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Automated Control Systems in Next-Generation Energy Carrier Networks: From Biomethane to Green Hydrogen

Abstract

The purpose of this study is to examine how automation and digital control systems can enable the safe and efficient integration and transportation of next-generation gaseous energy carriers, primarily biomethane and green hydrogen, through existing pipeline infrastructure originally designed for natural gas. *Methodology.* The study is based on a structured review of peer-reviewed literature addressing four interconnected areas: modernisation of control systems on linear pipeline networks; gas quality monitoring, metering, and pressure management requirements for biomethane and hydrogen; infrastructure compatibility constraints arising from hydrogen's material and physical properties; and the specific conditions of Ukrainian biomethane projects as a near-term energy transition pathway. *Results.* The study develops the Pipeline Carrier Transition Readiness Framework (PCTR), a four-domain, multi-indicator scoring tool designed to assess the readiness of existing pipeline segments for transition from natural gas to biomethane, hydrogen blends, or pure hydrogen service. Application of the PCTR to the Ukrainian context identifies gas quality monitoring and regulatory certification as the most critical near-term gaps. The analysis further demonstrates that automated monitoring and SCADA modernisation constitute essential prerequisites for a responsible transition to alternative gaseous energy carriers. *Practical implications.* The proposed framework can support pipeline operators, engineers, infrastructure planners, and decision-makers in identifying technical and regulatory gaps, prioritising infrastructure upgrades, and determining appropriate transition pathways for individual pipeline segments. In the Ukrainian context, substantial biomethane potential provides a viable near-term opportunity for developing the technological, monitoring, and regulatory capabilities required for the subsequent transition toward hydrogen-ready infrastructure. *Value/originality.* The principal contribution of the study is the development of the PCTR as an integrated assessment instrument that brings together automation, gas quality control, infrastructure compatibility, and transition requirements within a single structured framework. Unlike approaches that examine biomethane or hydrogen integration separately, the proposed model conceptualises their deployment as successive stages of pipeline infrastructure transformation, positioning biomethane integration as a practical intermediate step toward the longer-term development of hydrogen-ready networks.

DOI: <https://doi.org/10.30525/2500-946X/2026-3-4>**Keywords**

biomethane, green hydrogen, pipeline automation, SCADA, gas quality monitoring, carrier transition, Ukraine, energy infrastructure

JEL: Q42, L95, O33

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1 Introduction

The switch to low-carbon energy sources will require the construction of new energy producing technology as well as the updating of large amounts of already built-in-frastructure to accommodate the new types of energy carrying substances. Pipelines of natural gas - each costing tens of millions of dollars to build and hundreds of kilometers long, with many years of operational history - have been identified as one possible conduit for transporting biomethane, hydrogen/natural-gas mixtures and eventually, hydrogen itself. Adapting pipelines to carry alternative fuels is an economic decision-making process. Operators and governments look to utilize existing

infrastructure to provide fuel through updates to the control systems used to monitor the operation of the existing network and by modifying the materials they use to handle the characteristics of the new fuel (Cerniauskas et al., 2020; Lipiäinen et al., 2023).

Biomethane, created by upgrading biogas from organic waste, agricultural waste, or dedicated bio-energy crops, has the same chemical composition as natural gas and primarily consists of methane (Kapoor et al., 2020). As such, it could be introduced into existing natural gas pipelines with minimal technical changes provided that certain gas quality standards are established (Angelidaki et al., 2018; Ardolino et al., 2021). Biomethane appears to offer a viable short- to mid-term transition carrier, especially where there

are ample quantities of organic waste available to produce the biomass. One example of a nation that could potentially realize a significant portion of its biomethane production potential is Ukraine. Geletukha et al. (2022) estimate that Ukraine could produce approximately 7.8 billion cubic meters of biomethane annually if all organic waste was converted into biogas and upgraded into biomethane. If realized, Ukraine's biomethane production potential would likely place it among Europe's largest producers of biomethane. To achieve this potential however, Ukraine needs to update its existing pipeline control systems and establish quality monitoring programs and regulatory bodies which do not exist today.

In contrast to biomethane, green hydrogen represents a more challenging problem. Although green hydrogen can be produced using electrolysis and renewable energy generation - advances are occurring in this area (Brauns & Turek, 2020; Nguyen, Abdin, Holm & Mérida, 2019) - introducing hydrogen into pipelines will require significantly greater levels of pipeline upgrades. Hydrogen has several inherent physical and chemical properties that will necessitate different approaches to monitoring systems, leak detection, material certification, and Supervisory Control And Data Acquisition (SCADA) infrastructure when compared to biomethane (Kappes & Perez, 2023; Topolski et al., 2022; Zhang et al., 2024).

