RESEARCH ARTICLE

Check for updates

Natural Gas Transit from West Africa to Europe (Africa Atlantic Gas Pipeline) to Maximize Energy Security and Transit Revenues by 2050

Ayat-Allah Bouramdane[1,*]

[1] International University of Rabat, Rabat 11103, Morocco

Abstract

The Africa-Atlantic Gas Pipeline (AAGP), also known as the Nigeria-Morocco Gas Pipeline, is a major transcontinental infrastructure project poised to connect West African gas reserves with North African networks and European markets, potentially reshaping regional energy dynamics, boosting economic development, and enhancing energy security. Its strategic importance has grown amid Europe's urgent need to diversify away from Russian gas imports and Africa's dual challenge of resource-based development and sustainable local energy access. Despite increasing interest, there is a lack of integrated, quantitative evaluation of competing gas transit strategies considering technical, economic, environmental, and social criteria. This research fills that gap by applying a Multi-Criteria Decision-Making framework (AHP) to assess four transit strategies, highlighting Public-Private Partnerships and revenue-sharing as top options. The study also models Europe's future gas supply scenarios, showing that while African gas corridors like the AAGP could significantly reduce European dependence on Russian gas, full substitution requires coordinated investments and complementary measures. The findings offer policymakers a transparent, replicable methodology to make evidence-based decisions that align energy security, regional cooperation, and sustainability goals, while recognizing limitations due to data subjectivity and the need for broader impact assessments.

Keywords: Africa atlantic gas pipeline, analytic hierarchy process, energy security, multi-criteria decision-making, natural gas transit, transit revenues.

1 Introduction

According to a recent report by the Gas Exporting Countries Forum (GECF) [1], Africa is poised to strengthen its position as a strategic global supplier of natural gas by 2050, driven by its vast untapped reserves. The continent is projected to increase production by 119 billion cubic meters between 2030 and 2040, reaching an estimated 193 billion cubic meters by 2050 [1]. Notably, Nigeria and Algeria hold the largest proven natural gas reserves in Africa, with 210 trillion cubic feet (Tcf) and 159 Tcf respectively,

Submitted: 02 December 2025
Accepted: 21 January 2026
Published: 24 January 2026

Vol. 2, **No.** 1, 2026.
10.62762/JGEE.2025.372522

***Corresponding author:**
Ayat-Allah Bouramdane
ayatallahbouramdane95@gmail.com

Citation
Bouramdane, A. A. (2026). Natural Gas Transit from West Africa to Europe (Africa Atlantic Gas Pipeline) to Maximize Energy Security and Transit Revenues by 2050. *Journal of Geo-Energy and Environment*, 2(1), 1–33.

while Morocco's reserves stand at 39 billion cubic feet [2]. Within this context, the Africa-Atlantic Gas Pipeline (AAGP), also known as the Nigeria-Morocco Gas Pipeline, emerges as one of the most ambitious transcontinental energy infrastructure projects ever conceived. By linking the abundant gas resources of West Africa with North African transit networks and ultimately supplying European markets, the AAGP has the potential to reshape regional energy dynamics, stimulate economic development, and enhance energy security for numerous stakeholders.

The success of this high-stakes and complex endeavor, however, depends not only on sound technical design and favorable geopolitical alignment but also critically on the careful selection and prioritization of gas transit strategies that are robust, feasible, and sustainable amid future uncertainties. The European Union's urgent drive to diversify away from Russian natural gas imports—intensified by recent geopolitical tensions—has elevated the strategic significance of African gas corridors. At the same time, African countries confront the dual imperative of harnessing their natural gas resources to foster economic growth while ensuring sustainable and equitable local energy access. Thus, the AAGP is far more than a mere pipeline; it represents a multifaceted strategic opportunity requiring well-informed, evidence-based governance and decision-making.

Despite increasing interest in the AAGP, there remains a critical gap in the literature regarding comprehensive, integrated, and quantitative comparisons of alternative gas transit strategies across technical, economic, environmental, operational, and social dimensions. Many existing studies tend to rely on qualitative assessments or fail to adequately weigh the trade-offs between local benefits and external demands. Moreover, decision-making processes around strategy selection are often influenced by political expediency or historical path dependencies rather than by systematic, evidence-driven analysis.

This research seeks to fill this gap by employing a rigorous Multi-Criteria Decision-Making (MCDM) framework, specifically the Analytic Hierarchy Process (AHP), to objectively evaluate four distinct gas transit strategies for the AAGP. By deriving criteria weights and performance scores grounded in logical analysis and an extensive literature review—instead of relying solely on subjective expert opinions—this study offers a replicable, transparent, and methodologically sound approach. The ultimate goal is to empower policymakers, planners, and regional stakeholders to make strategic choices that are not only technically and economically viable but also aligned with broader imperatives of energy justice, regional integration, and sustainable long-term development.

The literature on natural gas transit strategies, particularly in the context of Africa-Europe energy corridors, has grown substantially in recent years, driven largely by geopolitical shifts and the urgent need to diversify energy supplies. Several studies have explored the technical and economic aspects of major pipelines such as the Trans-Saharan Gas Pipeline (TSGP), Medgaz, and the Nigeria-Morocco Gas Pipeline (AAGP). Research efforts have focused on infrastructure design, capacity optimization, geopolitical risk assessment, and regional energy security impact. Complementary analyses have also examined Europe's evolving gas supply landscape, modeling alternative supply routes in response to the decline of Russian imports. These works emphasize the roles of North African gas, LNG imports, and Norwegian sources, highlighting the strategic relevance of the Southern Corridor as a key component in Europe's diversification strategy. Additionally, studies on public-private partnerships (PPP) and market liberalization in gas sectors have provided insights into operational and regulatory frameworks that influence pipeline success. Multi-Criteria Decision-Making (MCDM) frameworks, particularly the Analytic Hierarchy Process (AHP), have been applied in various energy infrastructure evaluations. Prior research typically assesses renewable energy projects, regional infrastructure investments, or specific operational strategies, often considering technical, economic, and environmental factors. However, application to transcontinental gas transit strategies, especially within the African context, remains limited.

Despite these contributions, several critical gaps persist: (i) Existing assessments often focus on individual aspects such as technical feasibility or economic viability in isolation. Few studies conduct comprehensive, quantitative comparisons across multiple relevant criteria—technical, economic, environmental, operational, and social—within a unified MCDM framework. (ii) The Nigeria-Morocco Gas Pipeline, given its unique transcontinental scale and geopolitical context, has been underexplored in integrated strategic evaluations. There is a lack of systematic, transparent evaluation of alternative gas transit strategies tailored to this project's specific operational and regional challenges. (iii) Many MCDM applications depend heavily on expert opinions, which, while valuable, can introduce subjectivity and reduce reproducibility. There is a scarcity of studies that combine rigorous literature review and logical reasoning to derive evaluation parameters, enhancing methodological transparency and replicability. (iv) Prior models frequently overlook the nuanced trade-offs between local African benefits (energy security, revenue generation) and European energy diversification needs, or the long-term decarbonization imperatives impacting pipeline operations.

This study addresses these gaps by offering a novel, rigorous multi-criteria evaluation of four distinct gas transit strategies for the AAGP using the Analytic Hierarchy Process. The originality of this work lies in: (i) Incorporating five carefully defined criteria—technical feasibility, economic viability, environmental impact, operational complexity and maintainability, and regulatory compliance and social acceptance—reflects a holistic understanding of the multifaceted challenges faced by transcontinental gas infrastructure projects. (ii) Criteria weights and strategy performance scores are derived from a structured literature review and logical reasoning rather than relying solely on expert elicitation, thereby enhancing methodological rigor and enabling reproducibility in other contexts. (iii) The MCDM evaluation complements a robust multi-objective optimization framework developed in the study, linking strategic priorities like energy security, transit revenues, and European gas replacement within a realistic capacity and geopolitical risk-constrained setting. (iv) The results directly inform policymakers, infrastructure planners, and investors by providing a ranked, comparative analysis of viable strategies. The emphasis on balancing local benefits with external supply demands offers actionable guidance to harmonize regional development with global energy security goals. (v) By embedding environmental impact and regulatory/social acceptance criteria, the study acknowledges and anticipates the evolving decarbonization landscape, ensuring the strategic recommendations remain relevant amid shifting climate policies.

