GLOBAL PROSPERITY 2022 VOLUME 2 ISSUE 4

PI-MVS: MATHEMATICAL MODEL FOR UNCERTAINTY EVALUATION OF VIRTUAL INSTRUMENTS IN FLARE SYSTEMS AND AUDITABLE REPORTING TO THE NATIONAL PLATFORM «ECOSYSTEMA»

Andrii Syrotenko

Received: 2022-09-10
Accepted: 2022-10-12
DOI: http://doi.org/10.5281/zenodo.18877576

Abstract. This paper presents the PI-MVS (Physics-Informed Methane Verification System) methodology for continuous monitoring of industrial flare systems aimed at reducing the risk of unburned methane emissions and ensuring an auditable digital chain “measurement → interpretation → reporting”. The approach is motivated by two factors: (i) increasing pressure for climate verification and the practical loss of “invisibility” due to satellite and remote detection of large methane plumes; (ii) the operational “blind spot” between measured gas throughput and the actual flare plume composition under wind-driven flame lift-off, over-steaming, and unstable low-flow regimes. The method integrates multispectral optical and thermal data, meteorological inputs, and process variables, applies physically constrained combustion-regime reconstruction, and produces DRE_calc as a calculated estimate of methane destruction efficiency over a time interval. A dedicated data-quality loop assigns VALID/INVALID/ALARM states with reason codes to prevent erroneous decisions under degraded inputs. The methodology includes a Decision Engine with event tagging (e.g., CH4_risk_event, soot_event, flameout_event) and generates a machine-readable Eco-Report with qualified electronic signature and cryptographic hash references to local video fragments, enabling audit-proof integrity without transferring video outside the facility. The proposed alignment with national automated emission-monitoring logic supports PI-MVS as a “trust layer” for integration into the «Ecosystema» platform.

Keywords: flare system; methane; methane destruction efficiency; uncertainty evaluation; virtual measuring instrument; multispectral monitoring; sensor fusion; computer vision; environmental compliance; qualified e-signature; Ecosystema.

Introduction

Flare units have traditionally been operated as an element of process safety, where control was limited to confirming stable combustion, while quantitative assessment of unburned hydrocarbons in the plume was not a mandatory parameter of operational suitability. Under modern conditions, this logic has become insufficient due to the combination of climate obligations and the technical capability for remote detection of large methane anomalies that form an external observation perimeter for industrial sites [5; 6; 7]. A flare operator faces the risk of mismatch between internal accounting and external observation in the absence of reproducible combustion-quality indicators and an evidentiary data trajectory capable of explaining why methane-destruction degradation occurs in specific time intervals. The practical task is to reduce the "blind zone" between the supplied-gas flow rate and the actual plume composition without moving to excessively expensive measurement complexes as the only source of truth, and to ensure machine-readable reporting compatible with national digital environmental monitoring frameworks in accordance with the Resolution of the Cabinet of Ministers of Ukraine No. 272 [2] and No. 1181 [3].

Analysis of recent research and publications that initiated the solution to this problem and that the author relies on, and identification of previously unresolved parts of the general problem addressed by this article. Applied remote-sensing studies show that satellite and airborne observations can identify significant methane plumes; however, their interpretation substantially depends on meteorological conditions, imaging geometry, cloud cover, and background concentrations. As a result, such data function as a strong regulatory trigger but require local verification and explainable linkage to flare operating regimes [7]. At the same time, standard instrumentation on flares is focused on flow rate and ignition confirmation and does not reveal the completeness of hydrocarbon oxidation in the plume. An unresolved engineering task remains the integration of process variables, visual flame indicators, and data-quality procedures into a single control loop and machine-readable reporting compatible with the digital requirements of state platforms [3; 4], including automated emission-monitoring regulations and the Law of Ukraine 'On Atmospheric Air Protection' [1].

