Technical Sciences

UDC 662.767.2:621.643:681.5

Shcherba Andrii

Lead Specialist at Technological Process Automation Department

LLC "SERVISENERHOGROUP",

Engineer in Technological Process Automation

Ivano-Frankivsk National Technical University of Oil and Gas

ORCID: 0009-0009-8924-7862

DOI: https://doi.org/10.25313/2520-2057-2026-8-12136

BIOGAS PRODUCTION AND GRID INJECTION: A STAGE-GATE QUALITY AND METERING FRAMEWORK FOR AUTOMATION AND DISTRIBUTION INTEGRATION

Summary. *The integration of biogas into public gas distribution networks requires more than efficient production - it demands a tightly coordinated chain of automated measurement, quality control, and accounting systems that spans every stage from organic feedstock to the injection point. This paper proposes and applies a Stage-Gate Quality and Metering Framework (SGQMF) that maps six sequential production stages against four assessment dimensions: measurement accuracy requirements, SCADA and automation obligations, applicable quality standards, and grid integration readiness indicators. Drawing on 20 peer-reviewed sources, the framework is applied to assess the current state of Ukrainian biomethane development against EU best practice, with specific focus on the automation of digestion management, calorific value measurement, biogas upgrading, fiscal metering, and digital data exchange with distribution system operators (DSOs).*

Findings indicate that while upgrading technologies and SCADA architectures are technically mature, the metering infrastructure and DSO integration protocols required for commercial biomethane injection remain critically underdeveloped in Ukraine. The SGQMF provides gas sector operators, regulators, and project developers with a structured diagnostic tool to identify and prioritise investment in the weakest links of the production-to-grid chain. The paper concludes with targeted recommendations for Ukrainian biomethane infrastructure development aligned with EU energy community obligations.

Key words: *biogas, biomethane, anaerobic digestion, SCADA, fiscal metering, gas distribution, Stage-Gate Framework, Ukraine, biogas upgrading, cybersecurity.*

Introduction. The transition to renewable energy has placed renewable gas firmly in the center of decarbonization strategies for the gas industry. As a result, biogas - created via the anaerobic digestion (AD) of organic material - provides a dispatchable, carbon neutral substitute for fossil natural gas that may be delivered and utilized within the present gas transmission/distribution infrastructure without requiring a fundamental overhaul of those systems [11]. In contrast to variable sources of renewable energy such as wind or solar, biomethane can be injected into the grid based upon demand, stored in network linepack, and retrieved by end-users using typical metering devices. Such characteristics make it a strategic resource for inclusion in portfolios of renewable energy.

Over nearly two decades of policy incentives and technical standardization the European Union has established a well-developed biogas sector. Today thousands of biogas plants exist across Germany, Denmark, France, and Italy producing biomethane which is directly fed into national gas distribution systems utilizing feed-in tariffs, guarantees of origin, and standardized grid operating codes [20]. The underlying physical infrastructure - including gas chromatography equipment located at points where biogas is injected into pipelines; automated balancing systems which utilize data obtained from smart meters (SCADA), and are operated by Distribution System Operators (DSOs); etc. - have evolved incrementally; with each level of automation contributing to increasing accuracy in quality assurance/verification, and/or commercial accounting.

However, Ukraine presents a unique situation among countries experiencing biogas development. Possessing one of the largest agriculture sectors in Europe; significant volumes of municipal and industrial organic wastes; and gas distribution infrastructure inherited from the former Soviet Union, Ukraine has the raw material feedstocks and physical network structure to develop biomass-to-methane production in meaningful ways. According to estimates presented by Geletukha et al. (2022), Ukraine's total potential biomass production of biomethane per year amounts to roughly 7.8 billion cubic meters - providing a meaningful reduction in its reliance on imported fossil fuels [8]. Nevertheless, the technical and institutional frameworks for measuring quality, and for performing accountings for distributed biomethane remain mostly undeveloped, especially at the point of injecting into pipelines.

In addressing these deficiencies, this study proposes the Stage-Gate Quality and Metering Framework (SGQMF) - an entirely new analytical model developed by the author to map the entire biomethane production cycle from feedstocks to the point of injection into pipelines according to measurements and automations necessary at each stage. The SGQMF will also be used to assess the degree to which Ukrainian biomethane infrastructure meets EU operational standards; identifying investments that will provide the greatest likelihood of initiating commercial-scale biomethane injections into Ukrainian gas grids. The primary research inquiries addressed in this study include:

- At what specific stages along the biogas production cycle do measurements and automations become critical for enabling commercial-scale biomethane injection into gas grids?
- At what stages along the biogas production cycle does Ukraine's infrastructure deviate most substantially from operational standards employed throughout the EU?
- What sequential investments should be made in order to address identified gaps in measurement/automation/quality assurance infrastructure?

