products. For example, the ECOWAS Refrigerators and Air Conditioners Initiative (ECOFRIDGES) launched a financial mechanism that uses the U4E Model Regulation Guidelines as the basis for product eligibility.[6] Consumers receive a voucher toward a future purchase if they turn in used but complete AC or refrigerating appliances. New products can be financed at 0% interest. This is a voluntary scheme for qualifying salaried employees [50].

The increasing demand for new cooling appliances in the coming years can yield greater opportunity to deploy smart cooling appliances embedding demand response capabilities. These capabilities help maintain electricity supply and demand balance in a power system, particularly in the peak periods, mitigating capacity requirements for rising peak loads due to cooling electricity demand. The successful adoption of demand response based on smart cooling largely depends on avoiding user thermal discomfort and integrating user feedback into the cooling control loop – and it depends on energy-efficient equipment. Advanced information technologies for cooling appliances combined with machine-learning algorithms can help energy systems identify optimized timing for precooling or temperature points around peak load times while considering building characteristics and user thermal comfort, responding to varying environmental and operating conditions such as building characteristics, climate, and, occupancy.[7] Utilities across the United States are offering incentives in return for the ability to adjust the temperature via smart cooling appliances. Utilities sponsor direct-installation thermostat programs, which require participants to register smart cooling appliances so the utilities can control the registered appliances during peak hours. Alternatively, bring-your-own-thermostat (BYOT) programs enable residential customers to participate in demand response through smart thermostats that plug in to cooling appliances [51].

3. Product certification and registration

Standards programs for energy-efficient and low-GWP cooling equipment depend on mechanisms for certifying and registering compliant equipment [41,52]. Fig. 3 shows a model framework for coordinated certification and registration. Manufacturers and suppliers of compliant products are provided a mechanism for certifying compliance [27]. For example, regulations might require every model of a product to be tested by an accredited laboratory before sale.[8] A sample of each model is sent to one of these laboratories for energy performance testing. If the manufacturer or importer accepts the results, this information is included on the energy label; if they do not accept the results, they can request tests of other samples of the same model [27,41,53]. To prevent differences between samples tested for reporting before sale and samples selected from the market, the government can test products selected randomly from the point of sale or distribution as, for example, Australia does [54]. As testing is completed to certify the compliance of various products, the regulatory body registers the products in a database, which consumers can use to identify compliant options. Variations on this approach include relying on self-certification by manufacturers (e.g., as done in the EU) and helping manufacturers self-certify based on prescribed rules and industry-sponsored third-party certification schemes (e.g., as done in the United States) [27,41].

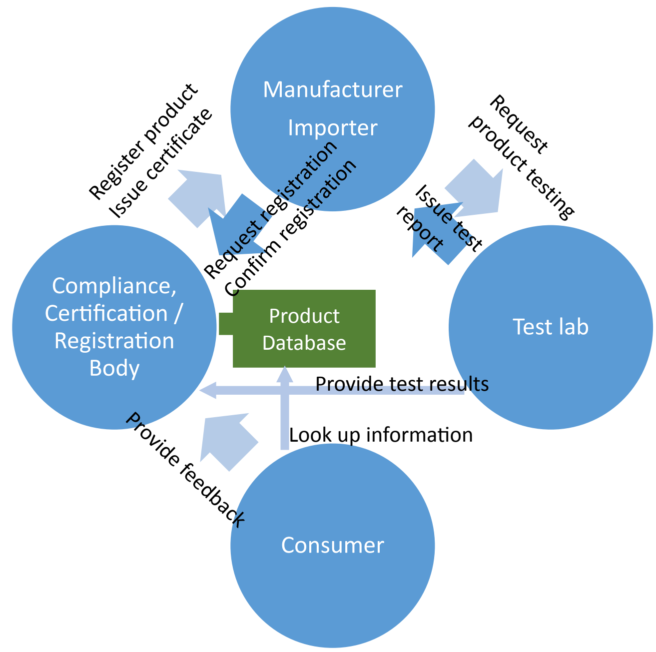


Fig. 3. Authors' work based on several sources [27,41,53]. Schematic of coordinated registration and certification.