In sum, this research contributes a methodologically innovative and practically relevant decision-support tool that can guide the strategic development of the AAGP and similar transcontinental energy projects. It facilitates informed, balanced decision-making that aligns technical, economic, environmental, and social considerations—critical for fostering sustainable, resilient, and equitable regional energy integration.

After this introduction, Section 2 offers an in-depth analysis of the global natural gas production landscape by continent (Section 2.1) and explores projected natural gas demand trends in Africa and Europe (Section 2.2), emphasizing their strategic relevance for future energy security and infrastructure development.

Section 2.3 provides an overview of the main transit corridors within the European Gas Network, detailing key infrastructure along three major axes: (a) the Eastern Corridor, which channels Russian gas through pipelines such as Nord Stream, Transgas, Yamal-Europe, and TurkStream; (b) the Southern Gas Corridor, which connects Northern and West African gas resources to Europe via networks including the Gazoduc Maghreb-Europe (GME), the Africa Atlantic Gas Pipeline (AAGP)/Nigeria-Morocco Gas Pipeline (NMGP), the Trans-Saharan Gas Pipeline (TSGP), Transmed, Medgaz, and Galsi; and (c) the Northern and Western Corridors, which deliver gas from Norway and the North Sea into the European system.

Section 3 undertakes a comprehensive quantitative assessment of Europe's ability to meet its natural gas demand by 2050 under the assumption of a complete and permanent cessation of Russian pipeline gas—previously constituting 40–45% of EU imports and over 155 bcm/year. Using a corridor-based modeling framework grounded in projected demand of 400 bcm/year and long-term infrastructure capacity estimates, the study evaluates the substitution potential of three major alternative supply routes: the Southern Corridor (North and West African pipelines), the Northern and Western Corridor (primarily Norwegian and UK infrastructure), and LNG imports via EU regasification terminals. The findings reveal that by 2050, Europe can collectively mobilize approximately 358.15 bcm/year from these non-Russian sources—falling short by 42 bcm/year. Specifically, the Southern Corridor could deliver 118.15 bcm/year through expanded projects like the Nigeria–Morocco and Trans-Saharan pipelines, though this path faces geopolitical and financial hurdles. The Northern Corridor, contributing 110 bcm/year, is deemed more reliable but constrained by mature gas fields and limited growth prospects. LNG, expected to supply 130 bcm/year, emerges as a flexible yet volatile option due to global market dependencies and environmental drawbacks. The simulation concludes that while full technical substitution of Russian gas is achievable, it hinges on early investment, geopolitical cooperation, and the deployment of complementary strategies—particularly demand reduction, green gas scaling (hydrogen and biomethane), and increased energy efficiency. The section highlights that Europe's energy security transition must be multi-pronged and resilient, acknowledging not only physical infrastructure limits but also economic and geopolitical risk factors.

Section 4 develops and applies a robust multi-objective optimization framework to assess the strategic viability of the AAGP—also known as the Nigeria-Morocco Gas Pipeline—by the year 2050. The model integrates three interconnected policy goals: maximizing energy security for African transit countries, enhancing local transit revenues, and reducing European dependence on Russian natural gas imports. These goals are quantified through an objective function $\mathcal{F}$ composed of three weighted components: the Energy Security Index (ES), Local Transit Revenues (REV), and the Degree of Gas Replacement (DGR), each mathematically defined and parametrized with empirical assumptions. Constraints such as pipeline capacity, supply-demand balance, and geopolitical risk levels are incorporated to ensure technical realism and political feasibility. Applying the model to a 2050 scenario—where the AAGP operates at 30 bcm/year capacity and supplies 25 bcm/year to the EU—the findings reveal that the pipeline would yield 75 million USD/year in transit revenues across five West African countries, improve their combined energy security index to 1.55 (via increased gas reserves and usage in electricity), and offset 16.7% of the EU's historical reliance on Russian gas. The overall objective function value, $\mathcal{F} = 30.5151$, encapsulates the aggregated benefits of these three dimensions, with revenue generation emerging as the most impactful contributor. The model not only highlights the AAGP's potential to stimulate localized economic development and improve energy reliability but also underscores its geopolitical significance in Europe's diversification strategy. However, it cautions against overlooking critical trade-offs, such as tensions between gas exports and domestic retention, and emphasizes the importance of long-term decarbonization compatibility. The section ultimately frames the AAGP as more than a pipeline—it is a strategic lever for sustainable regional integration, energy resilience, and cross-continental cooperation, provided that planning incorporates equitable benefit-sharing, energy transition foresight, and geopolitical coordination.

Section 6 presents the findings of the Analytic Hierarchy Process (AHP) applied to assess four natural gas transit strategies for the Africa-Atlantic Gas Pipeline (AAGP) (Section 5.1). The analysis is organized into two main outcomes. First, the relative importance of the evaluation criteria is established (Section 5.3), with their corresponding weights discussed in detail (Section 6.1). Second, the performance scores of the four strategies—(S1) Transit Revenue and Gas-Sharing Strategy, (S2) Backhaul or Reverse Flow Strategy, (S3) Public-Private Partnership (PPP), and (S4) Spot Gas Market Strategy (Section 5.2)—are derived based on their alignment with these weighted criteria (Section 6.2). Together, these results provide a structured and comparative framework to inform strategic decision-making for the AAGP.

The conclusion section (Section 7) synthesizes the key findings of the study, and offers policy-relevant insights to guide future infrastructure planning, regional cooperation, and sustainable energy development.

2 Overview of Global Natural Gas Production and Future Demand Trends in Africa and Europe

This section provides a comprehensive overview of the global distribution of natural gas production by continent (Section 2.1) and examines the evolving demand trajectories for natural gas in both Africa and Europe, highlighting key implications for energy security and infrastructure planning (Section 2.2).

2.1 Major Natural Gas Producers in the World by Continent

The world's largest natural gas producers are distributed significantly across continents, with key players dominating regional and global production (Table 1).

North America is the leading natural gas producing region globally, accounting for about 31.1% of the world's total production in 2023. The United States is the top global producer, contributing 25.5% of the total global output. Canada also plays a significant role with 4.7% of the world's production. This region benefits

Table 1. Global distribution of natural gas production by continent and key countries in 2023. North America leads global natural gas production, driven primarily by the United States, which alone accounts for over a quarter of total output [8, 9]. The CIS region, led by Russia, remains a key player with nearly one-fifth of global production despite geopolitical challenges [8, 9]. The Middle East holds a substantial share due to its vast reserves, with Iran and Qatar as leading producers [8, 9]. Asia is an emerging region with significant growth, especially led by China [8, 9]. Africa, although representing a smaller share, is growing rapidly with Algeria, Egypt, and Nigeria as major contributors, also important in LNG production [8, 10]. South America and Oceania have smaller but regionally important production levels [8, 10].

Continent / Region	Share of Global Production (%)	Main Producing Countries (Share %)
North America	31.1	United States (25.5), Canada (4.7)
CIS (Commonwealth of Independent States)	19.1	Russia (14.4), Turkmenistan (1.9), Uzbekistan (1.1)
Middle East	17.6	Iran (6.2), Qatar (4.5), Saudi Arabia (2.8), UAE (1.4)
Asia (excluding Middle East)	∼10	China (5.8), Indonesia (1.6), Malaysia (2.0), others
Africa	∼6.2	Algeria (>2.5), Egypt (∼1.5), Nigeria (∼1.1), others
South America	∼3.5	Argentina, Peru, Bolivia
Oceania	∼3.4	Australia, Papua New Guinea

from vast reserves and well-developed infrastructure that support high and sustained production levels [3].