Automation and control systems are central elements in both transition paths. Regardless of whether a system is designed to manage the quality of biomethane being injected into a natural gas pipeline, detect leaks in real-time due to hydrogen in a pipeline, or orchestrate pressures and flows through modified sections of a pipeline, automated control systems and related monitoring tools are essential for safe and efficient transport of either carrier (Majumdar et al., 2023). Unfortunately, the specific technical criteria that these systems must satisfy in order to support either biomethane or hydrogen services are not readily available within a single resource document and therefore cannot be effectively translated into a usable transition evaluation framework.

This research addresses this deficiency. First, we present an analytic summary of the automation, monitoring and control system requirements necessary for biomethane and hydrogen transport along natural gas pipelines. Second and most importantly, we introduce the Pipeline Carrier Transition Readiness Framework (PCTR) – a novel multi-domain assessment tool that translates the technical literature regarding SCADA/automated control systems into a standardized format for assessing how ready individual segments of a pipeline are to transition through four distinct carrier states: natural gas only, biomethane-ready, hydrogen-blend-ready, and pure-hydrogen-ready. We illustrate the application of the PCTR to the Ukrainian infrastructure context to show its practical value.

2 Literature Review

2.1 Biomethane as a Transition Energy Carrier

Biomethane is created through upgrading low-quality biogas into natural gas quality. Low-quality biogas is made by anaerobic digestion of an organic substrate, and low-quality biogas contains carbon dioxide, hydrogen sulphide, water vapor, and other trace contaminants. In order for low-quality biogas to be upgraded to natural gas quality, these contaminants must be removed. As noted in Angelidaki et al. (2018) and Muñoz et al. (2015), the removal of these contaminants will produce a high-quality biogas with methane levels above 95% when compared to a reference sample of natural gas. Provided the high-quality biogas meets applicable quality standards, the resultant biomethane can be injected into a natural gas distribution system (Ardolino et al., 2021; Golmakani, Ali Nabavi, Manovic & Moreira, 2022).

Scarlat et al. (2018) documented the recent growth of European biomethane development, citing the emergence of new grid injection projects throughout the continent resulting from the implementation of biomethane quality standards in various countries. According to Fagerström et al. (2018), biomethane represents a valuable component of the circular economy model. Not only does biomethane represent a renewable alternative to fossil fuels, but it also generates additional value streams which support the collection and processing of organic wastes.

Kabeyi and Olanrewaju (2022) conducted a comprehensive review of biogas production and application. Their work established that biogas may be generated using a wide variety of feedstocks including: agricultural waste, municipal solid waste, wastewater sludge, and specially grown "energy" crops. Additionally, their work highlighted the well-developed state of biogas generation technology and provided examples of successful deployments of these systems. Based upon the findings of Kabeyi and Olanrewaju (2022), among others, there appears to be significant global potential for biomethane as a transitional fuel source.

Specifically addressing the case study of Ukraine, Geletukha et al. (2022) estimated that Ukraine has approximately 7.8 billion m³/year worth of biomass resources suitable for conversion into biomethane. These estimates were based upon available agricultural residues, municipal waste, and energy crop substrates. The authors concluded that the lack of a national biomethane grid injection standard is currently the most limiting factor to adoption of biomethane as a transitional fuel in Ukraine. Further barriers include outdated metering and gas quality monitoring equipment at proposed injection points. As such, the lack of standardized monitoring equipment and regulatory requirements are motivating factors behind two key components of the PCTR Framework (i.e.

Gas Quality and Monitoring (D1) and Regulatory/Certification status (D4)).

2.2 Biogas Upgrading and Gas Quality Control

The quality control standards for injecting biomethane into a utility grid are much more stringent than those required for burning unprocessed biogas; this is due to the fact that when biomethane is injected into the utility grid it enters a system that supplies many different consumers whose quality requirements need to be met. In their review of biogas upgrading technologies – specifically, water scrubbing, pressure swing adsorption, membrane separation and chemical absorption – Angelidaki et al. (2018), noted that while these processes can achieve specific levels of contaminants (e.g., CO₂, O₂, H₂S, etc.), it was important to monitor the composition of the produced gas “on-line” at all times. This was necessary so that there would always be assurance that the produced gas meets the quality standards specified by the utility company in which it will be sold.

