

Blue Technology in Switchgear for Sustainable Power Transmission Systems: Dielectric, Switching, Life-Cycle and Techno-Economic Modelling of SF₆-Free Clean-Air and Vacuum Gas-Insulated Substations

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Blue Technology in Switchgear for Sustainable Power Transmission Systems: Dielectric, Switching, Life-Cycle and Techno-Economic Modelling of SF₆-Free Clean-Air and Vacuum Gas-Insulated Substations

Abstract—Sulphur hexafluoride (SF₆) has been the reference insulating and arc-quenching medium of high-voltage switchgear for six decades, but with a global warming potential of about 24 300 and an atmospheric residence time of the order of 3 200 years it is now the single largest direct greenhouse-gas liability of the transmission sector. "Blue" switchgear technology — vacuum interruption combined with clean-air (80 % N₂ / 20 % O₂) insulation — removes fluorinated gases from the substation entirely. This thesis develops an integrated engineering model of blue switchgear for sustainable power transmission and evaluates it against SF₆ and fluoronitrile (C₄-FN) alternatives for a 145 kV, 40 kA reference bay. A streamer-criterion dielectric model with Schwaiger field-utilisation and an empirical design-derating factor yields a clean-air design point of a 150 mm coaxial gap at 6.2 bar absolute for a 650 kV lightning impulse withstand level, against 95 mm at 4.4 bar for SF₆; the enclosure diameter grows from about 300 mm to 475 mm and the bay footprint by roughly 22 %. A vacuum-arc recovery model shows a dielectric-recovery rate of approximately 18 kV/μs against a transient recovery voltage of 2.0 kV/μs, giving an interruption margin of about nine. A Rayleigh-number-based thermal model shows that the lower volumetric heat capacity of clean air requires a 28 % larger conductor cross-section to hold the temperature rise below 65 K at 2 500 A. A cradle-to-grave life-cycle inventory gives 377 t CO₂-eq for the SF₆ bay against 92 t CO₂-eq for the blue bay, a 75.7 % reduction, of which 77 % of the SF₆ burden is gas leakage and end-of-life release. A discounted life-cycle cost model with a 9.5 % capital premium gives a break-even at service year 19 and a net present advantage of 3.9 % of capital cost at 40 years; sensitivity analysis shows that the business case is governed by capital premium, gas-handling and compliance cost, and discount rate, and only weakly by carbon price. A four-layer system architecture linking the primary plant, an IEC 61850 digital layer, an asset and carbon-accounting layer and the regulatory interface is proposed, together with a weighted multi-criteria sustainability index in which blue technology scores 0.89 against 0.73 for the fluoronitrile route and 0.54 for SF₆.

Index Terms—Blue technology, clean air insulation, gas-insulated switchgear, life-cycle assessment, SF₆-free switchgear, sustainable power transmission, transient recovery voltage, vacuum interrupter.

I. NOMENCLATURE

α, η	Townsend ionisation and attachment coefficients (m ⁻¹).
A_c	Conductor cross-sectional area (mm ²).

d	Coaxial insulating gap, $R - r$ (mm).
$(E/N)_{cr}$	Critical reduced electric field (Td).
$(E/p)_{cr}$	Critical reduced field strength (kV·cm ⁻¹ ·bar ⁻¹).
G_{tot}	Cradle-to-grave global warming potential (t CO ₂ -eq).
h	Convective heat-transfer coefficient (W·m ⁻² ·K ⁻¹).
k_{af}	Amplitude factor of the transient recovery voltage.
k_d	Design derating factor of the practical gas gap.
k_{pp}	First-pole-to-clear factor.
m_g	Gas mass per bay (kg).
r_a	Annual leakage rate (per unit per year).
R, r	Enclosure and conductor radii (mm).
S	Multi-criteria sustainability index.
t_3	Time to reach the TRV peak u_c (μs).
u_c	Peak transient recovery voltage (kV).
U_b	Intrinsic uniform-field breakdown voltage (kV).
U_w	Design withstand voltage (kV).
β	Weibull shape parameter.
δ	Relative gas density (per unit).
$\Delta\theta$	Conductor temperature rise above ambient (K).
η_{rec}	End-of-life gas recovery efficiency.
η_s	Schwaiger field-utilisation factor.

II. INTRODUCTION

A. Background and Motivation

Electric power transmission is simultaneously the enabler of decarbonisation and, through one specific material choice, a direct emitter of the most potent greenhouse gas in industrial use. Sulphur hexafluoride has been adopted universally in high-voltage switchgear since the 1960s because it combines an intrinsic dielectric strength roughly three times that of air at the same pressure with an outstanding arc-quenching capability and chemical inertness. These properties allowed gas-insulated switchgear (GIS) to compress an air-insulated switchyard into a fraction of its volume, which is why GIS dominates urban, offshore and space-constrained transmission substations worldwide.

The environmental cost of that choice has become unacceptable. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change assigns SF₆ a 100-year global warming potential of about 24 300 and an atmospheric lifetime of approximately 3 200 years, which means that essentially every kilogram released since the 1960s is still in the atmosphere. Continuous monitoring by the National Oceanic and Atmospheric Administration shows the global mean dry-air mole fraction rising from about 1 ppt in 1980 to more than 12 ppt today, with an annual increment that has not slowed despite four decades of handling improvements. For many transmission system operators, SF₆ leakage is now the dominant component of direct, Scope 1 emissions, in some reported cases exceeding seventy per cent of the total.

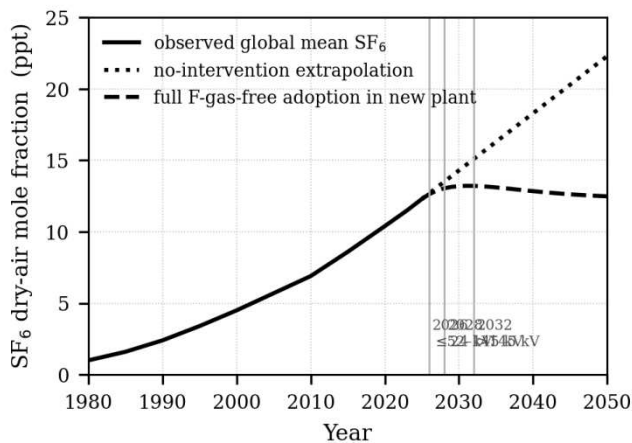


Fig. 1. Observed global mean atmospheric SF₆ dry-air mole fraction with an extrapolation of the present growth rate and a scenario in which all newly commissioned switchgear is F-gas free. Vertical lines mark the voltage-dependent prohibition dates of Regulation (EU) 2024/573.

Regulation has now overtaken voluntary action. Regulation (EU) 2024/573 on fluorinated greenhouse gases, in force since 11 March 2024, prohibits the commissioning of new switchgear that relies on fluorinated gases for insulation or interruption according to a voltage-dependent timetable: from 1 January 2026 for equipment up to and including 24 kV, from 1 January 2028 for equipment above 52 kV up to and including 145 kV at short-circuit currents up to 50 kA, from 1 January 2030 for the 24 kV to 52 kV range, and from 1 January 2032 for the remaining high-voltage equipment, in each case where the gas has a global warming potential of one or more. From 2035 only reclaimed or recycled SF₆ may be used for servicing. Because transmission switchgear is specified for a forty-year life, equipment ordered today will be operated deep into a regulatory environment in which fluorinated gases are prohibited, restricted in supply and priced for their climate impact.

Two families of replacement have emerged. The first substitutes a fluorinated gas of lower potency, typically a fluoronitrile (C₄F₇N, commonly written C₄-FN) or a fluoroketone in a carrier of carbon dioxide and oxygen, achieving a global warming potential in the region of a few

hundred rather than tens of thousands. The second eliminates fluorinated chemistry altogether by separating the two functions that SF₆ performs: interruption is assigned to a vacuum interrupter and insulation to clean synthetic air, a mixture of about 80 % nitrogen and 20 % oxygen at elevated pressure. This second approach, marketed in the industry under the "blue" designation and referred to throughout this work as blue technology, has a global warming potential of exactly zero, an ozone depletion potential of zero, and no decomposition by-products requiring specialised handling.

B. Problem Statement

Adopting blue technology is not a substitution of one gas for another. Clean air has roughly one third of the dielectric strength of SF₆ at equal pressure and a substantially lower volumetric heat capacity, so the entire electrical, thermal and mechanical design of the bay changes. Utilities and consultants preparing specifications therefore face a set of coupled questions that are rarely answered together in one place: how much larger and how much more highly pressurised must the enclosure be; whether vacuum interruption retains adequate margin against the transient recovery voltage at transmission voltages; what the continuous current rating penalty is; whether the additional aluminium and the higher capital cost are repaid by the avoided gas emissions and handling burden; and how the resulting trade-off should be scored when climate, cost, reliability and footprint all matter simultaneously.

C. Aim, Objectives and Scope

The aim of this thesis is to develop and apply an integrated engineering model of blue switchgear technology for sustainable power transmission, sufficient to support specification and investment decisions at transmission voltages. The specific objectives are to: (i) formulate a dielectric design model that relates the clean-air gap, pressure and enclosure geometry to the standard insulation levels of IEC 60071-1; (ii) formulate a switching model that verifies vacuum interruption against the transient recovery voltage envelopes of IEC 62271-100; (iii) formulate an electro-thermal model that quantifies the continuous current rating penalty of clean air; (iv) construct a cradle-to-grave life-cycle and techno-economic model consistent with ISO 14040 and ISO 14044; (v) propose a system architecture that integrates the primary plant with a digital monitoring layer and a carbon-accounting layer; and (vi) combine the results in a transparent multi-criteria sustainability index.

The scope is the 145 kV, 40 kA, 2 500 A gas-insulated bay, which is the segment the European timetable reaches first at transmission level and the segment for which commercial blue equipment is most mature. Extension to 420 kV is treated analytically but not validated. The models are deterministic and analytical, calibrated against published material properties and standard test requirements; they are intended to reproduce design trends and orders of magnitude, not to replace type testing or three-dimensional field computation.

D. Contribution and Organisation

The principal contribution is the coupling, within a single consistent parameter set, of the physical design of a clean-air and vacuum bay with its life-cycle carbon and economic performance, and the demonstration that the resulting investment case is dominated by capital premium and operational compliance cost rather than by carbon price — a result that is frequently assumed in the opposite sense. A second contribution is the four-layer architecture of Section VI, which makes the carbon account a measured quantity derived from the same sensor set that supports condition-based maintenance. Section III reviews the state of the art. Section IV establishes the physical principles of blue technology. Section V develops the mathematical model. Section VI presents the system architecture and Section VII the methodology. Section VIII reports results, Section IX applies them to a case study, Section X discusses limitations, and Section XI concludes.