The Commonwealth of Independent States (CIS), primarily led by Russia, represents approximately 19.1% of global natural gas production. Russia is the world's second-largest producer, responsible for 14.4% of global production. Other CIS countries such as Turkmenistan (1.9%) and Uzbekistan (1.1%) also contribute to regional output, albeit on a smaller scale [3, 4].

The Middle East holds a substantial share of global production, around 17.6%. Key producers include Iran (6.2%), Qatar (4.5%), Saudi Arabia (2.8%), and the United Arab Emirates (1.4%). This region is rich in natural gas reserves, which explains its significant role in global production. The Middle East has experienced remarkable growth in natural gas output over recent decades [3, 4].

In Asia, China is a major player with 5.8% of global production, followed by Indonesia (1.6%), Malaysia (2%), and other countries like Thailand and Pakistan with smaller production volumes. Asia is an emerging region in the natural gas sector, with notable growth especially in China and Southeast Asia [3, 4].

Africa produced approximately 253 billion cubic meters of natural gas in 2023, marking significant growth over the past two decades. Leading producers include Algeria, the continent's top producer with over 100 billion cubic meters, followed by Egypt (around 59 billion) and Nigeria (about 42 billion). Countries such as Mozambique, Equatorial Guinea, Angola, Cameroon, and Congo are also increasingly important, particularly in liquefied natural gas (LNG) production. Algeria, Nigeria, and Egypt rank among the top 10 globally in LNG liquefaction capacity, highlighting their strategic importance. Africa's natural gas production and exports are expected to grow substantially in the coming decades [5, 6].

In South America, the main natural gas producers are Argentina, Peru, and Bolivia. These countries host large gas fields such as the San Martin-Cashiriari complex in Peru and several fields in Argentina's Neuquén province (Aguada Pichana, Fortin De Piedra, El Mangrullo). South America's production is smaller compared to other continents, with a projected decline until 2030. Nevertheless, these countries remain important suppliers within the region [7].

In summary, the largest natural gas producers are concentrated in North America (United States, Canada), Russia and the CIS countries, the Middle East (Iran, Qatar, Saudi Arabia), Asia (China, Indonesia), and Africa (Algeria, Nigeria, Egypt), while South America is represented mainly by Argentina, Peru, and Bolivia. Each continent plays a distinct role in the global natural gas balance, with particularly strong growth prospects in Africa and Asia.

2.2 Future Natural Gas Needs of Africa and Europe

2.2.1 Africa's Future Natural Gas Needs

Africa's natural gas sector is poised for significant growth driven by both domestic demand and export opportunities, particularly in liquefied natural gas (LNG). The continent currently holds about 6% of the world's natural gas supply, and this share is expected to grow by approximately 15% by 2030. This increase reflects rising energy needs across African countries as they pursue economic development, industrialization, and increased access to electricity [11–13].

Many African countries are expanding their power generation capacity, with natural gas playing a crucial role as a cleaner alternative to coal and oil. The demand for natural gas in residential, commercial, and industrial sectors is expected to increase substantially. The African Development Bank (AfDB) highlights that Africa is investing heavily to expand electricity access, with a strategy that includes renewable energy but also natural gas as a key source to diversify the energy mix and reduce reliance on more polluting fossil fuels. The "Light up and Power Africa" initiative aims to achieve universal electricity access by 2030, relying on projects that integrate natural gas [14]. The International Energy Agency (IEA) 2025 reports emphasize several gas projects in Africa, such as the Kudu power plant in Namibia (885 MW) and the Sandiara plant in Senegal, illustrating the growing importance of natural gas in power generation to meet increasing demand in residential, commercial, and industrial sectors. These projects also aim to enhance grid stability and support the energy transition [15]. The African Energy Chamber 2025 report states that natural gas production and consumption in Africa are growing, with sustained demand for electricity generated from gas, seen as a cleaner solution than coal and oil, especially in urban and industrial areas [16, 17]. The Djeno power plant project in the Republic of Congo, which is transitioning from oil to natural gas, exemplifies the trend of substituting more polluting sources with natural gas to increase power capacity and improve electricity access in urban and rural areas, directly impacting residential, commercial, and industrial sectors [18].

As African economies grow, industries such as manufacturing, petrochemicals, and fertilizers require more natural gas, both as feedstock and fuel. According to Business Day, African natural gas demand is primarily driven by power generation, industry, and transportation, with Egypt as the largest consumer. Industrial demand notably includes manufacturing and petrochemical sectors [19]. The Gas Exporting Countries Forum (GECF) report projects a 4% growth in Africa's gas consumption in 2025, fueled by industrialization and power sector demand. The report highlights gas-to-power projects in Algeria, Egypt, and Nigeria, where industry is a key natural gas user [20, 21]. The African Energy Chamber's 2025 report emphasizes the growing role of natural gas in African industries, especially petrochemicals and fertilizer production, which use gas both as fuel and feedstock. Expansion of gas capacity in Mozambique, Nigeria, Senegal, and Mauritania illustrates this increasing industrial potential [22–24]. The Africa Report notes that major gas discoveries in East and West Africa will support industrial growth, with significant investments in gas infrastructure to supply manufacturing, petrochemical, and fertilizer sectors [25].

Africa aims to become a major player in the global LNG market. Projects in Mozambique (Mozambique LNG), Nigeria, Senegal, and Mauritania are expected to significantly boost export capacity, helping to meet global demand while generating revenues for local economies [11, 13, 22].

Despite the potential, Africa faces challenges including infrastructure deficits, political instability, regulatory uncertainties, and financing hurdles that could delay project development and limit supply growth [11, 13, 26].

Overall, Africa's natural gas needs and production capacity are expected to expand steadily, with the continent playing a dual role as both a growing consumer and a key global supplier by 2030.

2.2.2 *Europe's Future Natural Gas Needs*

Europe's natural gas demand is influenced by a complex mix of energy transition goals, security considerations, and economic factors. While Europe is actively pursuing decarbonization and increased renewable energy deployment, natural gas remains a vital component for energy security and supply diversification.

Following recent geopolitical tensions and supply disruptions, Europe is focused on diversifying its gas sources, including increasing imports of LNG from Africa and other regions to reduce dependence on pipeline gas from Russia. The European Commission published a roadmap to fully end the EU's dependency on Russian energy by 2025, including national plans to diversify gas supply sources with an increased role for LNG imports from various regions, including Africa [27]. The AggregateEU mechanism launched by the European Commission coordinates medium-term gas purchases, enabling member states to access competitive offers from reliable international suppliers as part of a strategy to diversify supplies and reduce Russian dependence [28]. An Ember Energy report highlights that despite a temporary increase in Russian gas flows via TurkStream in early 2025, the EU is accelerating efforts to phase out Russian gas, notably by expanding LNG imports from alternative regions [29]. An analysis by the OSW (Centre for Eastern Studies, Warsaw) describes a turbulent European gas market in 2025, marked by geopolitical tensions and a strong political will to reduce Russian imports, with increased reliance on LNG and alternative suppliers [30]. Documents from the European Commission and academic studies emphasize the commercial and geopolitical challenges of supplier diversification but confirm that the EU is betting on LNG, including from Africa, to secure medium- and long-term supplies [31–33]. The Carnegie Endowment for International Peace notes that Eastern Europe has successfully diversified its gas sources in recent years, notably through LNG infrastructure development on the Baltic and Adriatic coasts, with diversification including LNG imports from Africa and other regions [34].