Literature Review

1. Feedstocks, Digestion, and Gas Quality Variability. The first major factor which affects both the quantity of biogas as well as the quality and subsequently the degree of difficulty associated with measuring it is the type of feedstocks selected. As was shown by Kapoor et al. (2020) there exists a relationship between the type of feedstocks used in an Indian setting (which is quite similar to Ukrainian agriculture), and the potential for generating large quantities of biogas on a continuous basis and in a closed-loop or "circular economy" format; however, the varying levels of heterogenity in feedstocks will result in differences in gas quality throughout the biogas supply chain [12]. Ramos-Suárez et al. (2019) determined that under constant temperature of 35-37C, consistent gas compositions were achieved through mesophilic digestion, thus minimizing the amount of dynamic variation in the range that downstream analysers and meters need to be able to measure [19].

An advantage of co-digestion includes increased methane content and therefore greater total yield by up to 30%; however, increased compositional variability occurs at the exit of the digester. Bouaita et al. (2022), stated that the variability in composition due to co-digestion results in variability in gas composition, which results in variability in gas quality [4]. Variability in gas quality requires that the instruments analyzing and/or measuring the quality of the biogas sample and deliver frequency be adjusted to account for variability [4]. Schroer and Just (2023) developed a solution to the problem of variable gas quality due to variable feedstock mixtures using supervised machine learning algorithms to predict biogas production due to co-digestion operations [21]. These predictive models, if embedded into a SCADA architecture, allow operators to have sufficient time to adjust quality prior to injection; thereby changing the quality control strategy from one based on reaction to one based on prevention.

Fagerström et al. (2018) placed biogas production into a larger framework of Circular Economy principles stating that full realization of economic value is dependent upon managing all of the physical materials (biogas, digestate, CO_2, heat etc.) as part of an Integrated Management System [7]. Therefore, Ukraine operators who wish to inject their biogas onto the electric distribution system would require an underlying data infrastructure that goes beyond just the specific gas flow measurements to include overall facility level material and energy accounting.

2. Upgrading Technologies and Their Metering Implications. Raw biogas is comprised of approximately 50–70% Methane (CH4) and 30–45% Carbon Dioxide (CO2) along with traces of Hydrogen Sulphide (H2S), Water Vapour (H2O), Siloxanes etc. Therefore it needs to be upgraded into Biomethane - generally exceeding 95% CH4 - prior to being injected into the Grid [2].

Muñoz et al. (2015) published a foundational Comparative Review of Upgrading Technologies - and identified Pressure Swing Adsorption (PSA), Aqueous Scrubbing (Water Washing), Amine Scrubbing & Membrane Separation as the four predominant Commercial Pathways for Biogas Purification/Upgrading [16].

Ardolino et al. (2021) carried out a Lifecycle Comparative Assessment and concluded that PSA has achieved the Highest Methane Recovery (>98%) and produced an Output Stream having the Lowest Compositional Variance - which is a Property that Directly Reduces Measurement Uncertainty at the Fiscal Meter [3].

Golmakani et al. (2022) reported that Advances in Membrane Materials since 2015 have largely closed the Purity Gap relative to PSA; however Polishing Stages are still Required to Consistently Meet EN 16723-1 Specifications for Injection into the Grid [9].

Iglesias et al. (2021) reviewed all aspects of Upgrading Developments - and stated that Technology Selection must Consider both Plant Scale and the Specific Quality Tolerances required by the Receiving Grid Operator [10].

Morero et al. (2017) utilised Response Surface Simulation to demonstrate that Upgrading Process Parameters and Gas Quality Outputs may be Modelled Jointly - thereby allowing Operators to Define Optimal Operating Windows that Simultaneously Satisfy Production Requirements and those of the Fiscal Meter [15].

3. SCADA Systems, Automation, and Cybersecurity. SCADA systems are now the "backbone" of operations for most modern biogas plants by controlling the closed loop for digester conditions, gas capture, gas treatment unit operating parameters and collecting all other relevant data on both process performance and measurements. Cherdantseva et al. (2016) identified the first general framework of cybersecurity risks associated with SCADA systems used in critical infrastructure, pointing out that gas processing and transportation systems have an increased likelihood of suffering from adverse effects of loss of data integrity [5]. Ding et al. (2018), presented a survey of detection methods and control security methods for Industrial Cyber-Physical Systems; these detection methods represent the technical foundation for developing defensive architecture for biogas metering applications [6].