III. REVIEW OF THE STATE OF THE ART

A. Dielectric Behaviour of SF₆ and Its Alternatives

The dielectric superiority of SF₆ originates in the large electron-attachment cross-section of the molecule, which removes free electrons from the developing avalanche. Christophorou and Olthoff compiled the electron-interaction data that underpin the accepted critical reduced field of about 360 Td, corresponding to a uniform-field strength near 89 kV·cm⁻¹·bar⁻¹ at 20 °C. Air, having no strongly electronegative constituent other than oxygen, sustains about 24.4 kV·cm⁻¹·bar⁻¹ under the classical Schumann relation, a ratio close to one third. Carbon dioxide and CO₂/O₂ mixtures improve on air only marginally, while fluoronitrile mixtures at the concentrations permitted by their liquefaction temperature reach roughly 80 % to 90 % of SF₆.

A recurring finding in the literature, and one central to this thesis, is that the ratio of intrinsic strengths overstates the practical penalty. Cookson and later authors established that compressed SF₆ is exceptionally sensitive to conducting particles, electrode surface roughness and the area effect, so that practical GIS is designed at only about a quarter to a third of the intrinsic uniform-field strength. Air and its mixtures degrade far less under the same defects, so the effective design ratio is nearer one half than one third. Rabie and Franck screened several thousand candidate molecules against dielectric strength, boiling point, toxicity and global warming potential and concluded that no single substance reproduces the SF₆ property set, which supports the functional separation adopted by blue technology.

B. Vacuum Interruption at Transmission Voltage

Vacuum interruption has been the dominant medium-voltage technology for four decades. Its physics, set out comprehensively by Slade and by Greenwood, rests on the rapid dispersal of the metal-vapour plasma at current zero: because there is no gas to be de-ionised, the dielectric strength of the gap is re-established within microseconds, an order of magnitude faster than in gas. The historical barrier at transmission voltage was not interruption but withstand: a single vacuum gap saturates in withstand capability beyond

roughly 60 mm of contact separation, so 145 kV requires careful contact and shield design and 420 kV generally requires two interrupters in series. Axial magnetic field contacts, which hold the arc in the diffuse mode up to 40 kA and above, were the enabling development. Field experience reported for 145 kV and 245 kV vacuum circuit-breakers, and more recently for a 252 kV outdoor vacuum breaker with nitrogen insulation in service since 2024, confirms that the technology is no longer experimental at these ratings.

C. Non-SF₆ Switchgear in Service

Three commercial routes are now in service at transmission voltage. Fluoronitrile mixtures are used in gas-insulated lines and switchgear up to 420 kV, retaining gas-blast interruption and therefore compact dimensions, at the cost of a residual global warming potential, a liquefaction temperature that constrains the mixing ratio in cold climates and continuing fluorinated-chemistry supply and disposal obligations. Carbon dioxide and oxygen mixtures are used by several manufacturers for both insulation and interruption in outdoor breakers at 145 kV and 420 kV with dimensions comparable to SF₆. Clean air with vacuum interruption — blue technology — has been supplied for 145 kV gas-insulated switchgear since 2017 and has been extended to 420 kV. Comparative assessments by CIGRE working groups conclude that all three routes can meet the rating and testing requirements of IEC 62271, and that the differentiators are footprint, life-cycle emissions, handling obligation and long-term regulatory exposure rather than functional capability.

D. Life-Cycle and Techno-Economic Studies

Published life-cycle assessments of gas-insulated switchgear agree that for SF₆ equipment the use phase dominates, that the dominant use-phase term is leakage rather than ohmic loss, and that the end-of-life recovery efficiency is a decisive and poorly evidenced parameter. Reported leakage rates span an order of magnitude, from the 0.1 % per year achievable in sealed-pressure systems to the one to two per cent per year historically measured in older installations. Regulation (EU) 2024/573 itself exempts equipment from periodic leak checking only where the tested rate is below 0.1 % per year or where density monitoring with automatic alerting is fitted, which makes the monitored density signal both an environmental and a compliance instrument. Techno-economic comparisons are sparser and generally assume a strong carbon-price effect; one purpose of Section VIII is to test that assumption quantitatively.

E. Research Gap

The literature treats the dielectric, switching, thermal, environmental and economic aspects of SF₆ replacement largely in separate publications, each with its own reference design and assumptions, which makes the trade-offs difficult to combine. There is no widely available treatment that begins from the same 145 kV bay, derives the clean-air geometry from first principles, verifies the switching duty against the standard envelope, carries the resulting mass and loss figures into a life-cycle inventory and a discounted cash-flow model,

and closes with an explicit, auditable multi-criteria decision. This thesis addresses that gap.

IV. PRINCIPLES OF BLUE TECHNOLOGY

A. Functional Separation

The defining idea of blue technology is that the two duties conflated in SF₆ are separated and each assigned to the medium that performs it best without environmental penalty. Current interruption, which requires extremely rapid recovery of dielectric strength after an arc, is assigned to a sealed vacuum interrupter. Continuous insulation of the busbar, disconnectors, earthing switches and instrument transformers, which requires only a high and stable withstand capability, is assigned to clean air at elevated pressure. Neither medium contains a fluorinated compound, so the bay has no Scope 1 emission, no fluorinated decomposition products, no gas-handling certification requirement and no end-of-life recovery obligation beyond ordinary pressure-vessel practice.

B. The Vacuum Interrupter

A vacuum interrupter is a sealed ceramic or glass envelope evacuated below 10^{-4} Pa containing a fixed and a moving contact, a metal bellows that permits contact travel without breaking the seal, and a metal-vapour shield that condenses the eroded contact material and protects the insulating envelope. At contact separation the current is carried by a metal-vapour plasma generated at cathode spots in a copper-chromium contact alloy. Above a few kiloamperes the diffuse arc tends to constrict into a damaging columnar mode, and the function of the axial magnetic field produced by slotted or coil-type contacts is to suppress that constriction so that erosion remains uniform up to the full rated short-circuit current.

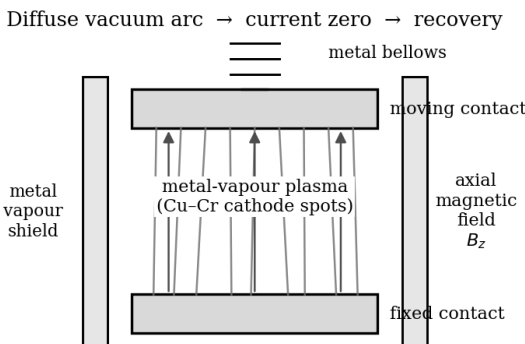


Fig. 2. Diffuse vacuum arc between axial-magnetic-field contacts. The axial field B_z maintains the diffuse mode up to the rated short-circuit current,

distributing erosion over the contact face; the metal-vapour shield condenses eroded material and protects the ceramic envelope.

At current zero the plasma is not de-ionised in the gaseous sense; it is removed, because the residual metal vapour condenses on the shield and contacts within microseconds. A positive-ion sheath grows in front of the post-arc cathode as the recovery voltage is applied, and the interrupter withstands that voltage once the sheath exceeds the thickness required for the instantaneous stress. This mechanism gives the vacuum gap a dielectric-recovery rate one to two orders of magnitude above the rate of rise of the recovery voltage imposed by the network, which is quantified in Section V-B. The practical consequences are a mechanical endurance of 10 000 operations or more, an electrical endurance class of E2 requiring no contact maintenance for the design life, and a stored energy requirement small enough for a compact spring or magnetic actuator.

C. Clean Air as the Insulating Medium

Clean air in this context is synthetic, dried and filtered air, typically 80 % nitrogen and 20 % oxygen by volume, free of moisture and particulates and supplied at a nominal 6 to 7 bar absolute. Oxygen is retained deliberately rather than using pure nitrogen: it suppresses the formation of nitrogen oxides in the event of an internal discharge and improves the behaviour of the mixture under partial discharge. The medium is non-toxic, non-flammable, does not liquefy at any temperature encountered in service, requires no recovery equipment, and can be replenished on site from a compressor and drier rather than from certified gas cylinders. The compensating requirements are a larger gap and a higher pressure, hence a larger and mechanically heavier enclosure, and a pressure-vessel design in a higher class.

D. Constructional Consequences

Fig. 3 shows the resulting bay. The earthed aluminium enclosure contains the high-voltage conductor supported on cast-resin barrier and support spacers, with the vacuum interrupter, a three-position disconnector and earthing switch, current and voltage sensors, and cable sealing ends or bushings at the terminations. Two features distinguish it from an SF₆ bay beyond its dimensions. First, the density monitor is no longer a gas-loss alarm for an expensive and regulated fluid but a simple mechanical integrity signal, since the medium itself is free and harmless; its role shifts from environmental compliance to insulation coordination. Second, the vacuum interrupter is a sealed sub-assembly whose remaining life can be inferred from contact travel, arcing time and accumulated interrupted current, which makes the bay naturally amenable to condition-based rather than time-based maintenance.