Iglesias et al. (2021) also reviewed recent advancements in upgrading technology and confirmed that, regardless of the method used to produce and clean up biogas to make it suitable for sale through the utility grid, the minimum parameters that need to be monitored include the concentrations of CO₂, H₂S, oxygen, and water vapor.

Morero et al. (2017) simulated several biogas upgrading scenarios, including varying degrees of efficiency and purity and presented data regarding how the resulting biogas composition varies depending upon the operating conditions – information that can inform decisions regarding what sensors should be used in the PCTR’s D1 domain to monitor and measure the composition of the gas being produced. Lastly, Golmakani et al. (2022) reviewed both challenges associated with removing impurities from biogas and also identified the main problem with automating quality control systems, i.e., variations in input substrate quality cause variation in quality of cleaned-up biogas.

2.3 Green Hydrogen Pipeline Transportation and Control Requirements

Green hydrogen transported via pipelines will present significant demands on automated control systems compared to biomethane injected into pipelines. Topolski et al. (2022) conducted a review of current technologies related to hydrogen mixing into the natural gas transmission infrastructure and found that hydrogen content needs to be continuously monitored in real time – both to meet the required hydrogen blend specification and to initiate a shutdown when the hydrogen concentration exceeds

the designed threshold of the system. Hydrogen sensor technologies are different than those employed for natural gas or biogas – they include catalytic bead, thermal conductivity, and electrochemistry; laser-based (optical) sensing was identified as being best suited for use in high accuracy and/or safety critical applications.

Majumdar et al. (2023) provided a review of the control and modeling techniques applicable to proton exchange membrane (PEM) type electrolyzers, and demonstrated how the inherent variability of renewable powered hydrogen generation – which results in output variation due to fluctuations in available solar or wind resources – generates immediate concerns regarding maintaining acceptable operating pressures and compositions in hydrogen rich gas feed streams to downstream pipeline systems. In addition to providing adequate real-time pressure regulation, control systems must also provide the capability to rapidly respond to variable rates of hydrogen injection, to maintain pipeline pressure within acceptable operating ranges while minimizing transient over-pressure conditions that may result in excessive hydrogen concentrations – exceeding safe blend levels.

Gondal (2019) developed a model that evaluated the feasibility of hydrogen integration into power-to-gas (PtG) networks and found that there exists a necessity for two-way communication between PtG electrolysis control systems and the supervisory control and data acquisition (SCADA) systems controlling the downstream pipeline network – in order to operate safely.

Witkowski et al. (2018) examined the thermodynamics of hydrogen pipeline systems employing multi-stage compression with inter-cooling and established that this method presents advantages for instrumentation and control requirements of compression stations. Guy and Julien (2022) characterized the risks associated with hydrogen as an energy carrier and determined that all hydrogen capable pipeline systems require specific leak detection methods, differing from those employed for natural gas leak detection – primarily due to differences in their respective sensitivity thresholds and sensor placement requirements.

2.4 Infrastructure Compatibility and Material Constraints

Compatibility of existing natural gas transmission lines to operate on hydrogen primarily relates to steel grade, the operating pressure of the line and contamination levels present within the gas stream (Messiaoudani et al., 2016). Kappes & Perez (2023) provided a comprehensive review of hydrogen embrittlement in natural gas transmission lines and concluded that lower strength grades of steel (e.g., X42 – X52) have significantly greater resistance to hydrogen

induced damage compared to newer higher strength grades (e.g., X65 – X80). A review of degradation mechanisms (corrosion and embrittlement) in hydrogen-natural gas transmission lines was conducted by Zhang et al. (2024), who identified water vapor and oxygen as primary contaminants responsible for accelerating degradation and thus controlling these contaminants will require improved quality standards for both upgraded biogas (biomethane) and hydrogen produced through an electrolysis process.

Safety issues associated with transporting hydrogen-blended natural gas were investigated by Tian & Pei (2023) where they found that ensuring seals and valves are compatible will need to be assessed at a component level prior to increasing hydrogen fractions within blends. Hassan et al. (2023) also reviewed hydrogen storage and compression systems. They stated that control system integration for high-pressure hydrogen applications is dependent upon specialized pressure sensors and flowmeters specifically designed for use with hydrogen, which differ from those used for natural gas in terms of both material properties and calibration requirements. Real world experiences with injecting hydrogen into the grid via various methods were documented by Quarton & Samsatli (2018) and they determined that the technical demands placed upon measurement instruments for accurate measurement of the hydrogen fraction within blended streams at hydrogen injection points are much greater than those required for the measurement of biomethane. As such, measurement instruments used for hydrogen injection point measurements must meet the same or equivalent standards used for custody transfer measurements.