Kayan et al. (2022) provided a review of the broad area of industrial cyber physical systems’ cybersecurity issues, and described how legacy SCADA architectures (commonly found in post Soviet energy infrastructure) present particular vulnerability based on older communication protocols, lack of network segmentation [13]. The findings of Kreso (2025) provide a mapping of the contemporary cyber threat environment for smart energy infrastructure, where he noted fiscal metering data is a high value target for attackers because it is involved in determining commercial settlements [14]. This has a significant practical implication: if the fiscal metering data feed is compromised, the operators may be able to submit false injection volumes and thereby disrupt the DSOs ability to balance their books and diminish regulatory confidence in the entire biomethane injection program.

Prenzel and Steinhorst (2022), proposed new self adaptive control architectures for industrial systems designed to operate continuously even when partially failed or under cyber attack [17]. Biogas metering would benefit from similar types of resilience mechanisms that would ensure that fiscal measurement functionality degrades gradually -- i.e., falls back to conservative estimates - as opposed to failing completely without generating detectable error(s). Alcaraz and Zeadally (2015), defined critical infrastructure protection as requiring continuous monitoring of each interface between IT and OT; this principle also applies directly to the telemetry connection between the biogas plant's SCADA system and the DSO's balancing system [1].

4. Grid Integration and Distribution Accounting. The commercial integration of biomethane into the gas network for distribution will need a commercially acceptable connection point for the biomethane to enter the gas distribution system and an accepted accounting mechanism by the producer of the biomethane and the Distribution System Operator (DSO).

Quarton & Samsatli (2018), reviewed power-to-gas demonstration project experiences; they found that there was no consistency in grid codes across Europe and that this would remain a major constraint on development of large-scale systems; also the level of complexity required to balance the grid increased exponentially with each additional biogas facility connected to it [18]. Together Fagerström et al. (2018) and Scarlat et al. (2018), documented how the European Union had progressed through time developing a regulatory structure enabling trade of biomethane as a commodity similar to natural gas, including guarantees of origin, capacity booking agreements and quality certificates [7; 20].

Geletukha et al. (2022) identified where in Ukraine the gaps exist, specifically, the absence of certificates of origin for biomethane, lack of calibrated measuring equipment at agricultural biogas production facilities and inadequate technical capabilities of regional DSOs to handle the flow of information related to injection of biomethane produced at multiple decentralized locations [8].

Methodology. This research paper utilizes a structured literature review approach to develop an evidence base for the Stage-Gate Quality and Metering Framework (SGQMF). As the primary analytical contribution of this paper, the SGQMF has been developed in accordance with the following steps:

1. A six-stage sequential decomposition of the biogas production-to-grid supply chain was completed. The six stages are: (i) Feedstock Reception and Pre-Treatment; (ii) Anaerobic Digestion and Gas Collection; (iii) Biogas Conditioning; (iv) Upgrading to Biomethane; (v) Quality Measurement and Fiscal Metering; and (vi) Grid Injection and Distribution Accounting. Each of these stages have been defined based upon functional discontinuities within the production-to-grid supply chain - each stage represents a qualitative transformation of the gas stream or a different institutional actor - and have been validated against the full-cycle process descriptions provided in Kabeyi and Olanrewaju (2022) and Angelidaki et al. (2018) [2; 11].

2. Four Assessment Dimensions were identified for each stage of the SGQMF. The four Assessment Dimensions include: (a) Measurement Accuracy Requirements - defining the required measurements and their associated precisions; (b) SCADA and Automation Requirements - outlining the control and data acquisition functions that must operate during that stage; (c) Applicable Quality Standards - providing lists of applicable EU Technical Norms and Regulatory Instruments that apply to that stage; and (d) Grid Integration Readiness Indicators - characterizing the conditions that must exist for the gas generated at each stage to meet the expectations of a Distribution System Operator (DSO). These Assessment Dimensions were chosen to illustrate the four domains - metrology, automation, regulation, and commercial operability - whose simultaneous alignment is essential for the successful integration of gases into electricity grids.