Earthed aluminium enclosure – clean air (80 % N₂ / 20 % O₂) at 6.6 bar absolute

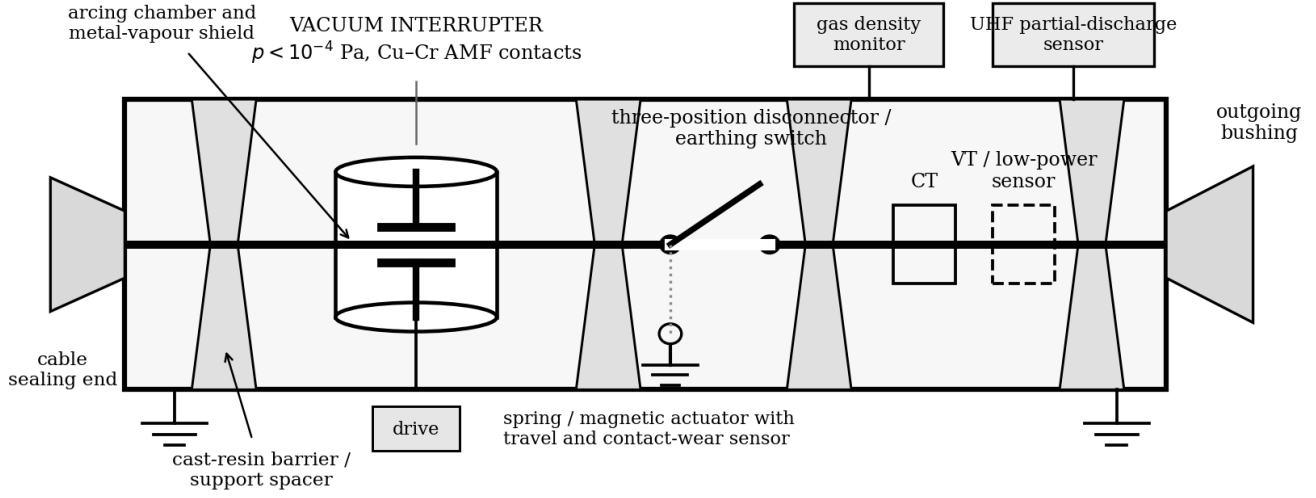


Fig. 3. Longitudinal section of the 145 kV blue gas-insulated bay. Interruption is performed by the sealed vacuum interrupter; all continuous insulation is provided by clean air at 6.2 bar absolute, supported by cast-resin barrier spacers. The density monitor and the UHF partial-discharge sensor feed the digital layer of Fig. 9.

V. MATHEMATICAL MODEL

This section develops the analytical model used throughout the thesis. It is organised as the design sequence itself: dielectric dimensioning, switching verification, thermal rating, life-cycle inventory, economics, reliability and finally the aggregation into a single decision index.

A. Dielectric Model

Breakdown in a compressed electronegative or weakly electronegative gas under the conditions of gas-insulated switchgear is governed by the streamer criterion. An avalanche launched at the highly stressed electrode becomes self-propagating when the space charge it accumulates reaches a critical number N_{cr} , so that

$$\int_0^{x_{cr}} (\alpha - \eta) dx = \ln N_{cr} = K \quad (1)$$

where α and η are the Townsend ionisation and attachment coefficients and K is approximately 10.5 for SF₆ and 9.15 for air. In the neighbourhood of the critical field the effective ionisation coefficient is very nearly linear in the reduced field,

$$(\alpha - \eta)/N = k[(E/N) - (E/N)_{cr}] \quad (2)$$

so that for a uniform field the withstand stress is fixed by the critical reduced field alone, and for a slightly non-uniform field the classical Schumann form applies:

$$U_b = [(E/p)_{cr} + C/\sqrt{pd}] \cdot pd \quad (3)$$

with $(E/p)_{cr}$ equal to 88.5 kV·cm⁻¹·bar⁻¹ for SF₆, 74 for a 6 % C₄-FN mixture in CO₂/O₂, 25.6 for CO₂/O₂ and 24.4 for clean air, and C taken as 10.5, 9.6, 6.8 and 6.5

(kV·cm⁻¹·bar⁻¹)·(bar·cm)^{0.5} respectively. Gas density rather than pressure is the physically correct variable, so all pressures are referred to 20 °C through the relative density

$$\delta = (p/p_0)(T_0/T) \quad (4)$$

Equation (3) is plotted in Fig. 4 against the reduced gap. The Townsend–Paschen solution for air is shown for comparison and coincides with the Schumann line above about 0.1 bar·cm, confirming that the streamer form is the appropriate one in the range of interest.

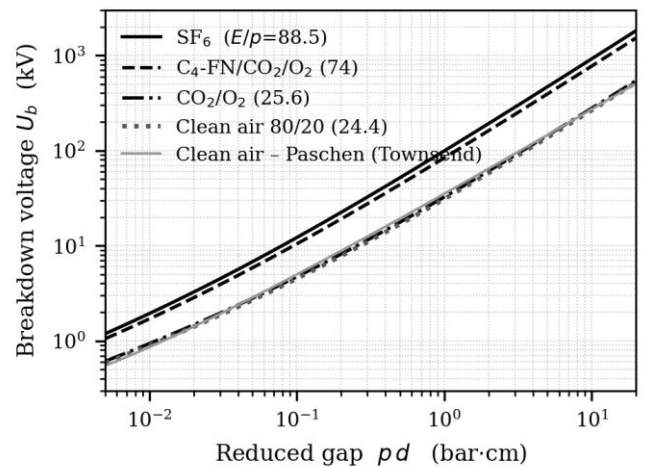


Fig. 4. Uniform-field breakdown voltage against reduced gap for SF₆, a fluoronitrile mixture, CO₂/O₂ and clean air, computed from (3). The Townsend–Paschen curve for air is shown for reference; the two formulations agree above about 0.1 bar·cm.

The gas-insulated bay is a coaxial system, in which the field at radius x between a conductor of radius r and an enclosure of radius R is

$$E(x) = U / [x \ln(R/r)], \quad E_{\max} = U / [r \ln(R/r)] \quad (5)$$

The non-uniformity is expressed by the Schwaiger field-utilisation factor, the ratio of the mean to the maximum stress,

$$\eta_s = E_{\text{mean}}/E_{\max} = r \ln(R/r) / (R - r) \quad (6)$$

Differentiating (5) at fixed enclosure radius shows that the maximum stress is minimised when

$$r/R = 1/e = 0.368, \quad E_{\max, \min} = eU/R \quad (7)$$

at which $\eta_s = 0.582$. Fig. 5 shows the utilisation factor and the normalised peak stress against the radius ratio; the optimum is shallow, so that any ratio between roughly 0.30 and 0.45 costs less than five per cent in peak stress, which leaves useful freedom for the thermal and mechanical design.

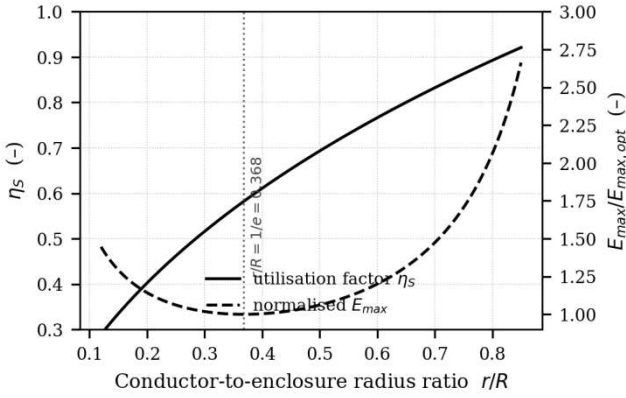


Fig. 5. Schwaiger field-utilisation factor and normalised maximum stress of the coaxial geometry against the conductor-to-enclosure radius ratio, from (5) to (7). The optimum at $r/R = 1/e$ is shallow.

The intrinsic strength of (3) is never realised in practice. Conducting particles, electrode surface roughness, the statistical area effect and spacer surface flashover reduce the achievable stress to a fraction of the intrinsic value, and that fraction differs strongly between gases because SF_6 is far more particle-sensitive than air. Introducing a design derating factor k_d calibrated on service experience, the design withstand is

$$U_w = \eta_s k_d U_b(\delta, d) \quad (8)$$

with k_d taken as 0.28 for SF_6 , 0.30 for the fluoronitrile mixture and 0.45 for clean air. Solving (8) for the pressure required to meet a 650 kV lightning impulse withstand level as a function of the gap gives the design chart of Fig. 6. The scatter of breakdown voltage about the design value is represented by a three-parameter Weibull distribution,

$$P(U) = 1 - \exp\{-[(U - U_0)/\alpha_w]^{\beta^*}\} \quad (9)$$

and the dependence of withstand on stressed area, which governs the extrapolation from laboratory electrodes to a full enclosure, follows the enlargement law

$$U_1/U_2 = (A_2/A_1)^{1/\beta^*} \quad (10)$$

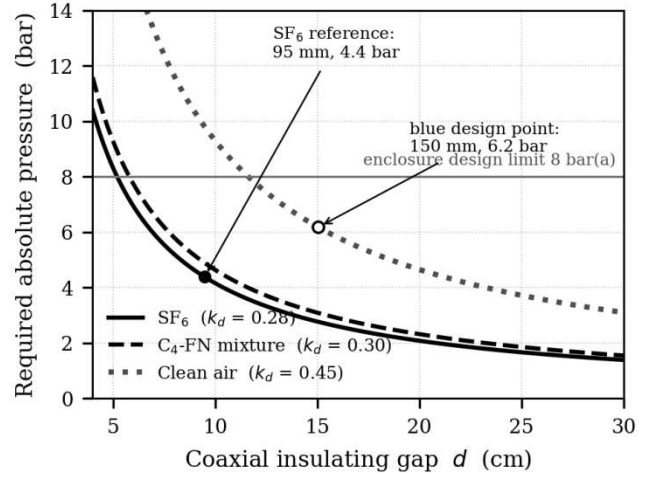


Fig. 6. Absolute pressure required to achieve a 650 kV lightning impulse withstand level as a function of the coaxial gap, from (3), (6) and (8), for the three media with their respective design derating factors. The blue design point is a 150 mm gap at 6.2 bar; the SF_6 reference is 95 mm at 4.4 bar.

B. Switching Model

Interruption in vacuum is verified by comparing the dielectric recovery of the gap with the transient recovery voltage imposed by the network. Following the Andrews–Varey treatment, the positive-ion sheath that forms in front of the post-arc cathode grows as

$$s(t) = [2\varepsilon_0 u(t) / (e n_i)]^{1/2} \quad (11)$$

where n_i is the residual ion density, and the post-arc current that flows while the sheath develops is

$$i_{\text{pa}}(t) = e n_i v_i A_s [1 - s(t)/s_{\max}] \quad (12)$$

Successful interruption requires that the sheath withstand capability exceed the applied stress at every instant. Because the residual plasma decays within a few microseconds, the recovery capability is well approximated over the interval of interest by a linear rate k_r , so that the interruption criterion and its margin are

$$m = \min_t [k_r t / u(t)] > 1 \quad (13)$$

The applied stress is the standard two-parameter transient recovery voltage of IEC 62271-100. For the terminal-fault test duty T100 the prospective recovery voltage is represented by

$$u(t) = (u_c/2)[1 - \cos(\pi t/t_3)] \quad (14)$$

$$u_c = k_{\text{pp}} k_{\text{af}} \sqrt{(2/3)} U_r \quad (15)$$

$$\text{RRRV} = u_c/t_3 \quad (16)$$

where k_{pp} is 1.3 for an effectively earthed 145 kV system and k_{af} is 1.4. Fig. 7 shows the arc current and arc voltage through the final loop and the onset of the recovery voltage; Fig. 8 compares the prospective recovery voltage, the standard envelope and the vacuum recovery characteristic. Contact erosion, which determines electrical endurance, is accumulated as

$$\Sigma W_{\text{arc}} = \Sigma \int u_a i \, dt \cong u_a \Sigma \int |i| \, dt \quad (17)$$

with the arc voltage u_a of a diffuse vacuum arc taken as a nearly constant 20 to 30 V, which is the physical reason why vacuum interruption dissipates one to two orders of magnitude less energy per operation than gas-blast interruption.