2.5 SCADA Modernisation and Cybersecurity in Carrier Transition

The upgrading of SCADA systems will be both an operational necessity due to the introduction of new carrier management, and also a cyber-security necessity. In terms of the type of operational environment in which they operate, Cherdantseva et al. (2016), found that SCADA systems based on legacy technology and operating in natural gas pipeline networks do not have all of the necessary features such as authentication mechanisms, encryption, or anomalous activity detection. Therefore, they are vulnerable to cyber-attacks – a vulnerability that is exacerbated by the increasing trend towards extending these systems to monitor and manage the delivery of new, more dangerous types of carrier. As demonstrated by Kayan et al. (2022), the integration of IT and OT systems results in increased physical-cyber vulnerabilities when used in industrial-type environments - including the modernized pipeline control systems being designed to include real time

sensor data related to gas quality, communication with electrolyzers, and remote access capability.

According to Gorji (2023) the cyber security of SCADA and monitoring systems is one of the largest risks associated with complex energy-based supply chain operations. Therefore, it is essential that security requirements be integrated into modernization programs of control systems at the onset, instead of retro-fitting them later. Prenzel & Steinhorst (2022) proposed a self-adaptable architecture for industrial control systems that would be able to dynamically alter its security posture depending upon whether it has been able to detect any potential anomalies – an approach that could also apply to the various types of pipeline SCADA systems used to manage multiple types of carrier having different levels of inherent safety. The PCTR framework that was developed in this paper includes a SCADA Cyber Security Indicator within Domain 3, in order to reflect the previously established principles that in modern pipelines, operational automation readiness and cyber security readiness are mutually exclusive.

3 Methodology

This study will be conducted through a two-stage process using systematic analytical review of existing literature and an original framework development process based on transition from natural gas to biomethane and hydrogen by pipeline carrier.

The first stage included the structured synthesis of the existing peer-reviewed literature within the four theme areas: (1) Biomethane Production, Upgrading, and Gas Quality Requirements; (2) Hydrogen Pipeline Transportation, Monitoring, and Safety; (3) Material Compatibility and Instrumentation Requirements of Infrastructure; and (4) Modernization of SCADA and Cybersecurity. Within these themes twenty references were found to be directly applicable to this research project, and they are referenced in detail. The context of Ukraine regarding biomethane (Geletukha, Kucheruk & Matveev, 2022) has been selected as a representative example of near term applications of this technology. It has provided geographical specificity and grounded the proposed framework to documented deployment environments.

The second stage includes the creation of the Pipeline Carrier Transition Readiness Framework (PCTR). The PCTR was developed through use of a multi-criteria scoring technique where four dimensions and eight sub-indicators have been determined from the technical requirements and operational constraints that exist within the reviewed literature. The four dimensions include: D1 Gas Quality and Monitoring; D2 Infrastructure Compatibility; D3 Automation and Control System Readiness; and D4 Regulatory and Certification Status. The PCTR assesses each indicator at four transition states – T0 (Natural Gas

Only); T1 (Biomethane Ready); T2 (Hydrogen Blend Ready); and T3 (Pure Hydrogen Ready) – representing increasing levels of readiness related to the technical and regulatory aspects required for safe and regulatory compliant carrier transition.

Domain weights were also defined and assigned to represent the relative importance of each dimension to safe operationally compliant carrier transition as established in the literature. Gas Quality and Monitoring carries the largest combined weight (50%); it represents the real time composition sensing and leak detection which provide the greatest operational risk factors for both biomethane and hydrogen service. These risks cannot be compensated by any other factor. Infrastructure Compatibility has a weight of 25%; it reflects the central role that material integrity plays in hydrogens service. Automation and Control Readiness has a weight of 15%; and Regulatory and Certification Status has a weight of 10%. They have a lower weight as they serve primarily as enabling functions and less directly constrain operations. The PCTR is represented as a practical tool for pipeline carriers, energy regulators and infrastructure developers to evaluate the potential to make transitions among carrier technologies (See Figure 1).

4 Findings

4.1 The Pipeline Carrier Transition Readiness Framework (PCTR)

Table 1 presents the full PCTR assessment matrix. Eight indicators are distributed across four weighted

domains, each assessed at four transition-state levels (T0–T3). The colour coding – red (T0, not ready), amber (T1, biomethane ready), light green (T2, hydrogen blend ready), and green (T3, pure hydrogen ready) – provides an immediate visual representation of a pipeline segment's transition position across each indicator. A segment's overall PCTR score is calculated as the weighted sum of its indicator scores, normalised to a 0–3 scale (See Table 1).