Purpose of the article (task statement). The purpose is to describe the PI-MVS methodology (Physics-Informed Methane Verification System) as an integrated toolset that combines multispectral observations, combustion-regime reconstruction, the DRE_calc indicator, event tagging, and mechanisms for generating an "Eco-Report" for submission into the state digital loop in accordance with the Resolution of the Cabinet of Ministers of Ukraine No. 1065 'On Approval of the Regulation on the Unified Environmental Platform "EcoSystem"'[4]. The task is to formalize the functional blocks, the minimum requirements for input channels, and the interpretation/validation rules, as well as to demonstrate methodological alignment with automated emission-monitoring procedures and digital data-transfer requirements defined by regulatory documents [2; 3; 4].

Results

The conceptual basis of the methodology is that methane has a substantially higher climate impact than CO_2 over short time horizons; therefore, even short-lived regimes of incomplete destruction may contribute disproportionately to CO_2e accounting and increase regulatory and reputational risks [5; 6]. Engineering-relevant degradation factors include wind (crosswind drift and flame lift-off), excessive steam injection (cooling of the flame core and reduction of reaction temperatures), gas-composition variability, and instability at low flow rates [7]. To overcome the "blind zone", PI-MVS

[8] applies a hybrid methodology: process measurements (gas/steam flow rates, igniter status), meteorological data, and visual–optical flame indicators (geometry, luminosity, optical density/opalescence of the plume, lift-off signs) are synchronized in a time container and interpreted by a physically constrained model. The key output metric DRE_calc is defined as a calculated estimate of methane destruction efficiency over a time interval; it is used not as a replacement for gas analysis but as a reproducible numerical marker of combustion-regime degradation suitable for event dispatching and explainable reporting.

In physical terms, methane destruction efficiency in a flare system is described as the fraction of methane that does not enter the plume in an unburned state over a specified time interval. For an interval the basic definition is:Δt

$$DRE = 1 - \frac{\dot{m}_{CH_4,out}}{\dot{m}_{CH_4,in}}$$

where $\dot{m}_{CH_4,in}$ is the mass flow rate of methane entering the flare, and $\dot{m}_{CH_4,out}$ is the mass flow rate of unburned methane crossing a control surface in the plume. The input term can be expressed via the measured gas flow rate and the mass (or molar) fraction of methane:

$$\dot{m}_{CH_4,in} = \dot{m}_{gas,in}\, Y_{CH_4,in}$$

The output term, in the general case, is associated with transport of the species through a control surface in space:S

$$\dot{m}_{CH_4,out} = \iint_S \rho_{CH_4}(x,y)\, v_{\perp}(x,y)\, dS$$

In PI-MVS, continuous direct measurement ρ_{CH_4} throughout the entire plume is not declared as a mandatory condition; instead, DRE_{calc} is treated as a physically constrained estimate DRE obtained from combustion-regime reconstruction and consistent optical/thermal/process features. This is formalized by mapping the features to a numerical indicator:

$$DRE_{calc}(t) = f\,(R(t), x(t))$$

where $R(t)$ is a discretized/class representation of the combustion regime (in particular, stable combustion, lift-off, over-steaming, extinction with an existing flow), and $x(t)$ is a vector of synchronized features formed from multispectral data (optical/thermal indicators), meteorological data, and process variables.

The radiative component in the multispectral channel is interpreted through standard radiation-transport constraints (an effective form of the Beer–Lambert–Bouguer law), which provide a link between the measured attenuation and the integrated amount of the absorbing component along the line of sight:

$$\tau(x,y) = ln\, \frac{I_0(x,y)}{I(x,y)} \int c(x,y,z)\, dz = \frac{\tau(x,y)}{\kappa_{eff}}$$

where I_0 and I are the intensities "without gas/with gas" in the selected spectral window, τ is the optical thickness, κ_{eff} is the effective absorption coefficient (a calibration parameter for a given channel/filter/scene), and c is the volumetric concentration. Within PI-MVS, these constraints are used not to claim an "absolute" mass in every frame under any conditions, but as a physical basis to eliminate impossible interpretations and to stabilize reconstruction of combustion-degradation regimes.