Natural gas is widely regarded as a transitional fuel that facilitates the shift from coal and oil to cleaner energy sources by providing reliable and flexible backup for intermittent renewables such as wind and solar. It plays a crucial role in ensuring grid stability by rapidly responding to fluctuations in renewable generation, thereby complementing the variability of wind and solar power and reducing reliance on more polluting fuels like coal [35–39]. This flexibility enables a smoother and faster energy transition, making natural gas-fired power plants an essential partner to renewable energy expansion. The environmental advantages of natural gas, particularly in the form of LNG, further support its role as a bridge fuel during this critical period of decarbonization [36].

Europe's industrial base and residential heating sectors continue to demand significant volumes of natural gas due to their energy-intensive processes and heating requirements. However, ongoing improvements in energy efficiency and the increasing electrification of heating and industrial processes are expected to moderate natural gas consumption growth, potentially leading to a gradual decline in some sectors over the coming decades. These trends reflect Europe's broader climate goals and efforts to decarbonize its economy while maintaining energy security and affordability [40, 41].

According to international energy outlooks, Europe's natural gas consumption is expected to stabilize or slightly decline over the next decade, but demand for LNG imports is likely to increase to compensate for reduced pipeline supplies and to meet seasonal peaks [42, 43].

2.3 Main Transit Axes of the European Gas Network

The European gas network constitutes one of the most complex and strategically significant energy infrastructures in the world. As the European Union (EU) strives to enhance its energy security, decarbonize its economy, and diversify its energy supply sources, understanding the main gas transit routes is essential. These routes not only ensure the continuous delivery of natural gas to industries and households but also reflect the geopolitical and infrastructural dependencies across the continent. Broadly, the European gas transit system is structured around four major supply corridors: the Eastern Corridor, the Northern Corridor, the Southern Gas Corridor, and the Western Route (LNG and regional pipelines) [44–46].

2.3.1 The Eastern Corridor: Russian Gas Transit Routes

The Eastern Corridor comprises the principal natural gas pipelines that historically transported Russian gas to Europe, forming the backbone of the continent's gas supply network for decades. These include **the Nord Stream system under the Baltic Sea**, **the Transgas (or Brotherhood) pipeline through Ukraine**, **the Yamal-Europe pipeline via Belarus and Poland**, and **the TurkStream pipeline across the Black Sea to Southeast Europe**. Collectively, these routes have had the capacity to deliver well over 250 billion cubic meters (bcm) of gas annually to European markets. However, geopolitical shifts, particularly following the 2022 Russian invasion of Ukraine, have led to a dramatic decline in flows through most of these channels.

The Transgas (Brotherhood) pipeline has historically been the most important route, transporting gas from Russia's western Siberian fields through Ukraine, Slovakia, Czech Republic, and into Central and Western Europe (Austria, Germany, Hungary, Italy) [47, 48] (Figure 1). This route alone had a peak annual capacity of over 142 billion cubic meters (bcm), with Ukraine's gas transmission system playing a crucial role as the main transit state [48, 49]. For many years, this pipeline carried more than 80% of Russian gas exports to Europe, but its significance has diminished sharply due to political tensions, transit disputes, and the war in Ukraine. As of 2024, only one of the two main entry points into Ukraine remains operational (Sudzha), limiting volumes to well below

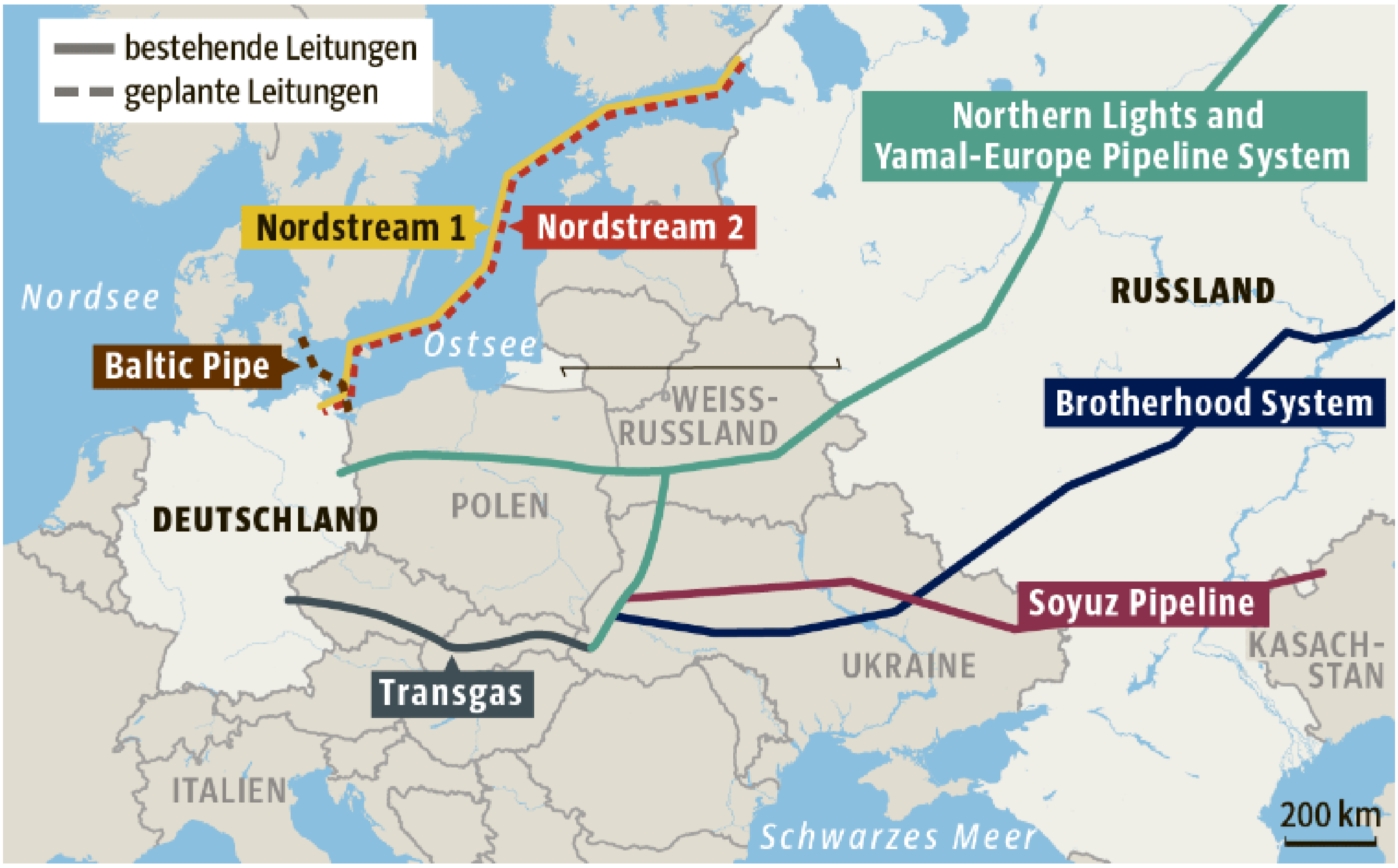

Figure 1. The Route of the Transgas (Brotherhood) Pipeline.

30 bcm/year, and future use remains uncertain amid infrastructure damage and strategic reorientation away from Russian gas [50–52].

The Yamal-Europe pipeline was designed in the 1990s as a strategic alternative to the Ukrainian route. It transports gas from the Torzhok hub in Russia across Belarus, Poland, and into Germany at the Mallnow interconnection point (Figure 2). With a designed capacity of 33 bcm/year, it became a key supply line for Central and Western Europe. However, tensions between the EU and Belarus, along with Poland's decision in 2022 not to renew its long-term contract with Gazprom, have effectively suspended its regular westbound flow. Since then, the pipeline has operated in reverse mode, with Germany sending gas eastward to meet Polish and regional demand, marking a symbolic shift in control and direction of energy flows [53–56].