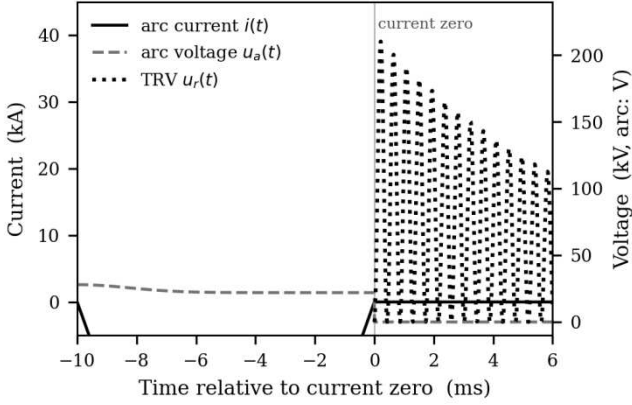


Fig. 7. Final current loop and arc voltage of the vacuum interrupter, with the onset of the transient recovery voltage after current zero. The nearly constant arc voltage of a diffuse vacuum arc keeps the arc energy of (17) very low.

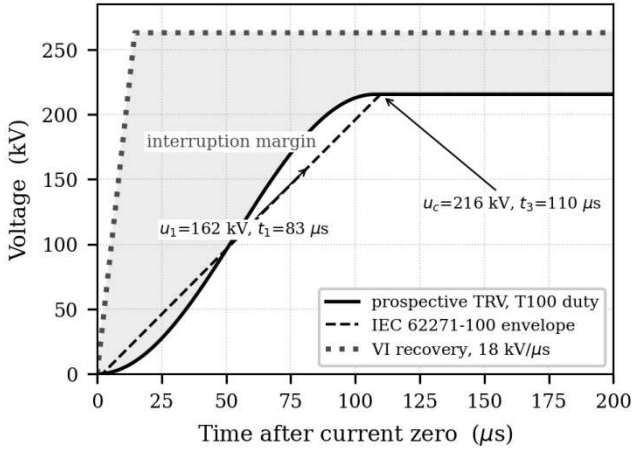


Fig. 8. Prospective transient recovery voltage for the T100 duty at 145 kV from (14) to (16), the IEC 62271-100 two-parameter envelope, and the dielectric recovery characteristic of the vacuum gap. The shaded area is the interruption margin of (13).

C. Electro-Thermal Model

The continuous current rating follows from the steady-state heat balance of the conductor inside the enclosure. Neglecting axial conduction,

$$3 P R(\theta) = h A_s(\theta_c - \theta_a) + \varepsilon \sigma A_s(T_c^4 - T_a^4) \quad (18)$$

$$R(\theta) = R_{20}[1 + \alpha_{20}(\theta - 20)] \quad (19)$$

The convective coefficient is obtained from the Rayleigh number of the enclosed gas,

$$Ra = g\beta\Delta\theta L^3 \rho^2 c_p / (\mu k), \quad Nu = C Ra^n, \quad h = Nu k/L \quad (20)$$

Since Ra varies as the square of the density, the ratio of the convective coefficients of two media at their respective service densities is

$$h_{air}/h_{SF6} = [(\rho_{air}/\rho_{SF6})^2 (c_{p,air}/c_{p,SF6}) (k_{air}/k_{SF6})^3 (\mu_{SF6}/\mu_{air})]^{1/4} \quad (21)$$

Evaluating (21) with SF_6 at 4.4 bar (density $26.4 \text{ kg}\cdot\text{m}^{-3}$, c_p $665 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) and clean air at 6.2 bar ($7.38 \text{ kg}\cdot\text{m}^{-3}$, $1005 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) gives a ratio of about 0.72: clean air removes roughly three quarters of the heat that SF_6 removes for the same geometry and temperature rise. Restoring the rating therefore requires the conductor cross-section to be increased, since from (18) and (19) the temperature rise scales approximately as

$$\Delta\theta \propto [P / (A_c h)]^{0.8} \quad (22)$$

D. Life-Cycle Model

The cradle-to-grave inventory is assembled per functional unit, defined as one 145 kV bay operated for 40 years, in accordance with ISO 14040 and ISO 14044. The total global warming potential is

$$G_{tot} = G_{mfg} + G_{leak} + G_{loss} + G_{col} \quad (23)$$

with the use-phase gas term and the end-of-life gas term

$$G_{leak} = m_g \cdot GWP \cdot r_a \cdot T_s \quad (24)$$

$$G_{col} = m_g(1 - r_a T_s)(1 - \eta_{rec}) \cdot GWP + G_{mat} \quad (25)$$

and the loss term derived from the ohmic energy dissipated over the life,

$$G_{loss} = 3 I_f^2 R_{dc} k_f LF^2 \cdot 8760 \cdot T_s \cdot EF \quad (26)$$

where LF is the load factor, k_f the skin- and proximity-effect factor and EF the grid emission factor. The climate benefit of replacing a gas of high potency by additional material is meaningful only if the embodied carbon of that material is repaid, which defines a carbon payback time

$$T_{pb} = (G_{mfg,blue} - G_{mfg,SF6}) / (m_g \cdot GWP \cdot r_a) \quad (27)$$

E. Techno-Economic Model

The life-cycle cost is evaluated as a net present value over the service life at a real discount rate r ,

$$NPV = C_{cap} + \sum_{t=1}^{N^*} [C_{om,t} + C_{gas,t} + G_a p_c(1+g)^t] / (1+r)^t \quad (28)$$

where G_a is the annual emission and p_c the carbon price escalating at g . Where the two technologies differ only in capital cost, annual operating cost and annual emission, the net present advantage of blue technology reduces to a compact form in which the annuity factor makes the structure of the result transparent:

$$\Delta NPV = (\Delta C_{om} + \Delta G_a p_c) \cdot AF(r, N) - \Delta C_{cap} \quad (29)$$

$$AF(r, N) = [1 - (1+r)^{-N^*}] / r \quad (30)$$

F. Reliability Model

Availability is evaluated from a two-state Markov representation of the bay in which the failure rate is reduced and the repair time shortened in proportion to the condition-monitoring coverage c :

$$\lambda(c) = \lambda_0 + \lambda_g(1 - \kappa c), \quad MTTR(c) = MTTR_0(1 - \nu c) \quad (31)$$

$$A = MTBF / (MTBF + MTTR) = [1/\lambda] / [1/\lambda + MTTR] \quad (32)$$

where λ_g is the component of the failure rate attributable to loss of insulating medium, κ the detection effectiveness and ν the reduction in repair time obtained from advance warning.

G. Multi-Criteria Aggregation

The criteria are made commensurate by min–max normalisation, benefit criteria taking the first form and cost criteria the second,

$$\hat{x}_k = (x_k - x_{k,\min}) / (x_{k,\max} - x_{k,\min}), \quad \hat{x}_k = 1 - (\cdot) \quad (33)$$

and aggregated with weights obtained from a pairwise-comparison matrix by the analytic hierarchy process:

$$S = \sum_{k=1}^{*K} w_k \hat{x}_k, \quad \sum w_k = 1 \quad (34)$$

$$CR = CI/RI, \quad CI = (\lambda_{\max} - K) / (K - 1) \quad (35)$$

A consistency ratio CR below 0.10 is required for the weight vector to be accepted.

VI. SYSTEM ARCHITECTURE

A sustainable transmission system is not obtained by exchanging one component for another; the environmental performance has to become an observable, reported quantity of the asset. The architecture proposed here therefore organises the substation into four layers, shown in Fig. 9, in which the same measurements that support protection and condition-based maintenance also produce the carbon account and the compliance record.