Table 2 presents the four PCTR transition tier classifications and their associated recommended pathways. A segment scoring 2.8–3.0 is classified as Full Transition Capable and may proceed to pure hydrogen service subject to annual integrity audit. A segment scoring below 1.2 is classified as Transition Not Ready, and biomethane or hydrogen injection should be deferred until foundational metering, structural, and SCADA deficiencies are addressed.

4.2 Application to the Ukrainian Biomethane Context

Table 3 applies the PCTR framework illustratively to Ukraine's gas transmission network, drawing on the assessment by Geletukha et al. (2022) of infrastructure and regulatory conditions. The analysis identifies Gas Quality and Monitoring (D1) and Regulatory and Certification Status (D4) as the two domains where the current gap between existing conditions and T1 (biomethane-ready) requirements is most significant. Infrastructure Compatibility (D2) presents a mixed picture – pipeline steel grades are predominantly within acceptable ranges for biomethane service, but

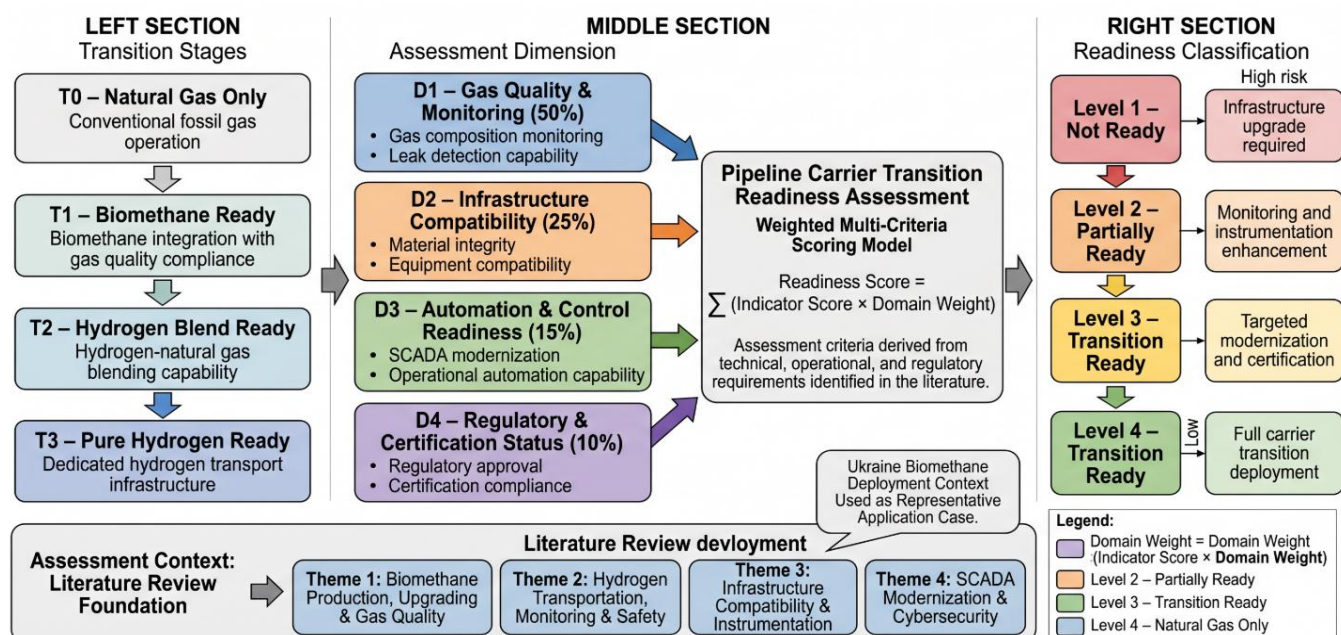


FIGURE 1 Pipeline Carrier Transition Readiness Framework (PCTR)