Figure 2. Transit Path of the Yamal–Europe Gas Pipeline. Source: [57].

The Nord Stream 1 pipeline—arguably the most emblematic of EU-Russia energy cooperation in the early 21st century—runs under the Baltic Sea, directly connecting Russia (Vyborg) to Germany (Greifswald) (Figure 3). Operational since 2011, it had a capacity of 55 bcm/year, supplying a significant portion of German and European gas demand while bypassing transit countries [58, 59]. Its twin, **Nord Stream 2**, was intended to double this capacity to 110 bcm/year but was never brought online due to regulatory delays and was subsequently sanctioned and suspended following Russia's military escalation in Ukraine. In late 2022, both Nord Stream 1 and Nord Stream 2 were severely damaged in a suspected act of sabotage, rendering them inoperable. These events, combined with the EU's urgent push to end reliance on Russian fossil fuels, have marked the effective collapse of the Nord Stream route as a viable long-term supply option [60].

Figure 3. Spatial Configuration of Nord Stream 1 and 2 Pipelines. Source: [65].

The TurkStream pipeline is the most recent addition to Russia's strategic bypass infrastructure. Commissioned in 2020, it comprises two parallel lines of 15.75 bcm/year each, transporting gas from Russia (Anapa) under the Black Sea to Turkey (Kıyıköy) (Figure 4). While the first string supplies Turkish domestic demand, the second transits gas into Southeast Europe—namely Bulgaria, Serbia, and Hungary, with potential flows extending to Bosnia and Herzegovina, North Macedonia, and Austria. This makes TurkStream a crucial conduit for Russian gas into Balkan markets, particularly after the decline of other routes. As of 2024, it remains fully operational and politically supported by regional governments, though its long-term viability is increasingly questioned in light of EU decarbonization and diversification policies [61–63].

In summary, the Eastern Corridor's main transit routes once enabled over 250 bcm of Russian gas per year to flow into Europe across a network spanning Russia, Ukraine, Belarus, Poland, Germany, Slovakia, Czech Republic, Turkey, and several Southeast European

Figure 4. Route of the TurkStream pipeline. Source: [64].

countries. However, due to a convergence of geopolitical ruptures, energy market reform, and strategic realignment, most of these routes are now operating at minimal capacity or have been suspended altogether. The collapse of Nord Stream, the stagnation of Yamal-Europe, and the partial functionality of Transgas highlight the EU's accelerating shift toward energy independence, with only TurkStream retaining a consistent role in the new gas geography of Europe.

2.3.2 The Southern Gas Corridor: North and West African Gas Transit Routes to Europe

The Southern Gas Corridor (SGC) represents a strategic framework for diversifying Europe's gas imports by harnessing reserves from non-Russian sources—particularly those in North and sub-Saharan Africa. As Europe accelerates its energy diversification away from Russian gas, the corridor's western routes—anchored by the Gazoduc Maghreb-Europe (GME), the planned Africa Atlantic Gas Pipeline (AAGP), the Trans-Saharan Gas Pipeline (TSGP), and the Medgaz, Galsi, and Transmed pipelines—are gaining renewed geopolitical and commercial significance. These pipelines are envisioned as vital conduits connecting Africa's abundant natural gas reserves with European markets through the Iberian Peninsula and Mediterranean, forming both operational and aspirational components of Europe's evolving gas architecture.

The Gazoduc Maghreb-Europe (GME) is the most established infrastructure within this corridor. Commissioned in 1996, the pipeline transports natural gas from Hassi R'Mel in Algeria through Morocco, across the Strait of Gibraltar, and into Spain and

Portugal. The GME was originally constructed with a capacity of around 12–13 billion cubic meters (bcm) per year, although effective throughput has fluctuated due to contractual dynamics and political tensions. For over two decades, it played a key role in securing Iberian gas supplies while offering transit benefits to Morocco. However, in October 2021, Algeria chose not to renew the gas transit contract with Morocco amid diplomatic tensions, halting direct flow through GME. Since then, gas exports to Spain have continued via the Medgaz subsea pipeline, bypassing Morocco. Nonetheless, GME remains a physically intact and geopolitically valuable asset, and in light of the EU's post-2022 diversification strategy, there is growing interest—particularly from Morocco and Spain—in reactivating or even reversing the pipeline to allow for bidirectional trade, possibly including green hydrogen in the future [66–68].

In a bid to amplify the strategic role of West Africa in the Southern Gas Corridor, **the Africa Atlantic Gas Pipeline (AAGP)**—also known as **the Nigeria-Morocco Gas Pipeline (NMGP)**—is currently in planning and early implementation stages. AAGP is a major infrastructure project designed to connect Nigeria's vast natural gas reserves to Morocco and eventually to Europe to provide an alternative or complement to Russia gas for Europe. Initiated in 2016 and valued at approximately $25–26 billion, the pipeline aims to transport up to 30 billion cubic meters of natural gas per year and will stretch between 5,600 and 7,000 kilometers, crossing 13 countries along the Atlantic coast,—including Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Liberia, Sierra Leone, Guinea, Guinea-Bissau, Gambia, Senegal, Mauritania, before reaching Morocco (Figure 5)—-and integrating with the existing West African Gas Pipeline network.

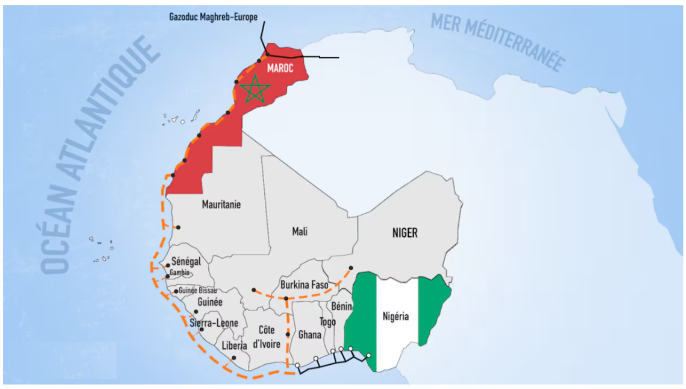

Figure 5. Route of the African Atlantic Gas Pipeline (AAGP), also referred to as the Nigeria–Morocco Gas Pipeline [71].

The construction of the Atlantic Africa gas pipeline will unfold in three distinct phases. From the outset, two sections will be developed simultaneously: (i) in the north, a route will connect Morocco, Mauritania, and Senegal, with an interconnection to the European network via the Maghreb-Europe Gas Pipeline (GME) planned as early as 2029; (ii) in the south, another section will link Nigeria, Ghana, and Côte d'Ivoire. The final phase (2035–2040) will focus on connecting these two segments to form an integrated 6,500 km gas corridor [69] (Figure 5).

The Atlantic Africa gas pipeline is expected to integrate with the gas infrastructure currently under development in Morocco. These infrastructure projects are part of the national natural gas roadmap (2024–2030). In the short term (2024–2026), priority projects focus on strengthening the gas network by connecting the new Tendrara fields (in the Oriental region) and Anchois fields (off the coast of Larache) to the Maghreb-Europe Gas Pipeline (GME). This also includes the development of several ports for importing liquefied natural gas (LNG)—notably the new Nador West Med port, as well as Mohammédia ("MOH"), Jorf Lasfar ("JL"), and a fourth port currently under study—and linking them to the GME, which is itself connected to natural gas-fired power plants in the north, particularly Al Wahda and Tahaddart. By 2030, coinciding with the anticipated completion of the first phase of the Atlantic Africa gas pipeline, construction of the pipelines connecting Mohammédia (set to be linked to the GME by 2026) to Dakhla will be finalized. Initially, this will allow for a connection to gas fields in Mauritania and Senegal, ahead of the full integration of the Atlantic Africa pipeline by 2035 [69].