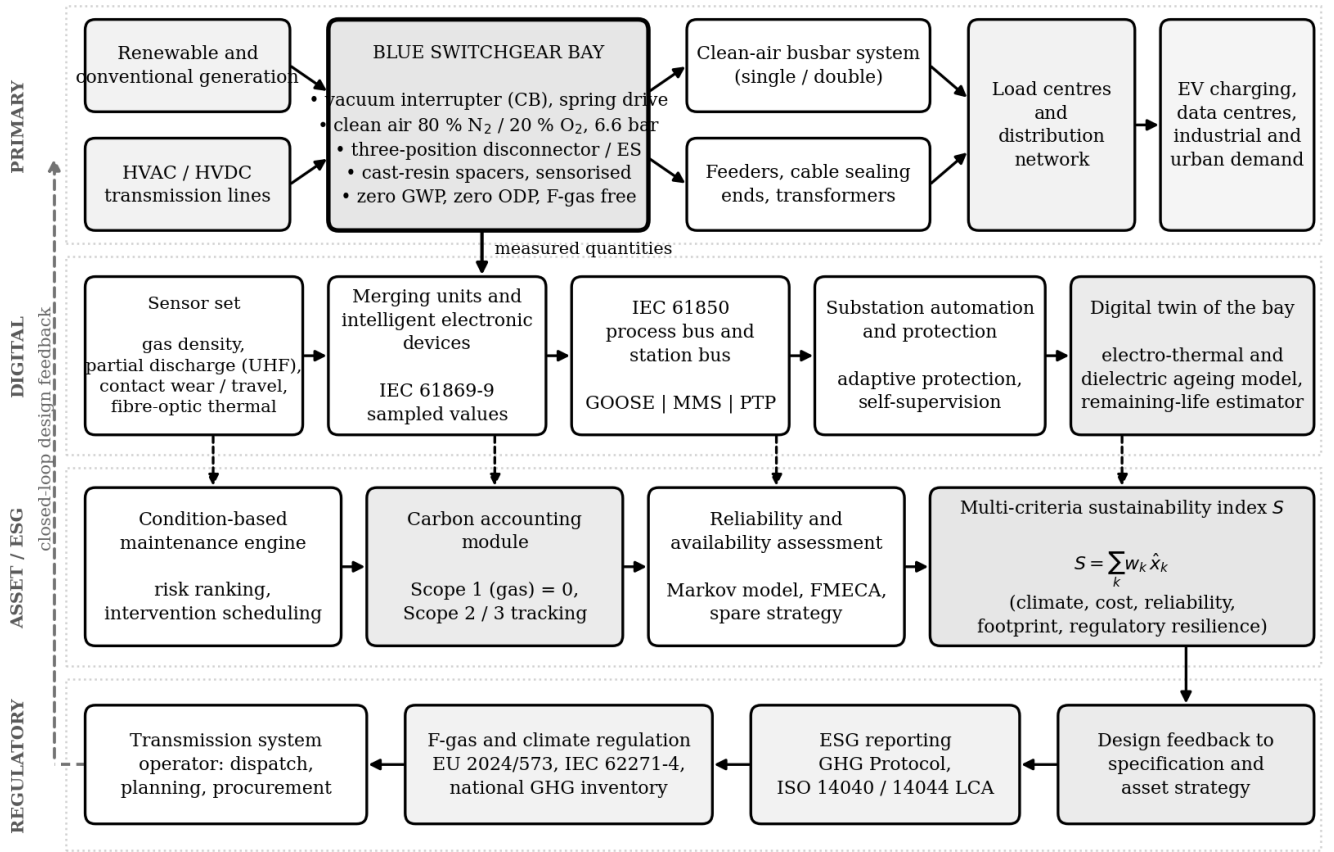


Fig. 9. Four-layer architecture of a transmission system built on blue switchgear. The primary layer contains no fluorinated gas; the digital layer converts the bay into an observable asset; the asset and sustainability layer converts those observations into maintenance, carbon and reliability decisions; and the regulatory interface closes the loop onto specification and procurement.

A. Primary Layer

The primary layer comprises the blue bays themselves, the clean-air busbar system, the feeders and terminations, and the connected generation and load. Its defining property is the absence of any fluorinated gas, which removes the bay from the scope of Regulation (EU) 2024/573 entirely rather than merely reducing its exposure. Scope 1 emission of the

substation becomes structurally zero: not a low number that must be measured, estimated and reported, but an absence.

B. Digital Layer

The digital layer instruments each bay with a gas-density sensor, a UHF partial-discharge coupler, contact travel and wear transducers on the vacuum interrupter drive, and fibre-optic thermal sensing on the conductor and joints. These feed

merging units that publish sampled values in accordance with IEC 61869-9 onto an IEC 61850 process bus, with GOOSE messaging for protection, MMS for reporting and PTP for time synchronisation. Because the interrupter is a sealed, maintenance-free sub-assembly, the value of the digital layer shifts from detecting gas loss to estimating remaining electrical endurance, which is the quantity that actually governs intervention in a vacuum-based bay.

A digital twin of the bay closes the layer. It runs the electro-thermal model of (18) to (22) against measured current and ambient temperature to estimate conductor temperature where no sensor exists, accumulates the arc energy of (17) to estimate contact erosion, and tracks the density signal against the pressure–temperature locus of Fig. 10 to separate a genuine slow leak from the ordinary thermal excursion of a sealed volume. This last distinction is important: in a clean-air system a density excursion is an insulation-coordination question and not an environmental incident, so the alarm philosophy differs fundamentally from SF₆ practice.

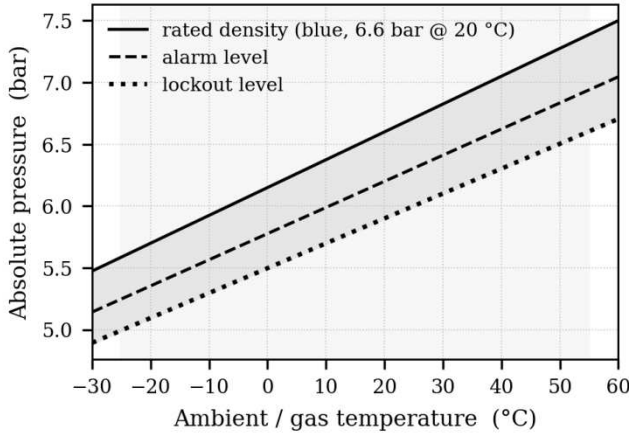


Fig. 10. Density-monitoring operating envelope of the clean-air enclosure. Because dielectric strength follows density rather than pressure, the alarm and lockout thresholds are isodensity loci; the shaded band is the permitted operating region across the ambient range.

C. Asset and Sustainability Layer

This layer converts the measured state of each bay into three decisions. The condition-based maintenance engine ranks bays by the product of estimated failure probability and consequence, replacing fixed intervals with evidence. The carbon-accounting module evaluates (23) to (26) continuously, using measured load for the loss term; for a blue bay the gas term is identically zero, so the reported figure is dominated by the ohmic loss and is reduced by grid decarbonisation rather than by maintenance practice. The reliability assessment evaluates (31) and (32) with the monitoring coverage actually achieved, which allows the value of additional sensing to be tested against its cost rather than assumed.

D. Regulatory Interface

The outermost layer serves the transmission system operator, the F-gas and climate regulator, and the corporate sustainability report. Its function in the architecture is to feed

the evidence back into specification and procurement, so that observed leakage, observed availability and observed loss modify the next technical specification instead of remaining in an annual report. This feedback path is drawn explicitly in Fig. 9 because it is the mechanism by which a fleet, rather than a single bay, becomes sustainable.

VII. METHODOLOGY AND REFERENCE DESIGN

The models of Section V are applied in the sequence of Fig. 11 to a single functional unit: one 145 kV, 40 kA, 2 500 A gas-insulated bay with a 650 kV lightning impulse and 275 kV power-frequency withstand level, operated for 40 years at a load factor of 0.6. The same functional unit is dimensioned three times, once for each medium, so that every downstream result is attributable to the medium and not to a difference in duty.

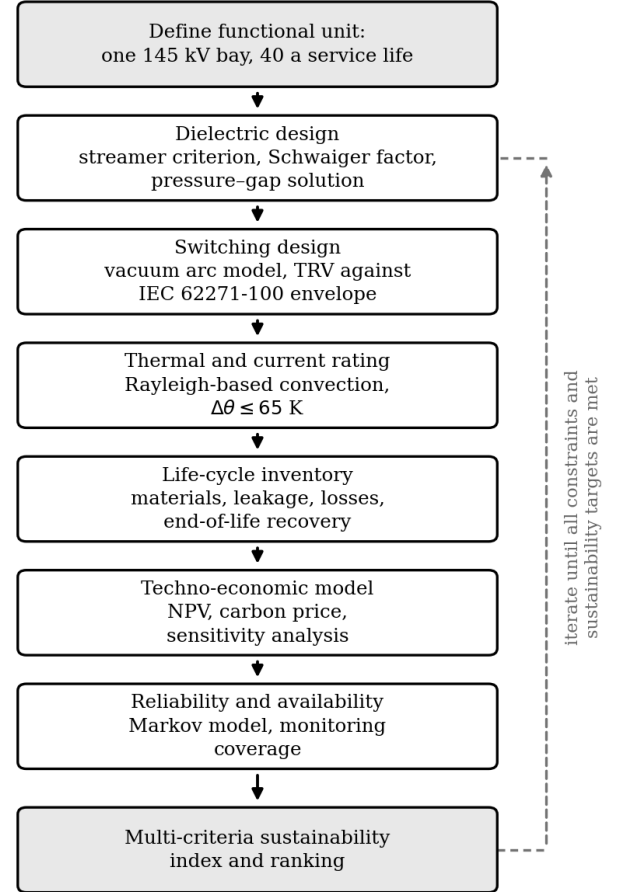


Fig. 11. Methodology. The design loop is iterated until the dielectric, switching and thermal constraints are satisfied simultaneously, after which the resulting geometry and mass feed the life-cycle, economic and reliability models.

TABLE I PROPERTIES OF THE CANDIDATE INSULATING AND INTERRUPTING MEDIA				
Property	SF ₆	C ₄ -FN mix	CO ₂ /O ₂	Clean air

Property	SF ₆	C ₄ -FN mix	CO ₂ /O ₂	Clean air
(E/p) _{cr} (kV/cm·bar)	88.5	74	25.6	24.4
GWP (100 a, AR6)	24 300	≈ 327	1	0
Ozone depletion potential	0	0	0	0
Atmospheric lifetime (a)	≈ 3 200	≈ 30	—	—
Liquefaction limit	− 30 °C	mix-limited	none	none
Toxic by-products	yes (S ₂ F ₁₀ , SOF ₂)	yes	CO	none
Recovery obligation	mandatory	mandatory	none	none
On-site replenishment	certified only	certified only	possible	compressor
Interrupting duty	gas blast	gas blast	gas blast	vacuum

Table I summarises the media properties used as inputs. Table II gives the reference design data common to all three variants. The dielectric loop solves (8) for the smallest enclosure that satisfies the withstand requirement at the optimum radius ratio of (7); the switching loop verifies (13) against the standard duties; the thermal loop applies (18) to (22) and returns the conductor cross-section to the dielectric loop if the temperature-rise limit is violated. Convergence is typically reached in two iterations because the enlarged conductor demanded by the thermal model is, for clean air, already implied by the enlarged radius demanded by the dielectric model.

TABLE II
REFERENCE BAY DESIGN DATA

Parameter	Symbol	Value
Rated voltage	U _r	145 kV
Lightning impulse withstand	LIWL	650 kV
Power-frequency withstand	U _d	275 kV
Rated short-circuit current	I _{sc}	40 kA
Rated continuous current	I _r	2 500 A
First-pole-to-clear factor	k _{pp}	1.3
Service life	T _s	40 a
Load factor	LF	0.6
Ambient design temperature	θ _a	− 5 to + 50 °C
Grid emission factor	EF	0.40 kg CO ₂ /kWh
Real discount rate	r	6 % per year
Carbon price (year 1)	pc	45 USD/t, + 6 %/a

VIII. RESULTS AND DISCUSSION

A. Dielectric Dimensioning

Solving (3), (6) and (8) for the 650 kV withstand requirement gives the design chart of Fig. 6 and the geometry of Table III. Clean air requires a 150 mm coaxial gap at 6.2 bar absolute against 95 mm at 4.4 bar for SF₆; the fluoronitrile mixture falls between at 105 mm and 4.6 bar. Holding the optimum radius ratio of (7) in every case, the enclosure internal diameter grows from 301 mm to 475 mm, an increase of 58 %, and the enclosed cross-sectional area by a factor of 2.5. The maximum conductor stress falls from 11.8 kV/mm to 7.4 kV/mm, which is the quantitative expression of the fact that clean air is operated closer to its intrinsic capability than SF₆, whose practical stress is held far below its intrinsic strength by particle sensitivity.