The functional dependence of the calculated indicator DRE_{calc} on destabilizing factors is described by the following empirical model:

$$DRE_{calc} = \eta_{base} - \Delta_{wind} - \Delta_{steam} - \Delta_{flow}$$

where η_{base} is the baseline efficiency level; .$\Delta_{wind}, \Delta_{steam}, \Delta_{flow}$ are calculated efficiency losses caused by crosswind, excessive steam addition, and low gas-jet momentum, respectively

In this article, DRE_{calc} accuracy is appropriately described as metrologically managed uncertainty that depends on the quality of input channels, calibration, and observability of regime features. For a standard assessment, the combined standard uncertainty is introduced:

$$u^2\,(DRE_{calc}) = \sum_i \left(\frac{\partial DRE_{calc}}{\partial x_i}\right)^2 u^2(x_i) + u_{model}^2$$

where $u(x_i)$ are the standard uncertainties of individual input variables/features (in particular, meteorological data, process flows, optical parameters, stability of segmentation/detection), and u_{model} is the component that aggregates the uncertainty of the regime-reconstruction model. For reporting tasks, expanded uncertainty may be applied:

$$U\,(DRE_{calc}) = k\,u\,(DRE_{calc}), k \approx 2$$

This aligns with the logic of data-quality loops: VALID means that input channels and features are sufficient to form DRE_{calc} with controlled uncertainty; INVALID means technical/informational unsuitability of a frame for forming DRE_{calc}; ALARM means a technically valid frame with features of an elevated environmental-risk event, regardless of whether a numerical estimate has been produced (thresholds and escalation rules remain at the enterprise level, consistent with the already defined VALID/INVALID/ALARM statuses).

To verify accuracy (in those regimes where an independent reference is available), the error can be described by comparison with a reference estimate DRE_{ref} obtained instrumentally or via a control test:

$$\varepsilon_{abs} = DRE_{calc} - DRE_{ref}\varepsilon_{rel} = \frac{DRE_{calc} - DRE_{ref}}{DRE_{ref}} RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N} \left(DRE_{ref,j}\right)^2}$$

The built-in data-quality loop tags results with VALID/INVALID/ALARM statuses with coded reasons, preventing the use of DRE_calc when key channels degrade. The event-driven Decision Engine converts consistent features into controllable events and recommendations for steam injection, while the reporting layer generates a machine-readable "Eco-Report" package (JSON), signed with a QES, with hash references to local video fragments as a mechanism of evidentiary integrity without transferring video outside the facility.

The simulation results provide a quantitative basis for the proposed verification methodology:

The plot on Fig. 1a. demonstrates high system robustness to meteorological disturbances: destruction efficiency remains above the regulatory threshold of 98.5% at crosswind speeds up to 12 m/s.

Mathematical modeling confirms a nonlinear drop in oxidation completeness when the steam-to-fuel-gas mass ratio exceeds 3.5. As shown in Fig. 1b, the cooling of the flame core results in a rapid crossing of the critical "ALARM" boundary even under moderate wind gusts (5–7 m/s). This validates the system's ability to identify "hidden" methane emission that traditional flowmeters fail to detect.

The sensitivity DRE_{calc} analysis under low gas-outlet momentum reveals a loss of flare aerodynamic stability. In this regime, the jet lacks the kinetic energy to resist crosswind displacement. The system predicts a premature drop in efficiency, providing a proactive trigger for the Decision Engine to adjust steam injection or activate standby burners, thereby preventing a "cold vent" event.