The AAGP project is generating strong international interest, particularly from the United States, which is considering investing in the pipeline as part of an energy and geopolitical strategy in Africa. China is also involved through the Jingye Group, which will supply the steel needed for the pipeline's construction [70].

This pipeline is in competition with **the Trans-Saharan Gas Pipeline (TSGP)** — also known as **the Nigeria-Niger-Algeria Gas Pipeline**— supported by Nigeria, Niger, and Algeria. First conceptualized in the 1980s, it aims to transport Nigerian natural gas to Europe via Niger and Algeria. Despite early ambitions, the implementation agreement between Nigeria, Algeria, and Niger was only signed in July 2009. The pipeline was initially scheduled to begin operations in 2027. However, security risks in the Niger Delta, northern Niger, and southern Algeria have significantly delayed progress. A protocol was signed again in July 2022 amidst rising energy prices following the war in Ukraine, but the 2023 coup in Niger placed the country under sanctions, further stalling the project [2]. The pipeline is approximately 4,128 kilometers long and is expected to have a capacity of 30 billion cubic meters of gas per year. The TSGP starts in Warri, Nigeria, runs north through Niger, and reaches Hassi R'Mel in Algeria, where it connects to existing pipelines such as the Trans-Mediterranean, Maghreb–Europe, Medgaz, and Galsi pipelines (Figure 6). These connections enable gas exports to European markets via Algeria's Mediterranean coast.

The Transmed (Trans-Mediterranean Pipeline), inaugurated in the early 1980s, is one of the oldest and most reliable conduits for Algerian gas into Europe. It originates in Hassi R'Mel, Algeria's key gas hub, and traverses Tunisia before crossing the Sicilian Channel via the undersea Enrico Mattei pipeline, reaching Sicily, mainland Italy, and further north to Slovenia and Austria. Transmed has an annual technical capacity of around 33 bcm, with Algeria and Italy having periodically ramped up volumes in response to market needs. Following the Russia–Ukraine war, Transmed's strategic value has increased significantly: Italy has expanded its import volumes via this route to compensate for lost Russian supplies, with the Italian government and Sonatrach (Algeria's national oil and gas company) signing new supply agreements that aim to push usage close to maximum capacity [72–74].

The Medgaz pipeline provides a direct subsea link between Algeria and Spain, bypassing transit through Morocco. Commissioned in 2011, it runs from Beni Saf on Algeria's coast to Almería in southeastern Spain. With an initial capacity of 8 bcm/year, it has since been expanded to 10–11 bcm/year. Medgaz has become increasingly important since the diplomatic breakdown between Algeria and Morocco in 2021, which led to the non-renewal of the GME transit agreement. Consequently, all of Algeria's gas exports to Spain now go through Medgaz, although volumes have fluctuated due to political tensions between Algeria and Madrid over the Western Sahara issue. The pipeline is jointly owned by Sonatrach and international partners and represents a technically efficient, albeit geopolitically sensitive, lifeline in the Mediterranean gas supply chain [75, 76].

Figure 6. Major gas export pipelines from North and West Africa to Europe. The map illustrates the key operational and planned infrastructures forming the Southern Gas Corridor: **(i) The Transmed (Trans-Mediterranean Pipeline)** transports Algerian gas via Tunisia to Italy, with a capacity of 33 bcm/year. **(ii) The Medgaz Pipeline** directly links Algeria (Beni Saf) to Spain (Almería), with a capacity of 10–11 bcm/year. **(iii) The Gazoduc Maghreb-Europe (GME)** crosses Algeria, Morocco, and the Strait of Gibraltar to supply Spain, with a former capacity of 12–13 bcm/year (currently inactive since 2021). **(iv) The proposed Galsi Pipeline** would link Algeria to Sardinia and mainland Italy, with a planned capacity of 8 bcm/year. **(v) The Trans-Saharan Gas Pipeline (TSGP)**, under consideration, would connect Nigeria to Algeria via Niger, enabling up to 30 bcm/year of gas exports to Europe. **(vi) The Africa Atlantic Gas Pipeline (AAGP/NMGP)** is a planned 5,600 km project from Nigeria to Morocco, intended to supply West African nations and connect to Europe via the GME corridor, with a potential capacity of 30 bcm/year. These infrastructures collectively form a strategic alternative to Russian gas imports, enhancing EU energy security and fostering transcontinental energy cooperation. Source: [67].

Another notable infrastructure is **the Galsi (Gasdotto Algeria Sardegna Italia) pipeline**, a proposed but never-completed project aimed at linking Algeria directly with Sardinia and the Italian mainland. Galsi was conceived to diversify Algeria's export routes and strengthen Italy's gas import options through a 900-kilometer offshore pipeline with a planned capacity of around 8 bcm/year. The route would originate from Koudiet Draouche (Algeria) to Porto Botte (Sardinia) and on to Tuscany. Although feasibility studies were completed and intergovernmental agreements signed in the late 2000s, the project has stalled due to cost concerns, changing market dynamics, and more recently, a shifting European focus toward renewables and hydrogen. Nevertheless, Galsi is occasionally revisited in Italian-Algerian bilateral dialogues and may resurface as part of hydrogen-ready infrastructure discussions.

In conclusion, the Southern Gas Corridor from Africa to Europe comprises both existing infrastructure—Transmed, Medgaz, GME—and planned megaprojects—Galsi, AAGP, TSGP—that collectively embody over 100 bcm/year of potential capacity. These pipelines traverse a mosaic of countries including Algeria, Tunisia, Morocco, Nigeria, Niger, Spain, Italy, and over ten West African coastal nations. While some pipelines are well-integrated into European energy markets, others remain aspirational, contingent upon geopolitical stability, financial viability, and alignment with Europe's energy transition goals. However, their combined significance is undeniable: they position Africa as an indispensable partner in Europe's evolving energy architecture—whether for natural gas, hydrogen, or future clean energy trade.

2.3.3 *The Northern and Western Gas Corridors: Norway and North Sea Flows into Europe*

The Northern and Western Gas Corridors comprise the pipeline systems transporting natural gas from the North Sea basin—primarily from Norway and to a lesser extent from the United Kingdom and the Netherlands—into continental Europe. Norway, now the largest pipeline gas supplier to the European Union, exported approximately 122 billion cubic meters (bcm) of gas in 2022–2023, accounting for over 25% of the EU's total gas imports. The Norwegian system, operated by Gassco, is anchored by major offshore pipelines: Europipe I & II and Norpipe to Germany (Dornum and Emden), Langeled to the United Kingdom (Easington), Zeepipe to Belgium (Zeebrugge), and Franpipe to France (Dunkerque), collectively capable of delivering over 120 bcm/year. These pipelines cross the North Sea, ensuring direct flows into Germany, France, Belgium, and the UK, from production fields such as Troll, Ormen Lange, and Åsgard. Additionally, the UK–Belgium Interconnector and Balgzand–Bacton Line (BBL) enable west–east flows of Norwegian gas from the UK to Belgium and the Netherlands, reinforcing regional flexibility. While Dutch gas production (notably from Groningen) has declined sharply and UK exports are modest, the corridor as a whole remains a strategic, high-volume, and politically stable supply route, underpinning Western Europe's energy diversification and resilience in the post-Russian gas era [77–80].