3. Following the development of the SGQMF, comparative analyses were conducted utilizing a series of cells populated with specific technical and regulatory requirements derived from literature reviews. Using Geletukha et al. (2022) as the principal source of evidence regarding Ukrainian practice, supplemented by analogical inference from structurally similar EU transition cases, this comparative analysis assessed how well current Ukrainian practices align with those requirements [8].

The author did not collect any new primary empirical data. Rather than collecting new data, the author used prior knowledge of Ukraine's biogas sector to create a structure around which could systematically analyze the gaps in current Ukrainian practice relative to established best-practice standards. Therefore, the analytic contributions made by this research lie in both the architecture of the SGQMF, and in applying it to the Ukrainian context (See Figure 1).

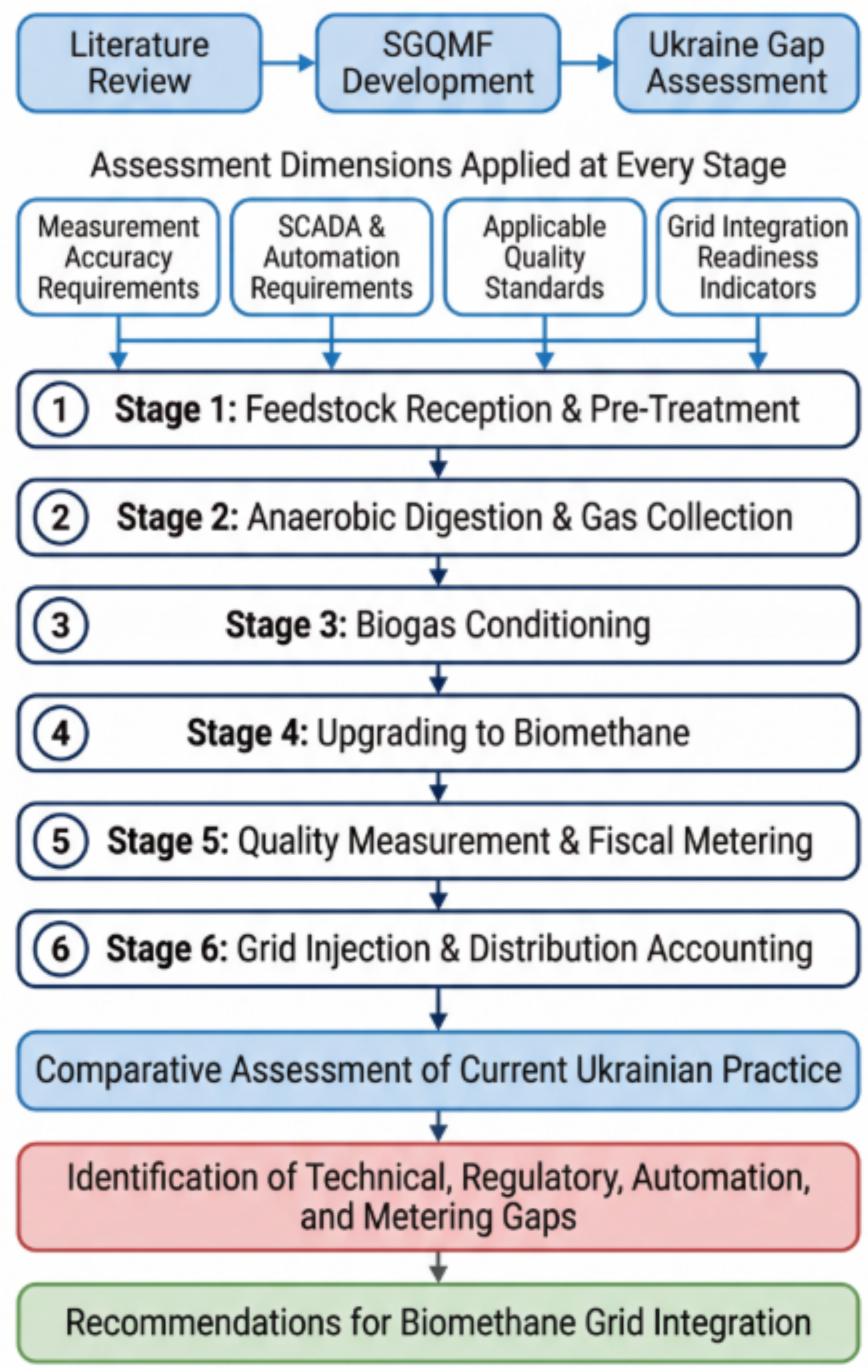

Fig. 1. Stage-Gate Quality and Metering Framework (SGQMF)

Source: generated by the author

4. The Stage-Gate Quality and Metering Framework (SGQMF). The SGQMF presented in Table 1 maps each of the six production stages against the four assessment dimensions. It is designed to function as both a diagnostic tool -

identifying where the chain breaks down - and a planning instrument - specifying what investments are needed and in what sequence. Each row represents a stage-gate: gas that does not meet the requirements of a given stage cannot reliably meet the requirements of any subsequent stage. This cascading dependency is the framework's core structural insight: metering failures at Stage 5 are frequently caused by unresolved deficiencies at Stages 2 or 3, not by the metering equipment itself.