We make the following recommendations for establishing product certification and registration systems in case efficiency-improvement activities are funded in parallel with refrigerant-transition activities funded under the Montreal Protocol.

i. *Implement product databases that include information on energy efficiency and refrigerant (e.g., type, GWP, charge amount) as well as related standards for installation, service, recycling or disposal, and building codes.*

Regardless of differences in approach to certification and registration, product databases serve as initial gateways for registering compliant products with regulatory authorities. Integrating information on energy efficiency, refrigerants, and other relevant issues into one database is a good starting point for simultaneously advancing the refrigerant transition and efficiency improvements. For additional detail on product registration systems, see the U4E Guidance Notes [55–58].

ii. *Harmonize databases regionally and allow data sharing*

Development and administration of integrated product registration databases could prove burdensome if undertaken by individual jurisdictions and regulatory agencies. Harmonizing the efforts across jurisdictions in a region would reduce this burden. For example, the U4E Product Registration System development project in Southeast Asia,

[6] ECOFRIDGES is a joint project of the Governments of Ghana and Senegal, the UNEP U4E Initiative, and the Basel Agency for Sustainable Energy. ECOWAS = Economic Community of West African States.

[7] A successful demand response program requires an automated operational framework that can sense and minimize user discomfort. For example, reinforcement learning, a flexible model-free approach that can incorporate complex environmental and human feedbacks into its learning logic, has been used to automatically control diverse energy systems such as heating, ventilation, and AC systems, smart appliances, and energy storage.

[8] Because efficiency tests for ACs and refrigerating appliances typically require a long time and sophisticated technical effort, it is practical to have multiple test laboratories accredited to conduct the specified tests and participate in the standards compliance process.

together with the Association of Southeast Asian Nations Centre for Energy, is helping member states align required system inputs. This coordination will reduce processing time by manufacturers/suppliers and allow data to be shared among countries via an application programming interface.

4. Infrastructure for testing energy-efficiency performance

Product testing is a key element of the product certification and registration process (Fig. 3). Test procedures must be repeatable, reproducible, representative, and enforceable so they can be used reliably to rate product performance [41].

We make the following recommendations for testing energy-efficiency performance in case efficiency-improvement activities are funded in parallel with refrigerant-transition activities funded under the Montreal Protocol.

i. *Assess the market before constructing test facilities and ensure these facilities have adequate revenue to operate.*

It is expensive to establish, commission, accredit, and maintain testing laboratories. A published estimate for a laboratory that can test three AC units simultaneously suggests a cost of about USD 1–1.5 million for the first year, including equipment, staff training, and calibration [26]. Quotes we received from two suppliers suggest a cost of approximately USD 1 million (for a 10-kW testing capacity) to USD 2 million (for a 34-kW capacity) for installation of an AC testing laboratory only.[9] Refrigeration-testing laboratories use a temperature- and humidity-controlled room to control environmental and operating conditions. An estimate for setting up a refrigeration-testing laboratory in Indonesia that can test three units simultaneously suggests a cost of USD 165000 for the first year, including equipment, staff training, and calibration [27]. SEAD is a resource that has more detailed information on appliance testing costs by region. However, the costs vary widely by the size of the equipment to be tested and the level of complexity [60]. In addition, it is best to engage experts familiar with ISO test laboratory accreditation and standards when designing a laboratory. Because of the expense involved, markets must provide a minimum level of business to sustain such laboratories. A market assessment should be performed before laboratory construction.

ii. *Explore testing collaboration opportunities through mutual recognition agreements among governments, governments and test laboratories, and test laboratories in different regions, particularly for smaller economies.*

A laboratory for verification testing must be independent and accredited in accordance with the ISO/International Electrotechnical Commission (IEC) 17025 standard. It should also be accredited to test specific products in accordance with energy performance test standards specified in the MEPS and energy labeling regulations. Accreditation alone may be insufficient for a test laboratory to produce results that are consistent with those found by other laboratories with an established track record. Government agencies must ensure the laboratory has conducted cross-testing with one or more well-respected international laboratories. Once repeatable test results are produced within an acceptable margin of error, the agency can be confident that its laboratory will yield legally enforceable test results [61].