The larger derating factor assumed for clean air is the single most influential assumption in the dielectric model. If k_d for clean air were reduced from 0.45 to the SF₆ value of 0.28, the required pressure at a 150 mm gap would rise from 6.2 bar to approximately 10 bar, which exceeds the practical enclosure limit and would force the gap beyond 200 mm. This sensitivity, rather than any dispute about the intrinsic strength of air, is what determines whether a clean-air design is feasible at a given voltage, and it is the parameter that type testing must confirm.

TABLE III
DIELECTRIC AND GEOMETRIC DESIGN RESULTS

Quantity	SF ₆	C ₄ -FN	Blue
Design derating factor k_d	0.28	0.30	0.45
Insulating gap d (mm)	95	105	150
Absolute pressure (bar)	4.4	4.6	6.2
Relative density at 20 °C	1.00	1.05	1.41
Conductor radius r (mm)	55	61	87
Enclosure inner dia. (mm)	301	333	475
Max. conductor stress (kV/mm)	11.8	10.6	7.4
Enclosed area (rel.)	1.00	1.22	2.49
Estimated bay footprint (rel.)	1.00	1.06	1.22
Estimated bay mass (rel.)	1.00	1.05	1.35

The statistical picture of Fig. 12 completes the dielectric result. The clean-air gap has a lower Weibull shape parameter, so its breakdown distribution is broader and the withstand level must be set at a larger number of standard deviations below the mean value. This is a real design cost, and it is the reason the derating factor and not the mean strength governs the geometry.

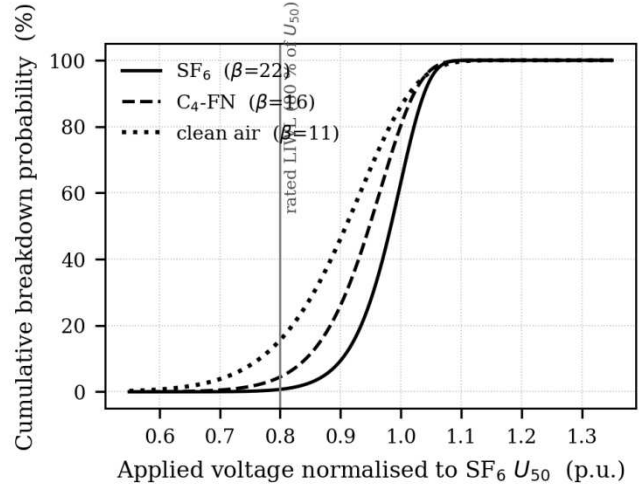


Fig. 12. Weibull breakdown probability of the three media from (9), normalised to the SF₆ fifty-per-cent breakdown voltage. The broader distribution of clean air requires a larger statistical margin between the design and mean values.

B. Switching Verification

Applying (14) to (16) to the standard terminal-fault and out-of-phase duties at 145 kV and comparing with a vacuum

dielectric-recovery rate of 18 kV/ μ s gives Table IV. The minimum transient margin of (13) occurs at the instant the recovery voltage reaches its peak and is 9.0 for the T100 duty; it falls as the duty becomes more severe in rate of rise, reaching 2.6 for the T10 duty, which is the governing case. In every duty the margin exceeds two, and the steady-state withstand margin after the transient has settled is 1.22. The physical reason for this comfortable position is the mechanism itself: the vacuum gap recovers by sheath formation in microseconds, whereas the network imposes a rate of rise measured in single kilovolts per microsecond.

TABLE IV
TRANSIENT RECOVERY VOLTAGE VERIFICATION AT 145 kV

Duty	kpp	kaf	uc (kV)	t3 (μ s)	Margin m
T100	1.3	1.40	215.5	108	9.0
T60	1.3	1.50	230.9	77	6.0
T30	1.3	1.54	237.0	47	3.6
T10	1.3	1.70	261.7	37	2.6
OP2	2.0	1.25	295.9	192	11.7

C. Thermal Rating

Evaluating (21) with the service densities of Table III gives a convective coefficient ratio of 0.72 for clean air relative to SF₆. Fig. 13 shows the resulting temperature rise. With the conductor unchanged, clean air reaches 56.1 K at the rated 2 500 A against 43.2 K for SF₆, and exceeds the 65 K limit of IEC 62271-1 at about 2 700 A. Restoring the rating requires a 28 % increase in conductor cross-section at 2 500 A and 33 % at 3 150 A.

The significant result is that this increase is obtained free of charge. The dielectric optimum of (7) already sets the conductor radius at 87 mm against 55 mm for SF₆, and a tubular conductor of 175 mm outside diameter and 8 mm wall provides 4 197 mm² against 3 142 mm² for a 110 mm by 10 mm tube, an increase of 34 %. The clean-air bay therefore has a lower direct-current resistance per unit length, 6.74 $\mu\Omega$ /m against 9.00 $\mu\Omega$ /m, and consequently lower ohmic losses than its SF₆ equivalent. The thermal penalty of the medium is more than offset by the geometry the dielectric requirement imposes.

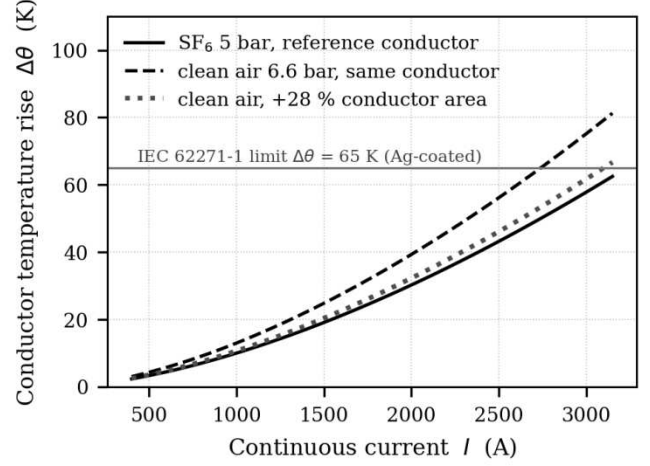


Fig. 13. Conductor temperature rise against continuous current from (18) to (22). Clean air with an unchanged conductor breaches the 65 K limit near 2 700 A; the enlarged conductor that the dielectric design already requires restores the rating with margin.

TABLE V
THERMAL AND LOSS RESULTS

Quantity	SF ₆	Blue	Unit
Gas density at service	26.4	7.38	kg/m ³
Convective coefficient (rel.)	1.00	0.72	–
Conductor tube	110 × 10	175 × 8	mm
Conductor area Ac	3 142	4 197	mm ²
DC resistance	9.00	6.74	$\mu\Omega$ /m
$\Delta\theta$ at 2 500 A	43.2	46.1	K
$\Delta\theta$ at 3 150 A	62.5	66.7	K
Loss-related GWP over 40 a	28.4	26.6	t CO _{2e}

D. Life-Cycle Assessment

Evaluating (23) to (26) with a gas charge of 50 kg of SF₆, 62 kg of fluoronitrile mixture and 70 kg of clean air, a leakage rate of 0.5 % per year, a recovery efficiency of 95 % and the AR6 global warming potential gives Fig. 14 and Table VI. The SF₆ bay accounts for 377 t CO₂-eq over its life, of which 243 t is operational leakage and a further 49 t is the residual charge lost at end of life, so that 77 % of the total burden is the gas. The blue bay accounts for 92 t CO₂-eq, a reduction of 75.7 %, despite 15 % higher embodied carbon in its larger aluminium enclosure.

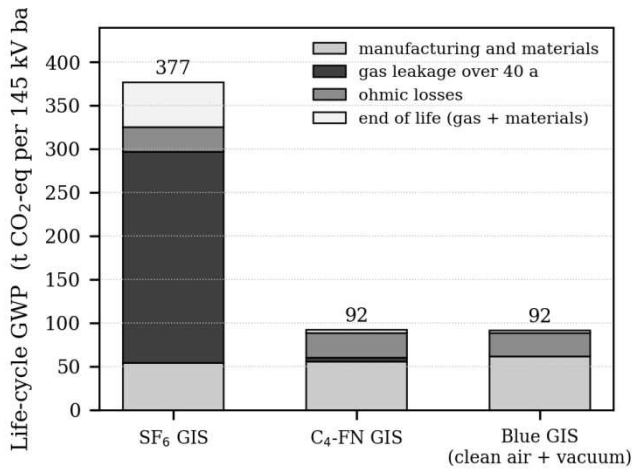


Fig. 14. Cradle-to-grave global warming potential of one 145 kV bay over 40 years, disaggregated by life-cycle stage. Gas leakage and end-of-life release account for 77 % of the SF₆ burden; the blue bay carries none of it.

The carbon payback of (27) is short. The additional 8 t CO₂-eq embodied in the larger enclosure is repaid by the avoided leakage of 6.075 t CO₂-eq per year in approximately sixteen months. Fig. 15 shows the cumulative trajectories: at the end of life the blue bay stands at 89 t against 325 t for the SF₆ bay at the assumed leakage rate and 568 t if the leakage rate is one per cent per year, a figure well within historically reported experience.

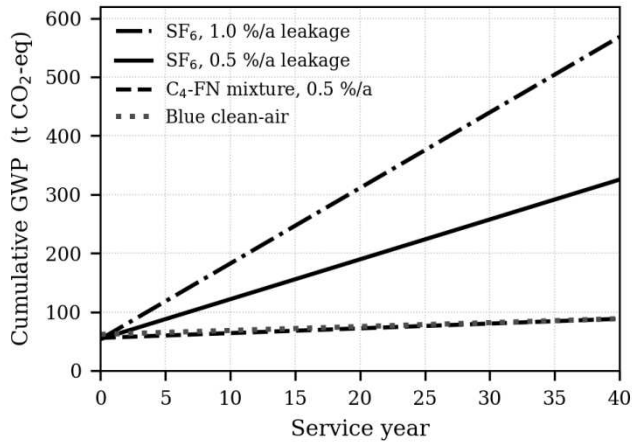


Fig. 15. Cumulative operational global warming potential against service year. The additional embodied carbon of the blue enclosure is repaid within about sixteen months of avoided leakage; the divergence thereafter is governed entirely by the assumed leakage rate.