Table 1

Stage-Gate Quality and Metering Framework (SGQMF) for Biogas Grid Injection

Production Stage	Measurement Accuracy Requirements	SCADA / Automation Requirement	Applicable Quality Standard	Grid Integration Readiness Indicator
Feedstock Reception & Pre-treatment	Moisture content, volatile solids (VS), C:N ratio of incoming material	Automated weighbridge logging; LIMS integration for feedstock batch tracking	No EU harmonised standard; operators apply internal quality protocols	Feedstock data must be archived for DSO traceability audits; gaps common in Ukraine (Geletukha et al., 2022)
Anaerobic Digestion & Gas Collection	CH_4 %, CO_2 %, H_2S ppm, digester temperature and pressure — continuous	SCADA PID loops for temperature; automated H_2S dosing; ML-assisted production forecasting (Schroer & Just, 2023)	EN ISO 15767 (gas quality monitoring); digester design per AD industry guidelines	Stable digestion is prerequisite for grid compliance; instability propagates to all downstream metering

Biogas Conditioning (Desulphurisation, Drying)	H_2S < 200 ppm pre-upgrading; dew point; siloxane concentration	Real-time H_2S analyser with automated iron-chloride dosing or biological desulphurisation control	EN ISO 16723-2 (gas for transport); internal plant specifications	Inadequate conditioning contaminates upgrading membranes/PSA, invalidating downstream quality readings
Upgrading to Biomethane	CH_4 purity ≥ 95–98%; CO_2 < 2.5%; O_2 < 0.5%; Wobbe index continuous	Upgrading unit PLC integrated into plant-wide SCADA; automatic diversion to flare if spec breached	EN 16723-1 (biomethane for grid injection); EN 16726 (gas quality groups)	This is the critical compliance gate; PSA achieves > 98% CH_4 (Ardolino et al., 2021); membrane may need polishing stage
Quality Measurement & Fiscal Metering	Wobbe index ± 0.5%; calorific value ± 0.5%; volume flow ± 1%; pressure & temperature compensation	Process gas chromatograph or Wobbe analyser at 1–5 min intervals; ultrasonic fiscal meter with SCADA telemetry	EN ISO 17089 (fiscal gas meters); MID Directive 2014/32/EU; OIML R 140	Fiscal meter data must feed DSO balancing system via standardised protocol (e.g., EDIGAS); absent in most Ukrainian plants (Geletukha et al., 2022)
Grid Injection & Distribution Accounting	Injected volume (m^3), energy (kWh/MJ), injection pressure; continuous remote data transmission	RTU/SCADA telemetry to DSO SCADA; cybersecurity-hardened communication channel (Kreso, 2025; Kayan et al., 2022)	EU Regulation 715/2009 (gas network access); national grid codes; biomethane certificates of origin	DSO balancing frameworks must be extended for distributed injection; near-real-time accounting required (Quarton & Samsatli, 2018)

Source: generated by the author

The framework reveals that the production chain contains two critical concentration points where failures have the highest downstream propagation risk. The first is Stage 2 (Anaerobic Digestion), where gas composition is established and where SCADA-managed process stability determines the measurement burden at every subsequent stage. The second is Stage 5 (Quality Measurement and Fiscal Metering), which is the legal and commercial boundary between producer and DSO - errors here have direct financial and regulatory consequences. Ukrainian infrastructure is most deficient at precisely these two stages [8].

Results. Application of the SGQMF to the Ukrainian biomethane context, drawing on Geletukha et al. (2022) and the wider literature, produces four structured findings [8].

Finding 1: Digestion stability is the upstream determinant of metering accuracy. Ukrainian agricultural biogas plants largely operate mesophilic digestion on mono-feedstock inputs (primarily cattle slurry), which produces relatively stable gas compositions [19]. This represents a latent advantage: the measurement burden at Stage 5 is lower than in facilities running complex co-digestion schemes. However, the absence of SCADA-integrated process monitoring at most Ukrainian facilities means this stability is not being systematically measured or verified - a gap that will become commercially significant when DSOs require documented quality histories as a condition of injection contracts.