Countries that do not have testing laboratories or need to improve existing testing facilities can consider other approaches. For example, Singapore relies on suppliers' reporting for registration. The National Energy Agency selects a random sample of registered goods for verification testing. Suppliers of the selected models provide the agency with samples for testing, which the agency seals at the warehouses. The agency engages a contractor, under a mutual recognition agreement, to collect and test the samples locally or abroad, and then it compares the verification test results against the test reports submitted by suppliers during registration. If the results are within conformance limits—generally within 10%–15% of the supplier's declared test result—the verification testing is complete [61].

Overall, the cost of testing laboratories can be mitigated via mutual recognition agreements among governments, governments and test laboratories, and test laboratories in different regions [26,27]. Global cooling equipment manufacturers often sell their products in multiple markets, and these products are often tested by laboratories accredited by national, regional, or international bodies, such as the International Laboratory Accreditation Cooperation. Authorizing the use of mutual recognition agreements to accept testing reports from non-domestic entities reduces the burden of testing on government, importers, manufacturers, and laboratories while simplifying cross-border trade [26]. Such collaboration is particularly relevant for countries with smaller economies, which are disproportionately burdened by the cost of setting up domestic laboratories.

iii. *Effectively communicate seasonal energy efficiency and distinctions among various types of cooling equipment, accounting for differences across regions based on efficiency metrics, climate, and operating conditions.*

The energy-efficiency performance of AC systems has improved over time, largely owing to the rise of variable-speed (inverter-driven) products, which now dominate mature AC markets such as Australia, Europe, Japan, and the United States.[10] However, properly measuring the performance of ACs across different climates, operating conditions, technology types (e.g., vapor compression or evaporative cooling), and applications (e.g., residential or commercial) requires seasonal energy-efficiency ratio (SEER) metrics and corresponding test methods [46]. For example, adopting the ISO cooling seasonal performance factor (CSPF) metric would improve AC standards and labeling while facilitating harmonization with international AC-efficiency efforts [26,31,62]. As another example, China had been evaluating the energy performance of fixed-speed room ACs using the energy efficiency ratio (EER) while evaluating variable-speed room ACs using China's SEER for cooling-only products and annual performance factor (APF) for reversible-type heat pumps. The new MEPS and labels, effective on July 1, 2020, for Chinese room ACs are based on SEER (cooling-only) or APF (reversible) for both fixed- and variable-speed products [63]. Fig. 4 illustrates the calculation of CSPF under ISO 16358, based on test methods under ISO 5151.

Evaluating the energy performance of commercial ACs, such as multi-split systems, is more complex than evaluating the performance of residential ACs. Efficiency metrics used for commercial ACs may also differ from those for residential ACs. For evaluating the energy performance of multi-split systems, China had been using an integrated part-load value (IPLV) to set MEPS and labeling requirements. The IPLV metric for air-cooled multi-split systems is expected to be replaced by the APF metric to align with the new room AC standards and labels; water-cooled multi-split systems still use IPLV but with a revised equation [63].

[9] The calorimeter method of testing AC performance is very accurate and has a low risk of error but is relatively expensive and time consuming. The air enthalpy (psychrometric) method is cheaper and quicker but not as accurate [59]. This method is widely used internationally, because the range of error is considered acceptable.

[10] Variable-speed compressors enable an AC unit to respond to changes in cooling requirements by operating at full or partial loads. This flexibility improves efficiency performance and reduces power consumption compared to the efficiency performance and power consumption of conventional ACs with fixed-speed compressors that cycle on and off.