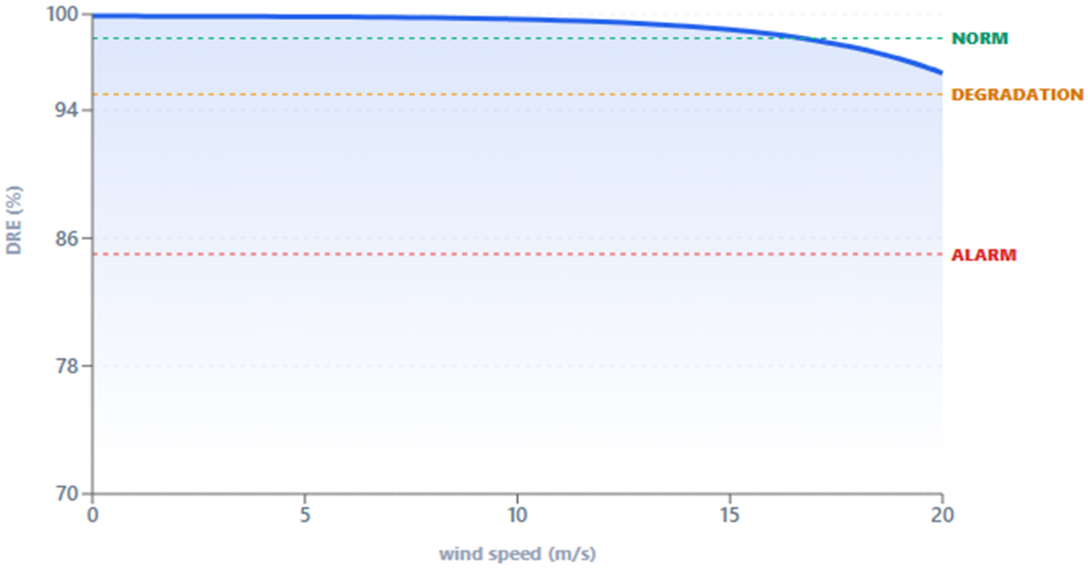

Fig. 1a. Calculated stability characteristic DRE_{calc} under nominal operating parameters. Steam mass to fuel-gas mass ratio = 0.5.

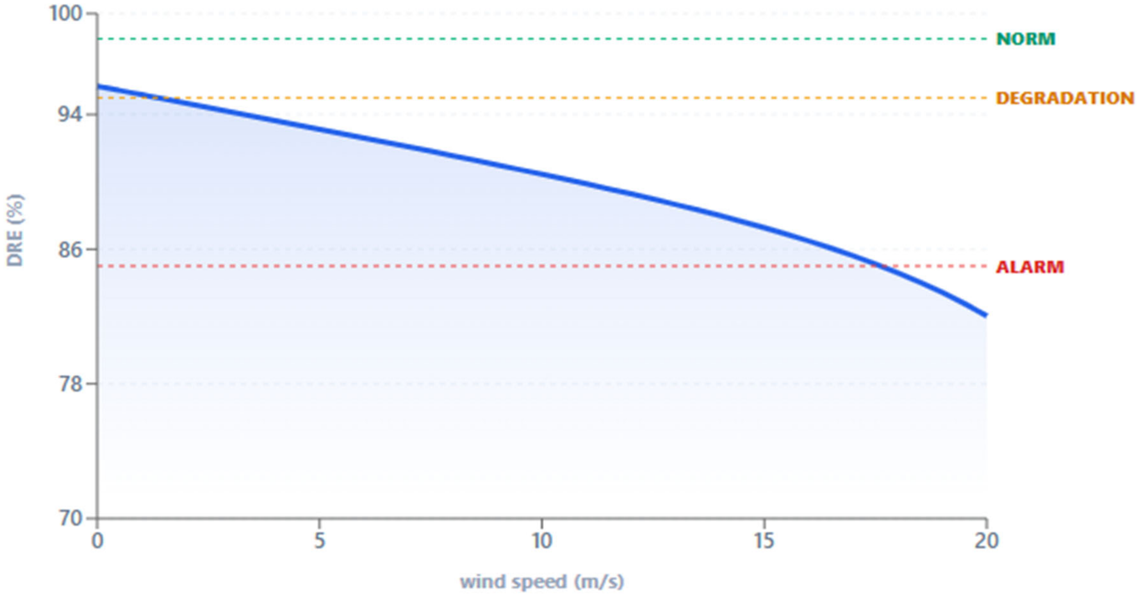

Fig. 1b. Mathematical modeling of efficiency degradation due to thermal quenching at a steam-to-fuel-gas mass ratio > 3.5.