An honest reading of Table VI must note that the fluoronitrile route reaches 92 t CO₂-eq, statistically indistinguishable from the blue result at this leakage rate. On carbon alone, and at a well-maintained 0.5 % per year, the two alternatives are equivalent. They separate on everything else: the fluoronitrile bay remains inside the scope of fluorinated-gas regulation, retains mandatory recovery, certified handling and leak-checking obligations, carries a decomposition-product hazard, and remains exposed to any future restriction of per- and polyfluoroalkyl substances. The case for blue

technology is therefore only partly a carbon case; it is substantially a regulatory-risk and operational-simplicity case.

TABLE VI
LIFE-CYCLE INVENTORY RESULTS (T CO₂-EQ PER BAY, 40 YEARS)

Life-cycle stage	SF ₆	C ₄ -FN	Blue
Manufacturing and materials	54.0	56.0	62.0
Gas leakage (0.5 %/a)	243.0	4.1	0.0
Ohmic losses	28.4	28.4	26.6
End of life (gas + materials)	51.6	3.8	3.0
Total	377.0	92.3	91.6
Reduction vs SF ₆	—	75.5 %	75.7 %
Gas share of total	77.9 %	5.3 %	0 %

E. Techno-Economic Assessment

The economic result is the least intuitive of the study. With a capital premium of 9.5 %, annual operating costs of 1.65 % of capital cost for the SF₆ bay against 0.82 % for the blue bay, a 6 % real discount rate and a carbon price of 45 USD/t escalating at 6 % per year, the cumulative net present values cross at service year 19 and the blue bay ends the 40-year life 3.9 % of capital cost ahead, as shown in Fig. 16. On a bay costing 1.2 million USD this is an advantage of about 47 000 USD.

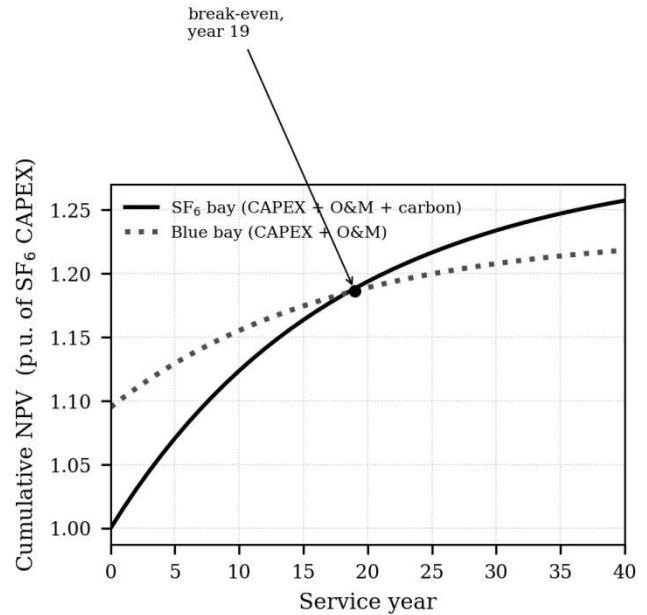


Fig. 16. Cumulative discounted life-cycle cost of the two bays, normalised to the capital cost of the SF₆ bay. The 9.5 % capital premium of the blue bay is recovered from lower operating cost by service year 19.

Decomposing (29) explains the shape of the result. The annuity factor at 6 % over 40 years is 15.05, so the operating-cost differential of 0.0083 per unit per year contributes 0.125 per unit of present value, against a capital premium of 0.095 per unit. The carbon term contributes only 0.004 per unit, a tenth of the advantage, because 6.075 t CO₂-eq per year priced at even 150 USD/t is less than 0.1 % of the capital cost of the bay annually. This is the central economic finding: at plausible

carbon prices, the internalised cost of SF₆ emission is far too small to drive the investment. What drives it is the avoided cost of certified gas handling, leak checking, record keeping, recovery at end of life and the personnel qualification that all of these require — and, above all, the regulatory prohibition itself, which removes the choice.

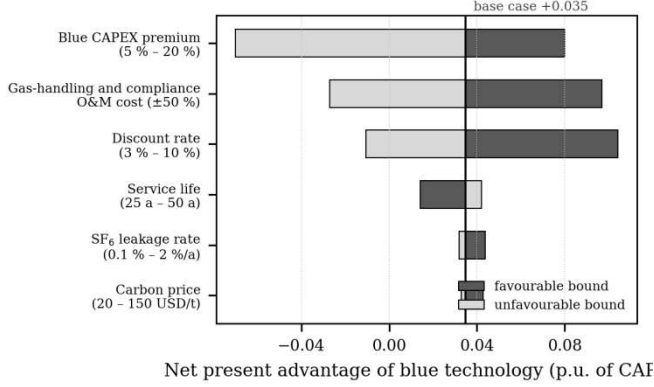


Fig. 17. Sensitivity of the net present advantage of blue technology. Capital premium, gas-handling and compliance cost, and discount rate dominate; carbon price and leakage rate are comparatively weak drivers.

Fig. 17 confirms this ranking. A capital premium at the low end of the plausible range of 5 % raises the advantage to 0.078 per unit, while a 20 % premium turns it negative at -0.072 . A 3 % discount rate, typical of regulated network investment, raises it to 0.102; a 10 % commercial rate makes it marginally negative. Varying the carbon price across the full range of 20 to 150 USD/t moves the result by only 0.010 per unit, and varying the leakage rate from 0.1 % to 2 % per year by 0.012. The practical implication for a utility is that negotiating the capital premium and quantifying the avoided handling cost matter far more to the business case than any assumption about future carbon pricing.

TABLE VII
TECHNO-ECONOMIC ASSUMPTIONS AND RESULTS

Quantity	Value	Unit
Reference bay capital cost	1.20	MUSD
Blue capital premium	9.5	%
O&M cost, SF ₆ bay	1.65	%/a of CAPEX
O&M cost, blue bay	0.82	%/a of CAPEX
Annual SF ₆ emission	6.075	t CO ₂ e/a
Annuity factor AF(6 %, 40 a)	15.05	—
Break-even year	19	a
ΔNPV at 40 a	+ 0.039	p.u. of CAPEX
of which carbon price	+ 0.004	p.u. of CAPEX
ΔNPV at 5 % premium	+ 0.078	p.u. of CAPEX
ΔNPV at 20 % premium	- 0.072	p.u. of CAPEX

F. Reliability and Availability

Evaluating (31) and (32) gives the curves of Fig. 18. Without condition monitoring the SF₆ bay shows an unavailability of about 83 minutes per year against 38 minutes for the blue bay, the difference arising almost entirely from the loss-of-medium failure mode, which in a clean-air system is

neither an environmental event nor a supply problem. Full monitoring coverage reduces these figures to about 24 and 16 minutes per year respectively. The marginal value of monitoring is therefore larger for the SF₆ bay, which is consistent with the regulatory position that density monitoring with automatic alerting can substitute for periodic leak checking; for the blue bay, monitoring is justified by endurance estimation rather than by leakage.

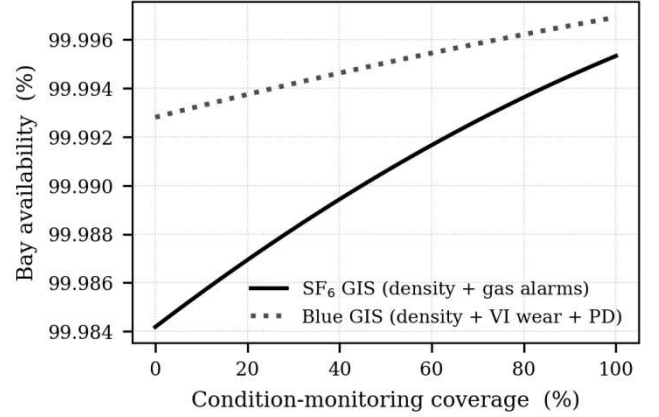


Fig. 18. Bay availability against condition-monitoring coverage from (31) and (32). Removing the loss-of-insulating-medium failure mode raises the availability floor of the blue bay; monitoring then adds endurance information rather than leak detection.

G. Multi-Criteria Result

Table VIII gives the normalised criterion scores and the analytic-hierarchy weights, for which the pairwise-comparison matrix yields a consistency ratio of 0.06, below the 0.10 acceptance threshold. Aggregating with (34) gives a sustainability index of 0.89 for blue technology, 0.73 for the fluoronitrile route and 0.54 for SF₆. Fig. 19 shows the profile. Blue technology leads decisively on climate impact, regulatory resilience, operation and maintenance simplicity and supply-chain security, leads modestly on life-cycle cost, and gives away compactness and a measure of dielectric performance. A Monte Carlo perturbation of the weight vector by ± 50 % with renormalisation, over ten thousand draws, never reversed the ranking of blue against SF₆ and reversed blue against fluoronitrile in under two per cent of draws, all of them cases in which compactness was weighted above 0.30.

TABLE VIII
MULTI-CRITERIA SCORES, WEIGHTS AND AGGREGATE INDEX

Criterion	wk	SF ₆	C ₄ -FN	Blue
Climate impact	0.24	0.18	0.74	0.99
Dielectric performance	0.18	0.98	0.92	0.84
Compact footprint	0.10	0.97	0.88	0.74
O&M simplicity	0.08	0.55	0.60	0.90
Regulatory resilience	0.14	0.22	0.68	0.97
Life-cycle cost	0.20	0.62	0.66	0.83
Supply-chain security	0.06	0.45	0.42	0.86
Aggregate index S	1.00	0.54	0.73	0.89

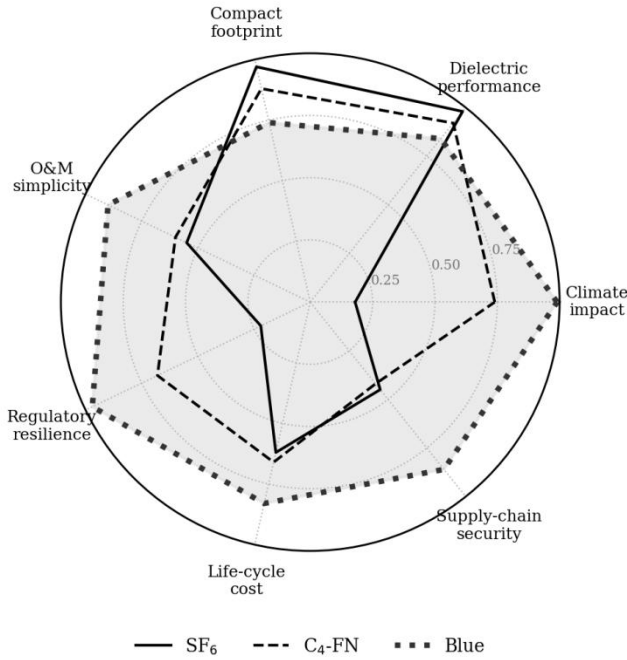


Fig. 19. Multi-criteria sustainability profile of the three technologies. Blue technology trades compactness and a margin of dielectric performance for decisive gains in climate impact, regulatory resilience and operational simplicity.