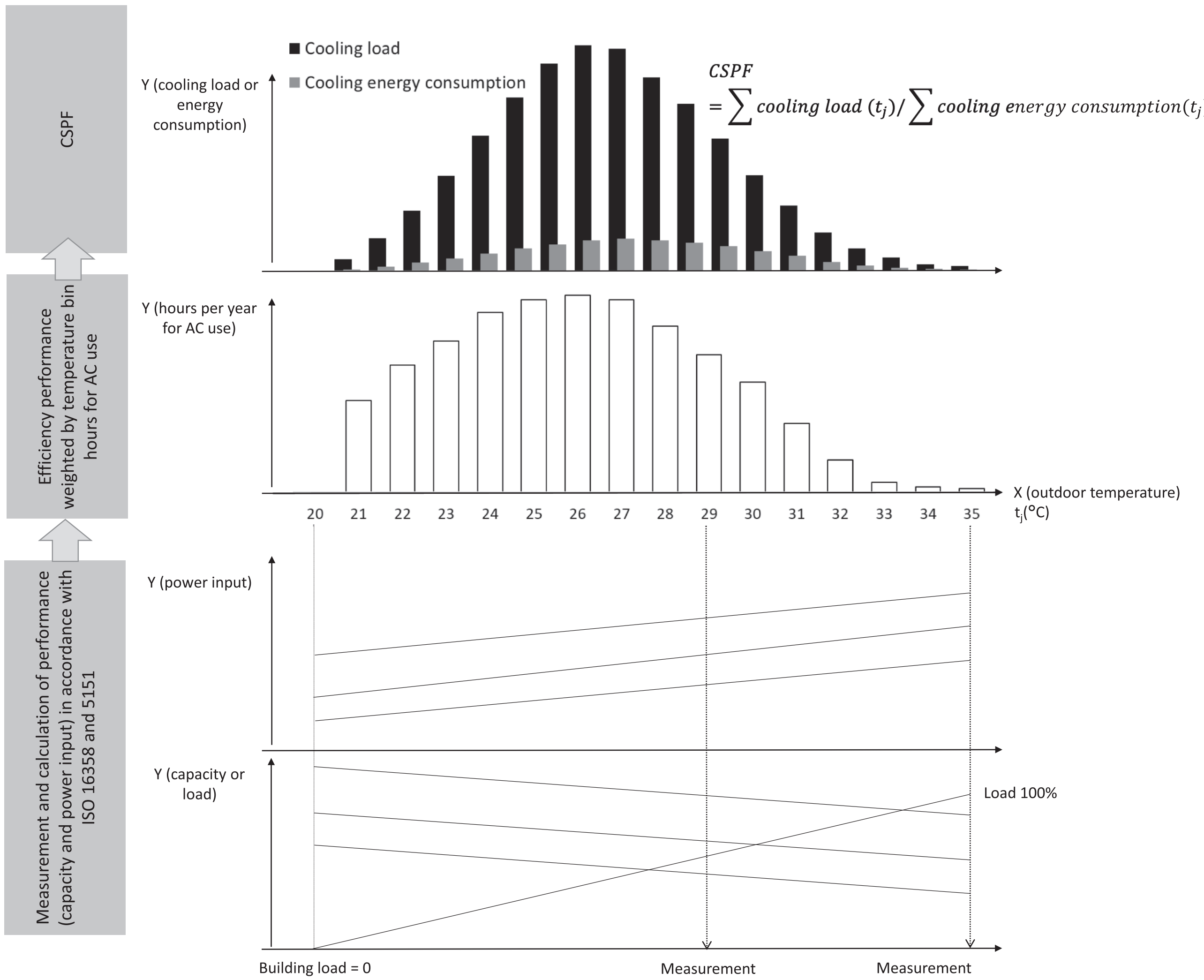


Fig. 4. Source: Authors' work based on ISO 16358-1:2013.
Schematic of the ISO 16358 CSPF calculation.

Table 2
Parameters Used To Define Product Categories in Energy-Efficiency Standards of Refrigerating Appliances

Type of Refrigerator/Freezer		Climate Classes	Built-in or Freestanding	Defrost	Ice Maker	Size
Refrigerator	Refrigerator only, refrigerator with freezer compartment	Subtropical (ST), Tropical (T), Sub-temperate (SN), Temperate (T)	Freestanding, built-in	Manual, automatic, partial automatic	Automatic icemaker, through-the-door ice service	For example, a product category with adjusted volume less than 300 L
Refrigerator-freezer	Top-mounted, bottom-mounted, side-mounted freezer					
Freezer	Chest (horizontal), upright (vertical)					
By compartment[a]						

Source: UNEP [48].
[a] IEC 62552 defines compartment as an enclosed space within a refrigerating appliance, which is directly accessible through one or more external doors. Energy consumption requirements in the new EU standard are based on individual compartments.