Finding 2: Upgrading technology selection is a binding constraint on metering precision. Ukraine has very limited commercial biomethane upgrading capacity. Where upgrading equipment has been installed, water scrubbing and basic membrane systems predominate. Ardolino et al. (2021) demonstrated that these technologies produce higher compositional variance in the output stream than PSA, requiring more frequent and more sensitive quality measurements at Stage 5 to maintain compliance with EN 16723-1 [3]. The combination of variable upgrading output and absent fiscal metering creates a compounding deficit at the injection boundary.

Finding 3: Cybersecurity of metering telemetry is an unaddressed systemic risk. The literature documents a clear threat to metering data integrity in SCADA-connected gas infrastructure [5; 13; 14]. Ukrainian energy sector SCADA infrastructure, much of which predates modern cybersecurity standards, faces elevated exposure. No Ukrainian regulatory framework currently mandates cybersecurity standards specifically for biomethane metering interfaces. This gap means that even if accurate metering equipment is installed, the data transmitted to DSO balancing platforms may be vulnerable to manipulation - undermining the commercial and regulatory integrity of the entire injection scheme.

Finding 4: DSO accounting frameworks are structurally unprepared for distributed injection. Ukrainian regional DSOs operate batch-accounting frameworks designed for unidirectional gas flow from transmission to distribution. Accommodating distributed biomethane injection - which creates bidirectional and variable flows at the distribution level - requires near-real-time balancing protocols equivalent to those operating in mature EU markets [18]. The absence of standardised digital exchange protocols between plant SCADA systems and DSO balancing platforms is the single most significant institutional barrier to commercial biomethane grid injection in Ukraine.

The Cascade Logic of the SGQMF and Its Implications for Investment Sequencing. The SGQMF's most important practical implication is that the production chain must be strengthened in stage order, not by addressing the most visible or politically salient deficiency first. A common error in infrastructure development programmes is to invest in the final-stage interface - the fiscal meter and grid connection - without having secured the upstream quality foundations on which accurate metering depends. The SGQMF makes this error structurally explicit: a fiscal meter installed downstream of an uncontrolled digestion process and inadequate upgrading unit will produce compliant-looking readings during stable periods and erratic readings during process upsets, generating disputes with DSOs that undermine confidence in the entire scheme.

For Ukrainian operators, this means the investment sequence should begin with SCADA installation at the digestion stage, proceed through upgrading technology assessment and, where necessary, upgrading system replacement or polishing stage addition, and only then advance to fiscal meter procurement and DSO interface development. Morero et al. (2017) provided the simulation tools to identify optimal upgrading operating windows that simultaneously minimise compositional variance and energy consumption - exactly the kind of integrated process-metering optimisation that underpins a reliable injection-ready facility [15].

SCADA as the Integration Backbone. The SGQMF identifies SCADA as the connective tissue of the entire production chain - the system that acquires measurement data at each stage, manages process control responses, and transmits fiscal data to the DSO. Schroer and Just (2023) demonstrated that machine-learning-enhanced SCADA systems can shift quality management from reactive to predictive, enabling the system to divert gas to buffer storage before off-spec material reaches the metering boundary [21]. This capability is particularly valuable in the Ukrainian context, where the absence of real-time quality monitoring means that off-spec gas injection events currently go undetected.

The cybersecurity architecture of the SCADA system must be treated as a first-order design requirement, not a post-installation consideration. Kayan et al. (2022) established that legacy industrial SCADA systems require network segmentation, protocol modernisation, and intrusion detection as a minimum baseline [13]. Prenzel and Steinhorst's (2022) self-adaptive architecture concept provides a practical model for Ukrainian operators building new SCADA installations: design the system to degrade gracefully under attack, maintaining conservative metering fallbacks rather than generating falsified readings [17]. Kreso's (2025) identification of metering data falsification as a high-impact attack vector makes this design choice not merely prudent but commercially necessary - DSOs will eventually require certified cybersecurity compliance as a condition of injection agreements [14].