Source: generated by the author

TABLE 1 Pipeline Carrier Transition Readiness Framework (PCTR) Assessment Matrix

Domain	Indicator	T0 NG Only	T1 Biomethane Ready	T2 H ₂ Blend Ready	T3 Pure H ₂ Ready	Wt.
D1: Gas Quality & Monitoring	Gas composition sensing	CH ₄ only / manual	CO ₂ , H ₂ S, CH ₄ online	Adds H ₂ % sensor	Full multi-gas analyser	20%
	Pressure & flow metering accuracy	Standard (±1%)	Enhanced (±0.5%)	High-accuracy (±0.2%)	Custody-transfer grade	15%
	Leak detection system	None / visual only	Periodic manual	Catalytic sensor network	Optical + acoustic + H ₂ -specific	15%
D2: Infrastructure Compatibility	Steel grade & weld certification	Any / unknown	Certified, any grade	X42–X52 confirmed	X42–X52 + full HIC test	15%
	Seals, valves & compressor compatibility	NG-only components	Biomethane-compatible seals	H ₂ -rated valves partial	Full H ₂ -service certification	10%
D3: Automation & Control Readiness	SCADA / remote monitoring capability	Manual / local only	Basic SCADA, limited sensors	Remote SCADA, gas-specific alarms	Integrated digital twin, AI anomaly	10%
	Control system cybersecurity posture	No OT security measures	Basic access controls	IT/OT segmentation partial	IEC 62443 zone/conduit model	5%
D4: Regulatory & Certification Status	Grid injection standard compliance	NG tariff only	Biomethane grid code met	National H ₂ blend limit recognised	Full H ₂ pipeline certification	10%

Note: Domain weights – D1: 50%, D2: 25%, D3: 15%, D4: 10%.

Source: synthesised by the author from Topolski et al. (2022), Kappes & Perez (2023), Majumdar et al. (2023), Geletukha et al. (2022), Cherdantseva et al. (2016)

TABLE 2 PCTR Transition Tier Classifications and Recommended Pathways

Tier	PCTR Score	Classification	Recommended Transition Pathway
T3 Pure H ₂ Ready	2.8 – 3.0	Full Transition Capable	Commission for pure H ₂ service; annual integrity audit; maintain SCADA cybersecurity programme
T2 H ₂ Blend Ready	2.0 – 2.79	Blend Transition Capable	Proceed with H ₂ blending ≤20%; upgrade seals and metering; develop pure H ₂ roadmap
T1 Biomethane Ready	1.2 – 1.99	Partial Transition Capable	Approve biomethane injection; upgrade gas quality sensors; develop H ₂ compatibility investment plan
T0 NG Only	< 1.2	Transition Not Ready	Defer biomethane/H ₂ transition; prioritise metering upgrade, structural assessment, and SCADA modernisation

Source: synthesised by the author from Cerniauskas et al. (2020), Lipiäinen et al. (2023), Gondal (2019), Quarton & Samsatli (2018)

TABLE 3 PCTR Domain Analysis Applied to the Ukrainian Gas Network – Biomethane Transition Pathway

PCTR Domain	Current State in Ukrainian Gas Network (indicative)	Requirement for Biomethane Injection	Priority Action
D1: Gas Quality & Monitoring	Legacy metering; limited online gas composition sensing	Online CO ₂ , H ₂ S, CH ₄ sensors; custody-transfer metering at injection points	Deploy online gas analysers at all biomethane injection nodes
D2: Infrastructure Compatibility	Mixed steel grades; partial weld documentation; aging seals	Biomethane-compatible elastomer seals; corrosion assessment for CO ₂ -enriched streams	Conduct systematic seal and valve audit; replace non-compatible components
D3: Automation & Control Readiness	Partially modernised SCADA; variable coverage across regional networks	Remote monitoring with gas-specific alarms; basic IT/OT segmentation	Accelerate SCADA modernisation programme; integrate biomethane-specific alarm thresholds
D4: Regulatory & Certification	NG grid code in force; biomethane injection regulation under development	Biomethane grid code; quality specifications aligned with EN 16723-1	Finalise national biomethane grid injection standard; establish certification pathway

Source: synthesised by the author from Geletukha et al. (2022), Angelidaki et al. (2018), Cherdantseva et al. (2016), Scarlet et al. (2018)

seal and valve documentation is incomplete in older network sections. Automation and Control Readiness (D3) is variable, with partially modernised SCADA systems in major transmission corridors but limited digital integration in regional distribution networks.

4.3 Monitoring Technology Requirements by Carrier Type

The literature review confirms that the gas quality monitoring requirements for biomethane and hydrogen service differ substantially in both technology type and precision level. For biomethane injection, online sensors for CO₂, H₂S, oxygen, and water vapour content are the primary requirement, supplemented by calorific value measurement to verify energy content compliance with grid specifications (Golmakani, Ali Nabavi, Manovic & Moreira, 2022; Iglesias et al., 2021). For hydrogen blending, dedicated hydrogen fraction analysers – with sub-1% measurement accuracy at blend concentrations up to 20% – must be integrated into the pipeline SCADA system, with catalytic or optical leak detection sensors deployed at compressor stations, valve chambers, and pipeline inspection gauge (PIG) trap locations (Guy & Julien, 2022; Topolski et al., 2022). These monitoring technology requirements are reflected in the progressive indicator definitions of the PCTR's D1 domain.