Although the standard for measuring refrigerator performance is broadly similar across countries, a number of factors can produce variations in energy consumption values (e.g., kWh/day or kWh/year) across countries owing to different specifications for ambient temperature, compartment internal temperature, and additional features in the test procedure (Table 2). These variations hinder comparison of efficiency across regions [47]. IEC 62552:2015 was developed to harmonize international residential refrigeration testing and efficiency metrics. China, the EU, and several other economies have already adopted or are planning to adopt the IEC 62,552 standard that measures energy consumption at 16 °C and 32 °C, providing improved information on the likely field performance of refrigerating appliances [47]. Countries can determine energy consumption requirements at a reference temperature between 16 °C and 32 °C.[11]

Commercial refrigeration equipment is complex in type, function, and test procedures. For example, the ISO 23953:2015 standard for refrigerated display cabinets – which are designed for storing, displaying, and allowing access to chilled or frozen items in a retail environment – identifies 13 families and 10 shapes of such cabinets. There are also refrigerated storage (or service) cabinets, which store but do not display items, and other types of commercial refrigeration equipment such as refrigerated vending machines and walk-in cold rooms. Table 3 shows categories of refrigerated cabinets summarized from existing standards.

Table 3
Refrigerated Cabinet Categories

Condensing Unit Location	Cabinet Operating Temperature	Orientation or Cabinet Configuration	Closure or Means of Access to Products	Air-Circulation Method
Integral Remote (direct, indirect)	Chilled Frozen Ice cream[a] Multi-temperature	Vertical Horizontal Chest Semi-vertical Multi-deck Combined Serve-over Roll-in Under-counter Pass-through Wall site Island	Open Glass door Solid door Drawer Combination	Static Forced

Source: MEA et al. [64].
[a] Ice cream refers to a specific cabinet operating temperature used in some regions.

5. Evaluation, measurement, and verification strategy

Predicted energy savings and emissions reductions from energy-efficiency programs are not necessarily realized. In fact, actual benefits often fall short of predicted benefits. Financial and human resources are needed to support EM&V activities to assess program impacts, processes, and market effects; most energy-efficiency program evaluations have focused on impacts [65–67]. Developing a long-term EM&V strategy at the time of program implementation—with appropriately planned and sequenced studies – can maximize program success.

We make the following recommendations for establishing an EM&V strategy in case efficiency-improvement activities are funded in parallel with refrigerant-transition activities funded under the Montreal Protocol.

i. *Regularly monitor compliance rates and potential savings from cooling equipment to maximize the benefits of compliance-improvement activities.*

One important function of a government authority is to regularly monitor the compliance of products supplied to the market. Governments can monitor products using different methods during different phases of the regulatory process [27]:

- Check product documentation for certification or registration in product registration systems.
- Verify energy-efficiency performance of select products.
- At customs, ensure all documentation for imported products is provided and meets requirements.
- In stores, check that energy labeling requirements are met.
- Monitor results shared by other economies—consider mutual recognition agreements.
- Evaluate the impacts of the energy-efficiency standards and labeling program.

For example, India's Bureau of Energy Efficiency (BEE) launched a standards and labeling program for residential appliances in 2006. BEE started the program as voluntary with four appliances and gradually expanded it to be mandatory for 23 products, including cooling, lighting, and industrial-application products. BEE has continuously strengthened the program, for example, by improving MEPS for refrigerating appliances by 49%–60% and room ACs by 35% – accounting for 76% of the total energy saved and equivalent emissions reduced in all products covered by the program since inception [68].