Standards Alignment and the Regulatory Pathway. The SGQMF's Standards column reveals the extent to which Ukrainian biomethane development requires regulatory as well as technical action. The applicable EU instruments - EN 16723-1 for biomethane grid injection quality, EN ISO 17089 for fiscal gas meters, the MID Directive for measurement instrument conformity, and EU Regulation 715/2009 for network access - constitute a coherent framework that Ukrainian energy law must progressively incorporate as part of its EU Energy Community obligations.

Geletukha et al. (2022) recommended the adoption of EU-aligned technical standards as the most direct pathway to unlocking biomethane investment [8]. This paper endorses that recommendation and adds specificity: the standards adoption must be accompanied by the establishment of an accredited metrology function capable of certifying fiscal meters at biogas injection points, the development of a biomethane certificate of origin registry compatible with the European Guarantees of Origin (GO) system, and the mandatory inclusion of cybersecurity specifications in technical requirements for SCADA systems at injection points. Without these institutional accompaniments, standards adoption on paper will not translate into the verified measurement environment that DSOs and investors require.

Learning from EU Integration Experience. Scarlat et al. (2018) documented how European biomethane markets developed incrementally - initial installations operated under ad hoc bilateral agreements between producers and DSOs before standardised grid codes were established [20]. Quarton and Samsatli (2018) synthesised the lessons of early power-to-gas injection projects, noting that DSO balancing complexity increased with each additional injection point and that near-real-time data exchange became operationally necessary beyond a relatively small number of distributed sources [18].

Ukraine should treat the EU's developmental sequence as informative rather than mandatory. Given the current urgency of energy security concerns and the availability of EU technical assistance mechanisms, Ukraine has an opportunity to adopt the regulatory and technical standards framework as a package - avoiding the iterative, decade-long harmonisation process that EU member states underwent - and to commission first facilities that are designed from the outset to meet mature injection standards. The SGQMF provides the diagnostic structure to specify what 'mature injection standard' means at each stage of the production chain.

Conclusions. This paper has proposed and applied the Stage-Gate Quality and Metering Framework (SGQMF) to examine the full cycle of biogas production and grid injection, with specific focus on automation, quality measurement, and distribution integration challenges in the Ukrainian context. The SGQMF advances beyond descriptive literature review by providing a structured diagnostic tool that maps measurement accuracy requirements, SCADA obligations, quality standards, and integration readiness indicators across six sequential production stages.

The application of the framework to Ukraine confirms that the country possesses favourable upstream conditions - adequate feedstock base and relatively stable mono-substrate digestion - but faces critical deficiencies at the downstream stages of upgrading, fiscal metering, and DSO accounting integration. The cybersecurity of SCADA-linked metering systems represents an additional systemic risk that current Ukrainian regulatory frameworks do not address.

Three sequenced priorities emerge from the analysis. First, investment in SCADA automation at the digestion and conditioning stages must precede fiscal metering installation - the upstream quality environment must be controlled before downstream measurement can be meaningful. Second, adoption of EU metrology standards (EN ISO 17089, EN 16723-1) must be accompanied by accredited certification infrastructure, not merely legislative transposition. Third, DSOs must develop near-real-time digital exchange protocols for biomethane injection accounting, supported by a national certificate of origin registry compatible with European GO systems.

The SGQMF is designed to be reusable: operators, regulators, and project developers can apply it to individual facility assessments or sector-wide planning exercises by updating the Standards and Integration Readiness cells as the regulatory environment evolves. Future empirical research should test the framework against operational data from existing Ukrainian biogas facilities to validate its diagnostic accuracy and refine the measurement parameter thresholds.

References

1. Alcaraz, C., & Zeadally, S. (2015). Critical infrastructure protection: Requirements and challenges for the 21st century. *International Journal of Critical Infrastructure Protection, 8,* 53–66. https://doi.org/10.1016/j.ijcip.2014.12.002

2. Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., & Kougias, P. G. (2018). Biogas upgrading and utilization: Current status and perspectives. *Biotechnology Advances, 36*(2), 452–466. https://doi.org/10.1016/j.biotechadv.2018.01.011

3. Ardolino, F., Cardamone, G. F., Parrillo, F., & Arena, U. (2021). Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective. *Renewable and Sustainable Energy Reviews, 139,* Article 110588. https://doi.org/10.1016/j.rser.2020.110588

4. Bouaita, R., Derbal, K., Panico, A., Iasimone, F., Pontoni, L., Fabbricino, M., & Pirozzi, F. (2022). Methane production from anaerobic co-digestion of orange peel waste and organic fraction of municipal solid waste in batch and semi-continuous reactors. *Biomass and Bioenergy, 160,* 106421. https://doi.org/10.1016/j.biombioe.2022.106421