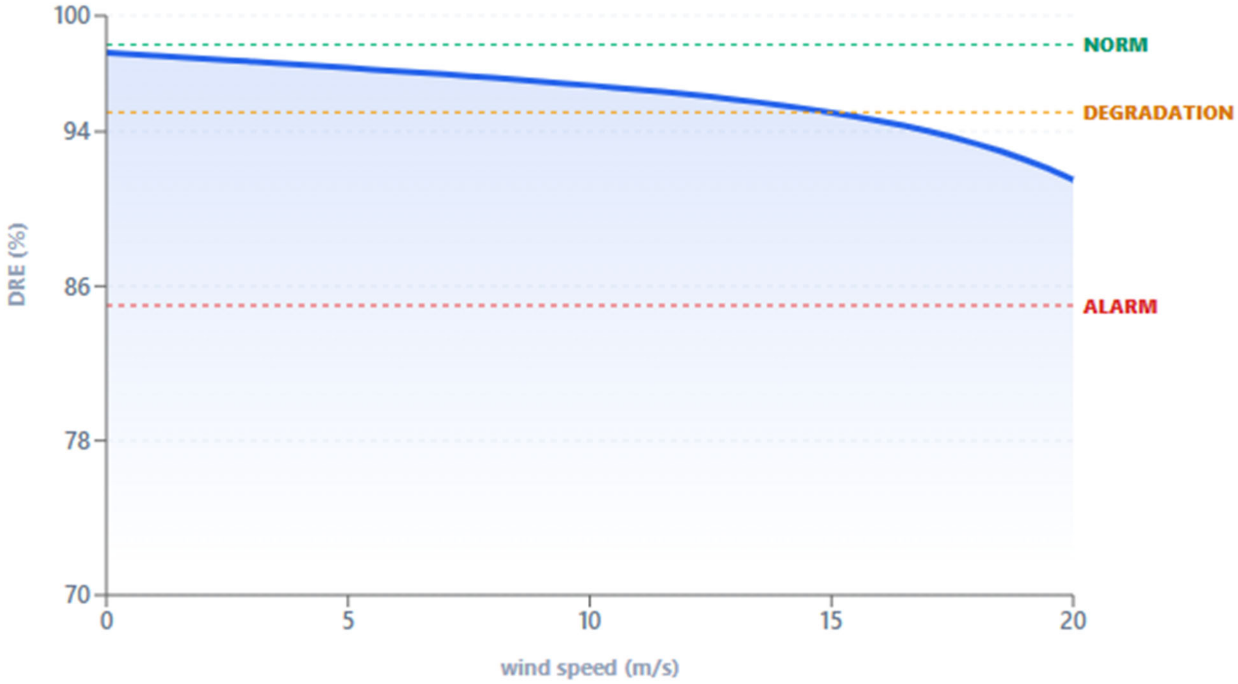

Fig. 1c. DRE_{calc} sensitivity to meteorological impact under low gas-outlet momentum.

Table 1. Alignment of regulatory requirements and PI-MVS functions

Regulatory requirement	Operationalization of the requirement	Technical implementation in PI-MVS	Output artifact for transfer/audit
Automated/instrumental measurements for organized stationary sources; use of metrologically correct instruments	Availability of verified/calibrated instruments; control of flow/emission parameters	Integration with gas/steam flowmeters; verification metadata log; control of gaps/anomalies	Measurement series + instrument metadata (identifiers, calibration)
Production control as a continuous enterprise function	Internal control and recording of events/regimes	Event tagging “normal mode / degradation / emergency mode”	Event register with time binding and signature
Continuous automated measurements of parameters, calculation of emission volumes, data transfer to the Ministry of Economy	Online time series; technical compatibility with transmission specifications	Transmission gateway; buffering; message integrity control	Stream of JSON messages per an agreed profile
Automated transmission of monitoring results in real time; authentication/identificat	Impossibility of backdating/substituting data	Qualified signature of the package; hashing of evidentiary artifacts (incl. video	Signed data package; hash references to local archive

ion		references)	

Table 2. Recommended message profile for automated transmission (compatible with real-time requirements and evidentiary reproducibility)

Field group	Content	Purpose in audit
Source identification	Flare/unit ID, georeference, operator/owner	Unambiguous binding of the record to a stationary source
Time and synchronization	Timestamp (UTC/local), time source (NTP/PTP), synchronization error	Eliminates disputes about “exactly when” the event occurred
Measured parameters	Gas flow, steam flow, igniter status/temperature, wind speed/direction	Input data for interpreting the combustion regime
Computed indicators	Opalescence/smokiness index, flame lift-off indicator, DRE_calc estimate (if enabled)	Technical explanation of discrepancies between “supplied” and “destroyed”
Quality status	VALID / INVALID / ALARM, reason code	Managing distrust in data without manual intervention
Integrity protection	QES of the package; hashes of evidentiary files	Impossibility of unnoticed data substitution