Monitoring compliance rates and potential savings helps identify areas for which focused compliance-improvement activities could maximize energy savings. Tracking sales-weighted efficiency trends over time is critical to assessing how well the market is becoming sustainable and energy efficient [52].

ii. *Account for direct emissions from refrigerants and indirect emissions from electricity production and thermal energy.*

Quantifying emissions-reduction impacts is the common objective that many evaluators, regulators, and program administrators consider under program evaluation. Most energy-efficiency programs calculate indirect emissions associated with the production of electricity and thermal energy from fossil fuels. Programs for cooling equipment and systems that use refrigerants must also account for direct emissions from those refrigerants [52,69].

iii. *Strengthen program design and implementation through process evaluation.*

Process evaluation helps identify areas of weakness in program design and implementation so these areas can be strengthened [70]. Process evaluation is needed to assess consumer priorities when purchasing an appliance, track consumer awareness, check that product labels are displayed correctly in retail showrooms, measure administrative efficiency (e.g., registration times), and verify manufacturer claims (to maintain program credibility). Process evaluation is also used to assess the attitudes and behaviors of other key players in the marketplace, including retailers, manufacturers, policymakers, and mass media [71,72].

[11] For example, the U4E Model Regulation Guidelines and the new EU standards have the reference temperature of 24°C (performance determined by measured performance at 16°C and 32°C, i.e., $EC_{24^\circ C} = 0.5 \times EC_{16^\circ C} + 0.5 \times EC_{32^\circ C}$, where EC_t is energy consumption at ambient temperature t).

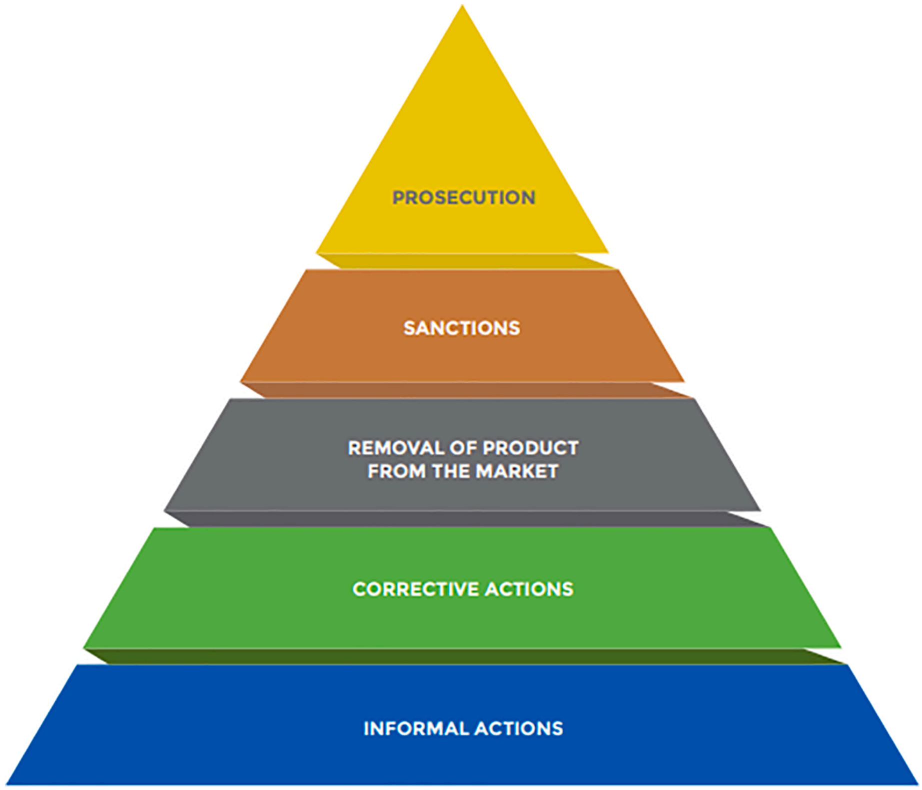


Fig. 5. Source: UNEP [27].
Pyramid of escalating enforcement.

iv. *Respond appropriately to noncompliance.*

Enforcement authorities should consider the degree of noncompliance when addressing cases of noncompliance so they can respond with proportionate enforcement action, including informal actions, corrective actions, removal of product from the market, sanctions, and prosecution [27]. Many authorities develop an "Enforcement Pyramid" (Fig. 5) to inform and manage their enforcement response strategies in accordance with legal requirements, available resources, and program characteristics.

v. *Align EM&V activities with emerging trends and other climate, energy, and sustainability efforts.*