5. Cherdantseva, Y., Burnap, P., Blyth, A., Eden, P., Jones, K., Soulsby, H., & Stoddart, K. (2016). A review of cyber security risk assessment methods for SCADA systems. *Computers & Security, 56,* 1–27. https://doi.org/10.1016/j.cose.2015.09.009

6. Ding, D., Han, Q.-L., Xiang, Y., Ge, X., & Zhang, X.-M. (2018). A survey on security control and attack detection for industrial cyber-physical systems. *Neurocomputing, 275,* 1674–1683. https://doi.org/10.1016/j.neucom.2017.10.009

7. Fagerström, A., Al Seadi, T., Rasi, S., & Briseid, T. (2018). The role of anaerobic digestion and biogas in the circular economy. *IEA Bioenergy,* Task 37, 1–24.

8. Geletukha, G. G., Kucheruk, P. P., & Matveev, Yu. B. (2022). Prospects and potential for biomethane production in Ukraine. *Ecological Engineering & Environmental Technology, 23*(4), 67–80. https://doi.org/10.12912/27197050/149995

9. Golmakani, A., Ali Nabavi, S., Manovic, V., & Moreira, D. (2022). Advances, challenges, and perspectives of biogas cleaning, upgrading, and utilisation. *Fuel,* 317, Article 123085. https://doi.org/10.1016/j.fuel.2021.123085

10. Iglesias, R., Muñoz, R., Polanco, M., Díaz, I., Susmozas, A., Moreno, A. D., Guirado, M., Carreras, N., & Ballesteros, M. (2021). Biogas from anaerobic digestion as an energy vector: Current upgrading development. *Energies,* 14(10), 2742. https://doi.org/10.3390/en14102742

11. Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas production and applications in the sustainable energy transition. *Journal of Energy,* 2022, Article 8750221. https://doi.org/10.1155/2022/8750221

12. Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S. S., Vijay, V., Kumar, V., Vijay, V. K., & Pant, D. (2020). Valorization of agricultural waste for biogas based circular economy in India: A research outlook. *Bioresource Technology,* 304, Article 123036. https://doi.org/10.1016/j.biortech.2020.123036

13. Kayan, H., Nunes, M., Rana, O., Burnap, P., & Perera, C. (2022). Cybersecurity of industrial cyber-physical systems: A review. *ACM Computing Surveys,* 54(11s), Article 250. https://doi.org/10.1145/3510410

14. Kreso, I. (2025). Cyber threats and vulnerability mapping in the energy sector: Laying the groundwork for smart grid resilience. *Applied Cybersecurity & Internet Governance.* https://doi.org/10.60097/ACIG/211124

15. Morero, B., Groppelli, E. S., & Campanela, E. A. (2017). Evaluation of biogas upgrading technologies using a response surface methodology for process simulation. *Journal of Cleaner Production, 141,* 978–988. https://doi.org/10.1016/j.jclepro.2016.09.167

16. Muñoz, R., Meier, L., Diaz, I., & Jeison, D. (2015). A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. *Reviews in Environmental Science and Bio/Technology, 14*(4), 727–759. https://doi.org/10.1007/s11157-015-9379-1

17. Prenzel, L., & Steinhorst, S. (2022). Towards resilience by self-adaptation of industrial control systems. *Proceedings of the 27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2022),* 1–8. https://doi.org/10.1109/ETFA52439.2022.9921597

18. Quarton, C. J., & Samsatli, S. (2018). Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and

systems modelling? *Renewable and Sustainable Energy Reviews, 98,* 302–316. https://doi.org/10.1016/j.rser.2018.09.007

19. Ramos-Suárez, J. L., Ritter, A., González, J. M., & Pérez, A. C. (2019). Biogas from animal manure: A sustainable energy opportunity in the Canary Islands. *Renewable and Sustainable Energy Reviews, 104,* 137–150. https://doi.org/10.1016/j.rser.2019.01.025

20. Scarlat, N., Dallemand, J.-F., & Fahl, F. (2018). Biogas: Developments and perspectives in Europe. *Renewable Energy, 129*(A), 457–472. https://doi.org/10.1016/j.renene.2018.03.006

21. Schroer, H. W., & Just, C. L. (2023). Feature engineering and supervised machine learning to forecast biogas production during municipal anaerobic co-digestion. *ACS ES&T Engineering, 4*(3), 631–644. https://doi.org/10.1021/acsestengg.3c00435