3 Simulating EU Gas Supply Security in a 2050 Scenario without Russian Pipeline Imports

The cessation of Russian pipeline gas—formerly a backbone of Europe's energy security—would constitute the most severe stress test for the European Union's natural gas system. Russia supplied approximately 40–45% of EU gas imports in 2021, a dependency that has proven geopolitically unsustainable. Assuming a complete halt in flows via the **Eastern Corridor**—comprising the Brotherhood (Transgas), Yamal-Europe, Nord Stream, and TurkStream pipelines—this section explores which supply corridors can fill the resulting gap by 2050. Corridor-based modeling is combined with infrastructure capacity assessments, using a quantitative approach grounded in gas flow optimization and long-term energy transition scenarios.

Let the projected total EU gas demand in 2050 be denoted as D_{EU}^{2050}. According to IEA and ENTSOG mid-range scenarios—accounting for decarbonization pathways, hydrogen substitution, electrification of end-uses, and building renovation policies—EU gas demand may range from 350 to 450 bcm/year. For this simulation, the assumption is set as follows:

$$D_{EU}^{2050} = 400\,\text{bcm/year}$$

Let total non-Russian pipeline gas supply be denoted as S_{NR}^{2050}, composed of:

$$S_{NR}^{2050} = S_{\text{South}}^{2050} + S_{\text{North}}^{2050} + S_{\text{LNG}}^{2050}$$

where S_{South}^{2050} denotes the supply from the Southern Gas Corridor, S_{North}^{2050} represents the supply from

Norway and the North Sea, and S_{LNG}^{2050} stands for liquefied natural gas imports via EU regasification terminals.

Under full Russian cutoff:

$$S_{\text{RU}}^{2050} = 0 \quad \Rightarrow \quad \Delta S = S_{\text{RU}}^{2021} \approx 155\,\text{bcm/year}$$

Our goal is to test whether:

$$S_{NR}^{2050} \geq D_{EU}^{2050}$$

If this condition fails, Europe must implement alternative measures: energy efficiency, green gases, or LNG expansion.

3.1 Eastern Corridor Deactivation

The following pipelines are fully decommissioned in this scenario: the Transgas (Brotherhood) pipeline via Ukraine to Central Europe, the Yamal-Europe line via Belarus and Poland, the Nord Stream 1 & 2 direct undersea lines to Germany (which have been non-operational since 2022), and the TurkStream pipeline under the Black Sea to Turkey and onward into Bulgaria and Serbia.

The cumulative capacity of these pipelines was $> 180\,\text{bcm/year}$, of which $\sim 155\,\text{bcm/year}$ was historically delivered.

$$S_{\text{RU}}^{2021} \approx 155\,\text{bcm/year} \quad \Rightarrow \quad \Delta S = 155\,\text{bcm/year}$$

3.2 Southern Gas Corridor Potential

The Southern Corridor connects North and West African gas fields to Europe. With infrastructure expansion and regional cooperation, it represents the most scalable terrestrial alternative.

Table 2 presents the pipeline capacity estimates for the Southern Gas Corridor, which comprises multiple pipelines with a total projected capacity of approximately 118.15 bcm/year by 2050.

$$\begin{aligned} S_{\text{South}}^{2050} &= \sum_{i=1}^{6} C_i \\ &= 10 + 30 + 30 + 30.15 + 8 + 10 \\ &= 118.15\,\text{bcm/year} \end{aligned}$$

The development and operation of major transcontinental gas infrastructure projects, such as the Nigeria–Morocco Gas Pipeline (NMGP), face several notable risks that must be addressed to ensure long-term viability.

Geopolitical risks remain a critical concern, particularly in regions like Northern Nigeria and Niger, which are historically prone to conflict and political instability. These conditions can threaten both the construction phase and the operational security of the pipeline.

Financing gaps pose another major challenge. Large-scale projects such as the NMGP require substantial investment—exceeding $25 billion in some estimates. Securing long-term funding from international financial institutions and public–private partnerships will be essential for advancing these initiatives.

Transit cooperation between countries is also a key element of risk mitigation. In particular, cooperation between Morocco and Algeria, as well as between Algeria and the European Union, must be enhanced to ensure smooth gas transit, regional coordination, and infrastructure interoperability.

Despite these risks, the strategic significance of these pipelines cannot be overstated. They represent stable, long-term assets that can support Europe's diversification efforts away from Russian gas, strengthen energy security, and promote economic integration across Africa and Europe.

3.3 Northern and Western Corridor Capacity

Norway, the UK (re-exporting), and the Netherlands are the pillars of the Northern Corridor, supplying via mature but reliable offshore infrastructure. The main pipelines, their capacities, and routes are summarised in Table 3.

Norwegian gas is characterised by its relatively low carbon intensity, making it one of the cleaner fossil fuel options available during the transition to net-zero energy systems. This makes it a strategically important supply source for Europe as it seeks to decarbonise without compromising energy security.

However, the majority of Norwegian fields are mature, and sustaining production levels will require continued investment in enhanced oil and gas recovery (EOR) technologies. These measures are essential to prolong field life and ensure stable output beyond 2030.

In contrast, some of the United Kingdom's offshore

Table 2. Southern corridor gas supply projections.

Pipeline	Capacity (bcm/year)	Status & Assumptions by 2050
Gazoduc Maghreb-Europe (GME) (Algeria-Morocco-Spain)	10	Reinstated by 2030
Africa Atlantic Gas Pipeline (AAGP/NMGP) (Nigeria-Morocco)	30	Commissioned by 2045
Trans-Saharan Gas Pipeline (TSGP) (Nigeria-Niger-Algeria)	30	Commissioned by 2040
Transmed Pipeline (Algeria-Tunisia-Italy)	33.5	90% utilization
Medgaz Pipeline (Algeria-Spain)	8	Fully utilized
GALSI Pipeline (Algeria-Sardinia-Italy)	10	Operational by 2045
Total	**118.15**	

gas fields are expected to enter decline in the coming years. Nevertheless, the UK may continue to play a key role in the gas supply chain through liquefied natural gas (LNG) imports and re-export activities. LNG regasification terminals in the UK can help balance regional supply and demand, particularly during peak winter months or in response to disruptions in continental supply routes.

LNG Imports and Flexibility

LNG plays a flexible balancing role—diversifying sources (US, Qatar, Nigeria, Mozambique). The total technical regasification capacity of EU LNG terminals, as shown in Table 4, is 190 bcm/year. This represents the infrastructure capacity—what the system can handle under ideal operational conditions.

Table 4. EU LNG terminal capacities (2030 and Beyond).

Country	Regasification Capacity (bcm/year)
Spain	65
France	40
Netherlands	25
Poland	15
Italy	20
Germany	25
Total	**190 (available)**

However, not all capacity is used 100% year-round (due to maintenance, shipping delays, or lack of contracts). There are utilization constraints, market dynamics, and realistic supply availability from exporters (e.g., US, Qatar).

$$S_{\text{LNG}}^{2050} = 130\,\text{bcm/year} \quad \text{(conservative scenario)}.$$

It reflects a realistic throughput estimate for 2050 under expected market and policy conditions, not the physical maximum.

Liquefied natural gas (LNG) presents several challenges that complicate its role as a reliable component of Europe's energy transition. One of the most significant issues is price volatility, which is heavily influenced by global market dynamics, particularly demand fluctuations in Asia. When Asian countries secure large volumes of LNG at premium prices, it can drive up costs and reduce availability for European buyers.

Additionally, the European Union has historically relied more on spot market purchases rather than securing long-term contracts, unlike many Asian countries. This exposes EU member states to greater price uncertainty and supply risks, especially during periods of market tightness or geopolitical tension.

From an environmental standpoint, LNG also carries a higher carbon footprint compared to pipeline gas. The processes involved in liquefaction (cooling the

Table 3. Main pipelines of the Northern Corridor and their capacities (updated in three-line format).