IX. CASE STUDY: AN EIGHT-BAY 145 kV SUBSTATION

The reference results are applied to a 145/33 kV indoor substation of eight bays supplying a mixed urban load of data centres and electric-vehicle charging infrastructure in a hot, humid, coastal climate with a design ambient of 50 °C. Two questions dominate such a project: whether the larger clean-air bay can be accommodated, and whether the rating survives the ambient.

On dimensions, the enclosure diameter rises from 301 mm to 475 mm and the estimated bay footprint by 22 %. For an eight-bay indoor building this is roughly 1.3 m of additional building length per bay row, which is normally accommodated within the civil tolerance of a new building but can be decisive in a retrofit inside an existing hall. Where it is not available, the clean-air bay becomes a poor fit and the fluoronitrile route, which costs only 6 % in footprint, is the rational compromise.

On rating, two effects act in opposite directions. Because dielectric strength follows density rather than pressure, (4) shows that a sealed enclosure filled to 6.2 bar at 20 °C rises to 6.83 bar at 50 °C with no change in withstand capability, so the insulation is unaffected by ambient temperature. The thermal limit does bind: with the permissible temperature rise reduced to 55 K at a 50 °C ambient, the enlarged conductor of Table V reaches the limit at approximately 2 780 A, retaining an 11 % margin on the 2 500 A rating. The bay is therefore rating-compliant at the design ambient without further enlargement.

Two local considerations favour the blue bay. Airborne dust and salt, which degrade air-insulated switchyards in this climate, are excluded by the sealed enclosure exactly as they

are for SF₆; and the elimination of certified gas handling removes a persistent logistical constraint in regions where certified recovery equipment and qualified personnel are scarce and where the reclaimed-SF₆ requirement from 2035 will be difficult to satisfy. Against this, the clean air must be dried to a dew point below − 40 °C at filling, which requires site drying equipment that an SF₆ project would obtain with the gas.

Scaled to eight bays over 40 years, the substation avoids approximately 2 280 t CO₂-eq relative to an SF₆ design, equivalent to the lifetime emission of about five hundred passenger cars for a year, and returns a net present advantage of approximately 374 000 USD, recovered from year 19. The capital exposure is an additional 912 000 USD at commissioning. A utility with a low regulated cost of capital will find this attractive; a developer discounting at 10 % will not, and will be driven by the regulatory prohibition rather than by the cash flow.

X. DISCUSSION AND LIMITATIONS

A. What the Results Establish

Three conclusions follow robustly from the analysis. First, the dielectric penalty of clean air is real but bounded: a 58 % larger enclosure and 41 % higher gas density buy the same 650 kV withstand level, and the practical gap between the media is narrower than the ratio of intrinsic strengths because SF₆ cannot be operated near its own intrinsic capability. Second, vacuum interruption is not a constraint at 145 kV; the governing duty, T10, retains a margin of 2.6 and the limitation at higher voltages is withstand across the open gap rather than interruption. Third, the environmental case is overwhelming and the economic case is positive but modest and fragile to the capital premium.

B. What the Results Do Not Establish

The dielectric model is analytical and assumes an ideal coaxial geometry. Real bays contain spacers, shields, disconnector contacts and triple junctions whose local field enhancement requires three-dimensional finite-element computation; the derating factor k_d is a lumped empirical surrogate for all of these and is the weakest link in the chain. Its value for clean air at transmission voltage rests on a comparatively thin body of published evidence and must be confirmed by type testing under IEC 62271-203, including the particle-contamination and long-duration tests that historically exposed the weakness of SF₆.

The life-cycle inventory is sensitive to parameters that are poorly evidenced in the public domain. The embodied carbon of the enclosure depends strongly on the recycled content of the aluminium, which can move the manufacturing term by ± 40 %; the end-of-life recovery efficiency for SF₆ is assumed at 95 % where field studies suggest wide variation; and the ohmic-loss term depends on a grid emission factor that will fall over the life of the asset, systematically reducing the loss contribution of both technologies and thereby increasing the relative weight of the gas term. None of these uncertainties is

large enough to reverse the comparison, but they are large enough to make precise figures unwarranted.

The economic model excludes two terms that can be decisive in practice. Land and building cost associated with the 22 % larger footprint is site-specific and can exceed the entire operating-cost advantage in a dense urban location. Conversely, the option value of regulatory compliance — the avoided risk of owning an asset that becomes unserviceable when reclaimed SF₆ is unavailable after 2035 — is not monetised here and would strengthen the blue case considerably if it were.

C. Extension to 420 kV

The models extend analytically but with two qualifications. The dielectric requirement at a 1 425 kV impulse level scales the gap to roughly 330 mm and the enclosure diameter beyond 1 m at a comparable pressure, at which point the mechanical design of the pressure vessel, not the gas, becomes the constraint. The vacuum interrupter does not scale: because the withstand of a single gap saturates above roughly 60 mm of contact separation, 420 kV requires two interrupters in series with capacitive voltage grading and synchronised operation, which adds mechanical complexity and a new failure mode. Published 420 kV clean-air installations confirm the approach is workable, but the analysis of this thesis should not be extrapolated to that rating without revalidation.

D. Implications for Specification

For a utility writing a specification today, the analysis supports four provisions: require an explicit statement of the design derating factor and the type-test evidence for it; require the density-monitoring signal to be published on the station bus as a measured value rather than as a binary alarm, since it is the compliance instrument as well as the insulation-coordination instrument; require the vacuum interrupter to report accumulated interrupted current so that endurance rather than elapsed time governs maintenance; and evaluate tenders on discounted life-cycle cost with the gas-handling and compliance burden priced explicitly, since that term, and not carbon price, carries the business case.

XI. CONCLUSION AND FUTURE WORK

This thesis has developed an integrated model of blue switchgear technology — vacuum interruption with clean-air insulation — for sustainable power transmission and applied it to a 145 kV, 40 kA, 2 500 A gas-insulated bay. A streamer-criterion dielectric model with Schwaiger field utilisation and an empirical derating factor gives a design point of a 150 mm gap at 6.2 bar for a 650 kV impulse withstand level, against 95 mm at 4.4 bar for SF₆, with the enclosure diameter growing from 301 mm to 475 mm and the bay footprint by 22 %. A sheath-growth model of vacuum recovery verified against the IEC 62271-100 envelopes gives interruption margins between 2.6 and 11.7 across the standard duties. A Rayleigh-based thermal model shows a 28 % conductor enlargement is needed to hold the 65 K limit at rated current, and that the dielectric

optimum supplies 34 % without additional cost, so that the clean-air bay is in fact the lower-loss design.

A cradle-to-grave inventory gives 377 t CO₂-eq for the SF₆ bay against 92 t CO₂-eq for the blue bay, a 75.7 % reduction, with 77 % of the SF₆ burden attributable to leakage and end-of-life release and a carbon payback on the additional enclosure material of about sixteen months. A discounted cash-flow model gives break-even at year 19 and a 3.9 % net present advantage at 40 years, dominated by avoided gas-handling and compliance cost rather than by carbon price, which contributes only a tenth of the advantage. A weighted multi-criteria index over seven criteria gives 0.89 for blue technology against 0.73 for the fluoronitrile route and 0.54 for SF₆, a ranking that survives a ± 50 % perturbation of the weights.

The practical conclusion is that blue technology is technically sufficient and environmentally decisive at 145 kV, that its economics are positive but sensitive to the capital premium and to the site cost of a larger footprint, and that the carbon price is not the mechanism by which the transition will be financed. The proposed four-layer architecture matters because it makes the environmental performance of the substation a measured output of the same digital infrastructure that already serves protection and maintenance, rather than an annual estimate.

Four lines of future work follow. The first is three-dimensional electrostatic and particle-trajectory computation of the complete bay to replace the lumped derating factor with a physically resolved value. The second is accelerated and long-duration ageing of cast-resin spacers in oxygen-bearing clean air at 6 bar, for which the published service record is short relative to a 40-year design life. The third is experimental characterisation of series vacuum interrupters with capacitive grading for the 420 kV extension. The fourth is a fleet-level study that couples the architecture of Section VI to a real asset register, so that the measured leakage, availability and loss data of an operating fleet feed back into specification — which is, in the end, the mechanism by which a transmission system becomes sustainable rather than merely compliant.

APPENDIX DERIVATION OF THE CONVECTIVE RATIO (21)

For natural convection in an enclosed horizontal annulus the Nusselt number follows $Nu = C Ra^n$ with $n \approx 0.25$ in the laminar regime. Writing the Rayleigh number as $Ra = g\beta\Delta\theta L^3\rho^2c_p/(\mu k)$ and the convective coefficient as $h = Nu k/L$, the geometric terms L and the buoyancy term $g\beta\Delta\theta$ cancel when two media are compared in the same enclosure at the same temperature rise, leaving

$$h_1/h_2 = [(\rho_1/\rho_2)^2(c_{p,1}/c_{p,2})(k_1/k_2)^3(\mu_2/\mu_1)]^{0.25} \quad (A1)$$

With $\rho = 26.4$ and $7.38 \text{ kg}\cdot\text{m}^{-3}$, $c_p = 665$ and $1\,005 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, $k = 0.0136$ and $0.0257 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and $\mu = 15.3$ and $18.2 \text{ }\mu\text{Pa}\cdot\text{s}$ for SF₆ and clean air respectively, (A1) evaluates to 0.72 for air relative to SF₆. The higher thermal conductivity of air partially compensates its much lower density, which is why the penalty is 28 % rather than the factor of three that the density ratio alone would suggest.

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