Table 3. Control and event-tagging logic (Decision Engine) in PI-MVS

Condition (consistent features)	Steam decision	Event tag	Expected effect
Opalescence above threshold with confirmed combustion; wind low/medium	Increase steam stepwise	“soot_event”	Reduced smokiness, stabilized mixing
High wind + flame lift-off sign + high steam	Reduce steam	“CH4_risk_event”	Less cooling, improved core stability
High steam + drop in luminosity/stability without soot signs	Reduce steam	“oversteam_event”	Restored thermal regime
Combustion not confirmed with gas flow present	Record emergency state; steam-control block switches to safe mode	“flameout_event” / “ALARM”	Escalation, minimized unburned CH_4, operator alert
Video poor quality or missing	Steam control only within process constraints; without DRE_calc	“INVALID” (quality)	Prevents erroneous decisions due to defective data

Table 4. Conditional classification of events by DRE_calc and data-quality statuses

Category	DRE_calc range	Quality status	Interpretation for reporting
Normal mode	≥99%	VALID	Modes without degradation signs; control within normal limits
Controlled degradation	95–99%	VALID	Signs of wind/steam impact exist, but without confirmed lift-off/extinction
Risk mode	80–95%	VALID or ALARM (per enterprise rules)	Likely breakthrough of part of the gas or unstable combustion; the event is subject to review
Emergency mode	<80% or "combustion not confirmed with gas flow present"	ALARM	Incident with high probability of unburned CH_4 emission; escalation required
Insufficient data quality	–	INVALID	A key channel is missing/incorrect; DRE_calc is not used

Conclusions

The PI-MVS methodology formalizes flare-system control as an information-and-measurement process in which environmentally significant conclusions are obtained by aligning process variables, multispectral flame indicators, and meteorological data with physically constrained combustion-regime reconstruction. The DRE_calc indicator, together with event markers and VALID/INVALID/ALARM statuses, creates a reproducible "control–reporting" loop that reduces the gap between accounting for supplied gas and the actual destruction outcome in the flare. Implementation of the "Eco-Report" in a machine-readable format with a QES and cryptographic references provides evidentiary data integrity for audit and for integration into state digital platforms. Further work should focus on metrological validation of DRE_calc across different flare types, improving the robustness of regime reconstruction under complex turbulence, and unifying data-transfer interfaces in accordance with national automated monitoring regulations.

References

1. Law of Ukraine "On Protection of Atmospheric Air". URL: https://zakon.rada.gov.ua/laws/show/2707-12

2. Cabinet of Ministers of Ukraine Resolution No. 272 "On approval of the Procedure for implementing mandatory automated control systems…". URL: https://zakon.rada.gov.ua/laws/show/272-2022-п

3. Cabinet of Ministers of Ukraine Resolution No. 1181 "On approval of the Procedure for automated transmission of emission monitoring results…".URL: https://zakon.rada.gov.ua/laws/show/1181-2023-п

4. Cabinet of Ministers of Ukraine Resolution No. 1065 “On approval of the Regulation on the Unified Environmental Platform ‘Ecosystema’”. https://zakon.rada.gov.ua/laws/show/1065-2021-п

5. IPCC. Sixth Assessment Report (AR6), Working Group I: The Physical Science Basis. (GWP estimates for CH_4). URL: https://www.ipcc.ch/report/ar6/wg1/

6. Global Methane Pledge: framework commitments to reduce anthropogenic methane emissions by 30% by 2030 (baseline year 2020). URL: https://www.globalmethanepledge.org/

7. Methane remote-sensing data: Sentinel-5P / TROPOMI and derived anomaly services. URL: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p

8. Internal document: Methodology for Reducing the Carbon Footprint in Industrial Flares, A. Syrotenko, 2021.