5 Discussion

5.1 Biomethane as the Optimal First Step in Infrastructure Transition

The analysis supports a strong analytical case for positioning biomethane injection as the first and most immediately achievable stage of pipeline carrier transition in contexts such as Ukraine. The technical barriers to biomethane grid injection are substantially lower than those for hydrogen: the gas is chemically similar to natural gas, the material compatibility risks are limited to seal and corrosion considerations associated with CO₂ and H₂S traces rather than embrittlement, and the monitoring technology requirements – while demanding – are commercially mature and widely deployed across European networks (Ardolino et al., 2021; Scarlat, Dallemand & Fahl, 2018). The PCTR framework reflects this logic in its tier structure: T1 (Biomethane Ready) requires a substantially lower weighted score than T2 or T3, and its indicator thresholds are achievable through targeted investment in gas quality sensors and regulatory alignment rather than wholesale infrastructure replacement.

For Ukraine specifically, the case is reinforced by the scale of available biomethane potential. Geletukha et al. (2022) estimated over 7.8 billion m³ per year of

achievable production, primarily from agricultural residues – a figure representing a substantial fraction of current domestic gas consumption. Realising even a portion of this potential would require the pipeline control system upgrades identified in Table 3: online gas quality monitoring at injection nodes, SCADA integration of new sensor streams, and finalisation of a national biomethane grid injection standard. These are not trivial investments, but they are bounded, technically well-defined, and aligned with the European biomethane regulatory models that Ukraine is progressively approximating through its EU association process.

5.2 The Staged Transition Logic: From Biomethane to Hydrogen

A central analytical contribution of the PCTR framework is its articulation of carrier transition as a staged, cumulative process in which investments made for biomethane readiness create partial foundations for subsequent hydrogen transition. This staged logic has not been systematically formalised in the existing literature, which tends to treat biomethane and hydrogen infrastructure requirements as separate domains. The PCTR bridges this gap by constructing a continuous scoring scale in which T1 indicators are necessary but not sufficient conditions for T2, and T2 for T3.

Specifically: the enhanced metering accuracy required for biomethane custody transfer (T1, D1) provides the foundation for the high-accuracy instrumentation needed for hydrogen blend fraction measurement (T2, D1). The seal and valve certification undertaken for biomethane compatibility (T1, D2) creates documented component records that reduce the scope of the additional assessment required for partial hydrogen-service certification (T2, D2). The SCADA gas-specific alarm thresholds programmed for biomethane monitoring (T1, D3) establish the control system architecture into which hydrogen sensor streams can be integrated at T2. This cumulative logic has direct implications for investment planning: operators who undertake biomethane-readiness upgrades with a view to eventual hydrogen transition should specify components and systems that meet T2 requirements from the outset, avoiding costly replacement cycles.

Cerniauskas et al. (2020) and Lipiäinen et al. (2023) both documented the economic case for incremental pipeline repurposing rather than new-build hydrogen infrastructure, but neither operationalised the transition pathway in terms of specific control system and monitoring requirements. The PCTR fills this gap by providing a decision-support structure that translates the economic logic of incremental repurposing into observable, assessable technical and regulatory criteria.

5.3 SCADA Modernisation as the Enabling Condition

Across both biomethane and hydrogen transition pathways, SCADA modernisation emerges from the analysis as the single enabling condition without which the monitoring, safety, and control requirements of new carrier service cannot be met. Legacy SCADA systems – common in older pipeline networks including much of Ukraine's gas infrastructure – typically lack the sensor integration capacity, communications bandwidth, and processing capability required to manage real-time gas quality data streams from multiple composition analysers, pressure transmitters, and leak detectors simultaneously (Nicholson et al., 2012).

The integration of new carrier-specific sensors into a modernised SCADA platform is not merely a hardware upgrade; it requires systematic configuration of alarm thresholds calibrated to the properties of the new carrier, modification of automated shutdown logic to respond to hydrogen-specific hazard scenarios, and validation of the overall control system response through functional safety assessment. Majumdar et al. (2023) demonstrated that the dynamic control requirements for hydrogen-producing electrolyser systems demand advanced control architectures; analogous sophistication is required in the pipeline SCADA systems that receive and manage the hydrogen output. Prenzel and Steinhorst (2022) proposed self-adaptive architectures that can dynamically reconfigure in response to changing operating conditions – an approach particularly relevant in systems managing variable hydrogen injection from renewable-powered electrolyzers.