Because of rapid technological and societal changes, EM&V activities must be continually reevaluated. For example, research has been uncovering the potential of information and communications technologies to change how energy-efficiency program administrators conduct EM&V on their efficiency measures, projects, and programs – forming the basis of "EM&V 2.0." Many ACs and other cooling products are now manufactured to communicate wirelessly with building management systems and to export information to remote operators through the Internet. Smart meters, the most visible component of the smart grid, enable bidirectional communication and load monitoring between utilities and customers [73]. EM&V 2.0 technologies will help energy-efficiency programs manage the expected increase in cooling-related energy consumption by increasing the accuracy and comprehensiveness of energy data [73,74]. EM&V 2.0 can also facilitate the non-energy benefits of high-efficiency cooling equipment – such as increased comfort, transmission and distribution loss reduction, benefits to disadvantaged communities, and avoidance of rate subsidies – in alignment with international climate, energy, and sustainability efforts. Ultimately, regulators will need to adopt a comprehensive method to evaluate energy efficiency, grid impacts, refrigerants, and climate change activities, as well as a unified set of policy rules that enable and encourage utilities to pursue combined opportunities via a single agreement with customers.

6. Summary of recommendations

Creating strong connections between cooling energy-efficiency standards and refrigerant-management programs – and between domestic practices and international obligations—will maximize the benefits of global climate change mitigation programs under the Montreal Protocol. However, achieving this synergy presents challenges, especially in countries that lack robust regulatory and technical capacity. The recommendations in this perspective are meant to help national, regional, and international communities optimize their investments in energy-efficiency compliance infrastructures in tandem with the refrigerant transition. The following is a summary of our recommendations.

a. Establish appropriate energy-efficiency standards and harmonize internationally.
   i. Implement energy-efficiency standards that consider low-GWP refrigerants along with improvement of safety standards.
   ii. Harmonize national/regional energy-efficiency and test standards with international standards to help the industry accelerate the market transition.
   iii. Improve links to other policy programs, such as building codes, incentives, and demand response.
b. Establish an appropriate infrastructure for product certification and registration.
   i. Implement product databases that include information on energy efficiency and refrigerant (e.g., type, GWP, charge amount) as well as related standards for installation, service, recycling or disposal, and building codes.
   ii. Harmonize databases regionally and allow data sharing.

c. Establish an appropriate infrastructure for testing energy-efficiency performance.
   i. Assess the market before constructing test facilities and ensure these facilities have adequate revenue to operate.
   ii. Explore testing collaboration opportunities through mutual recognition agreements among governments, governments and test laboratories, and test laboratories in different regions, particularly for smaller economies.
   iii. Effectively communicate seasonal energy efficiency and distinctions among various types of cooling equipment, accounting for differences across regions based on efficiency metrics, climate, and operating conditions.

d. Establish an appropriate EM&V strategy at the time of program implementation.
   i. Regularly monitor compliance rates and potential savings from cooling equipment to maximize the benefits of compliance-improvement activities.
   ii. Account for direct emissions from refrigerants and indirect emissions from electricity production and thermal energy.
   iii. Strengthen program design and implementation through process evaluation.
   iv. Respond appropriately to noncompliance.
   v. Align EM&V activities with emerging trends and other climate, energy, and sustainability efforts.

Further, it is critical to effectively coordinate with key market actors and voluntary programs such as those related to procurement and incentives. For example, because equipment manufacturers and suppliers play an important role in product certification and registration, regulatory bodies should ensure meaningful engagement with these stakeholders during efforts to improve compliance systems. Incentive programs for stimulating high-efficiency appliance purchases can help achieve additional socio-economic and environmental benefits [75]. In India, Energy Efficiency Services Limited (EESL) launched its Super-Efficient Air Conditioning Program through which consumers can buy high-efficiency ACs at prices comparable to the most efficient ACs on the market [76]. Award programs can help spur technological innovation [75]. The Global Cooling Prize, a competition initiated by Rocky Mountain Institute with India's Department of Science and Technology, aims to incentivize innovation in developing a cooling solution with at least five times less climate impact than standard room ACs on the market today [77].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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