The cybersecurity dimension of SCADA modernisation is equally important. Kayan et al. (2022) documented that IT-OT integration – a necessary component of modernised pipeline control systems – expands the cyber-physical attack surface significantly. Gorji (2023) identified SCADA security as a material risk factor in hydrogen supply chain operations. The PCTR's D3 domain addresses this explicitly through its cybersecurity posture indicator, which scores control systems from no OT security measures (T0) through to full IEC 62443 zone-and-conduit compliance (T3). This reflects the analytical judgement that cybersecurity cannot be decoupled from operational readiness in modern pipeline automation environments.

5.4 Regulatory Development as a Co-Investment Requirement

The PCTR's D4 domain carries a 10% weight – the lowest of the four domains – but this should not be interpreted as reflecting low importance. Rather, it reflects the analytical observation that regulatory

requirements, while essential, are typically enabling conditions that follow rather than precede technical readiness in most deployment contexts. Where the regulatory environment lags technology – as is the case for biomethane injection in Ukraine and for hydrogen blending in most jurisdictions (Gondal, 2019; Quarton & Samsatli, 2018) – technical readiness investments can proceed in anticipation of regulatory frameworks, provided that operators engage actively in the standard-setting process.

Scarlat et al. (2018) documented how the rapid growth of European biomethane grid injection was enabled by the progressive harmonisation of national quality standards, with countries that established clear regulatory frameworks earlier achieving substantially faster deployment. This experience is directly applicable to Ukraine: the development of a national biomethane injection standard, aligned with EN 16723-1 and the broader EU gas quality framework, would immediately elevate T1 readiness scores for pipeline segments that already meet the technical requirements. Gorji (2023) and Hassan et al. (2023) both identified regulatory uncertainty as a key factor inflating investment risk premiums in new energy carrier projects – reinforcing the economic case for proactive regulatory development as a co-investment alongside technical infrastructure upgrades.

5.5 Limitations of the PCTR and Future Development

The PCTR as presented is a first-generation analytical tool with acknowledged limitations. The indicator set covers the most critical dimensions identified in the literature but does not capture all relevant variables: pipeline diameter, operating pressure history, cathodic protection status, and terrain-specific dispersion risk are examples of factors that influence carrier transition feasibility but are not currently represented as explicit indicators. The transition state thresholds are derived from the current literature consensus and will require updating as new experimental data on hydrogen blend behaviour and biomethane quality specifications become available.

The illustrative application to Ukraine in Table 3 is indicative rather than empirically validated against specific pipeline segment data, and should be interpreted as a demonstration of the framework's analytical logic rather than a definitive assessment of Ukrainian infrastructure readiness. Empirical validation of the PCTR against documented pipeline case studies – including European biomethane injection projects and the growing number of hydrogen blending pilots – is a priority for future research, alongside calibration of domain weights through structured expert elicitation with pipeline engineers, gas quality specialists, and regulators.

6 Conclusions

This paper has examined the role of automated control systems in enabling the transition of natural gas pipeline infrastructure to next-generation energy carriers, with particular attention to biomethane injection and hydrogen blending as the two primary near-term transition pathways. The analysis demonstrates that while the technical foundations for both transitions exist in the literature, they have not previously been synthesised into a unified, operationalisable assessment framework for pipeline operators and regulators.

The Pipeline Carrier Transition Readiness Framework (PCTR), developed as the paper's primary original contribution, addresses this gap. Its four-domain, eight-indicator structure - spanning gas quality monitoring, infrastructure compatibility, SCADA automation readiness, and regulatory certification - provides a graduated, cumulative

scoring tool that maps observable technical and regulatory states onto four transition tiers from T0 (natural gas only) to T3 (pure hydrogen ready). Applied illustratively to Ukraine's gas network, the PCTR identifies gas quality monitoring modernisation and regulatory framework development as the most critical near-term actions for enabling biomethane injection - the logical and technically achievable first step on a longer carrier transition pathway.

The paper argues that SCADA modernisation is the enabling condition common to all transition stages, and that investment in biomethane-ready control systems, undertaken with hydrogen compatibility in mind, creates incremental foundations that reduce the total cost of eventual hydrogen transition. Future research should prioritise empirical validation of the PCTR, expansion of the indicator set, and comparative application across diverse European and post-Soviet pipeline infrastructure contexts.

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Received on: 20th of August, 2026

Accepted on: 27th of September, 2026

Published on: 16th of October, 2026