Pipeline	Capacity (bcm/year)	Main Route
Europipe I & II	40	Norway–Germany
Norpipe	20	Norway–Germany
Langeled	25	Norway–UK
UK–Belgium / UK–Netherlands Interconnectors	25	To EU mainland

gas), long-distance shipping, and regasification all contribute to additional CO_2 emissions. While cleaner than coal or oil, LNG still represents a significant source of greenhouse gas emissions, making its role in a climate-neutral future inherently limited.

Supply-Demand Balance

Combining all non-Russian corridors:

$$S_{NR}^{2050} = S_{\text{South}}^{2050} + S_{\text{North}}^{2050} + S_{\text{LNG}}^{2050}$$

$$S_{NR}^{2050} = 118.15 + 110 + 130 = 358.15\,\text{bcm/year}$$

Remaining supply gap:

$$\Delta_{\text{Gap}}^{2050} = D_{EU}^{2050} - S_{NR}^{2050} = 400 - 358.15 = 41.85\,\text{bcm/year}$$

Strategic Recommendations

To address the 42 bcm shortfall, the EU must deploy a combination of measures: enhancing energy efficiency and reducing demand by 10–15% through building retrofits and industrial optimization; scaling green gases (biomethane, hydrogen) by 20–30 bcm/year; expanding LNG import capacity by 10–20 bcm/year; and supporting flexible demand-side and seasonal storage measures.

Corridor-Based Substitution Potential

The substitution potential of different supply corridors for Russian gas is summarized in Table 5. The analysis shows that while alternative corridors collectively offer substantial capacity, significant gaps remain to be addressed.

While the simulation shows that the EU can technically replace all Russian gas imports by 2050, doing so requires full deployment of alternative corridors, high geopolitical cooperation, and early infrastructure investment. As indicated in Table 5, the Southern Corridor, while promising, is geopolitically fragile. The Northern Corridor offers stability, but limited scalability. LNG is indispensable but vulnerable to global price shocks. The final 10% gap will likely be closed through non-methane alternatives, demand reduction, and green gas expansion.

4 Optimization Model: Africa-Atlantic Gas Pipeline (AAGP) Scenario by 2050

4.1 Objective Function Framework: Maximizing Energy Security, Local Revenues, and European Energy Independence via the Africa Atlantic Gas Pipeline (AAGP)

To quantitatively evaluate the strategic role of the Africa Atlantic Gas Pipeline (AAGP), also known as the Nigeria-Morocco Gas Pipeline (NMGP), we construct a multi-objective optimization framework that captures the three interlinked policy goals: **(i)** Maximizing energy security for transit countries, **(ii)** Enhancing local economic revenue generation, **(iii)** Reducing European dependence on Russian gas.

We define an objective function $\mathcal{F}$ composed of three sub-functions:

$$\mathcal{F} = \alpha_1 \cdot ES + \alpha_2 \cdot REV + \alpha_3 \cdot DGR \tag{1}$$

where ES denotes the Energy Security Index for transit countries, REV represents the Annual Transit Revenue for local economies, DGR stands for the Degree of Gas Replacement defined as the share of Russian gas offset by AAGP gas in EU imports, and $\alpha_i \in [0, 1]$ are the weights assigned to each policy priority, with $\sum \alpha_i = 1$.

Energy Security Index for Transit Countries (ES)

$$ES = \sum_{i=1}^{n} \left(\omega_{i1} \cdot \frac{G_i^{\text{res}}}{G_i^{\text{demand}}} + \omega_{i2} \cdot \frac{P_i^{\text{gas}}}{P_i^{\text{total}}} \right) \tag{2}$$

where G_i^{res} denotes the strategic gas reserves in country i, G_i^{demand} represents the domestic annual gas demand in country i, P_i^{gas} stands for the gas-based power generation in country i, P_i^{total} indicates the total power generation in country i, and $\omega_{i1}, \omega_{i2} \in [0, 1]$ with $\omega_{i1} + \omega_{i2} = 1$.

Local Transit Revenues (REV)

$$REV = \sum_{i=1}^{n} (T_i \cdot V_i \cdot \pi) \tag{3}$$

where T_i is the tariff per cubic meter of gas transiting country i, V_i denotes the annual volume of gas transported through country i (in bcm/year), and π represents the average market price per unit of gas (in USD/m^3).

Degree of Gas Replacement (DGR)

$$DGR = \frac{V_{\text{AAGP}}^{\text{EU}}}{V_{\text{RUSSIA}}^{\text{base}}} \tag{4}$$

where $V_{\text{AAGP}}^{\text{EU}}$ denotes the annual volume of gas supplied by the AAGP to the EU (in bcm/year) and $V_{\text{RUSSIA}}^{\text{base}}$ represents the historical baseline volume of gas imported from Russia to the EU, typically set at a reference level such as that of 2021.

Table 5. Corridor-based substitution of Russian gas.

Corridor	Capacity (bcm/year)	Feasibility	Remarks
Southern	118.15	Medium-High	Depends on African geopolitics
Northern & Western	110	High	Based on stable Norwegian output
LNG	130	Medium	Price volatility, infra-dependent
Total	**358.15**	–	**Gap: 41.85 bcm**

4.2 Constraints

The optimization is subject to technical and geopolitical constraints:

- **Pipeline Capacity Constraint:**

$$V_i \leq C_{\text{AAGP}} \tag{5}$$

  where C_{AAGP} is the maximum design capacity of the pipeline.

- **Supply-Demand Balancing:**

$$\sum_{i=1}^{n} V_i \leq G_{\text{source}} \tag{6}$$

  where G_{source} is the annual gas supply capacity from Nigeria and other sources.

- **Security and Stability Constraint:**

$$R_i^{\text{risk}} \leq R_{\text{max}} \tag{7}$$

  where R_i^{risk} is the geopolitical or infrastructure risk index of country i.

This quantitative framework allows for scenario testing under different weightings of $\alpha_1, \alpha_2, \alpha_3$ to reflect European diversification objectives, African regional development priorities, and global security concerns. It provides a robust structure for evaluating the AAGP as a pivotal instrument in a cooperative and resilient energy transition by 2050.

4.3 Application of the Optimization Model: Africa-Atlantic Gas Pipeline (AAGP) Scenario by 2050

To demonstrate the policy applicability of the proposed optimization model, a 2050 scenario is simulated in which the Africa Atlantic Gas Pipeline (AAGP), also known as the Nigeria–Morocco Gas Pipeline (NMGP), is fully operational, transporting natural gas from Nigeria to Europe via West African countries and Morocco.

4.3.1 *Assumptions*

We consider the following assumptions: the pipeline capacity is set at $C_{\text{AAGP}} = 30$ bcm/year, based on the NMGP design; the available Nigerian export supply is $G_{\text{source}} = 35$ bcm/year; the annual exported volume to the EU is $V_{\text{AAGP}}^{\text{EU}} = 25$ bcm/year; the historical Russian gas import volume to the EU in 2021 is $V_{\text{RUSSIA}}^{\text{base}} = 150$ bcm/year; the average gas market price is $\pi = 10$ USD/m^3; transit tariffs are set at $T_i = 0.3$ USD/m^3 in each of the $n = 5$ transit countries; the domestic gas demand per transit country is $G_i^{\text{demand}} = 2$ bcm/year; the strategic gas reserves per transit country are $G_i^{\text{res}} = 0.5$ bcm/year; the share of gas in the national power mix is $P_i^{\text{gas}}/P_i^{\text{total}} = 0.40$; the weights in the energy security index are $\omega_{i1} = 0.6$ and $\omega_{i2} = 0.4$; and the weights in the objective function are $\alpha_1 = 0.3$, $\alpha_2 = 0.4$, and $\alpha_3 = 0.3$.

4.3.2 *Numerical Application*

Energy Security Index (ES):

$$\begin{aligned} ES &= \sum_{i=1}^{5}\left(0.6 \cdot \frac{0.5}{2} + 0.4 \cdot 0.40\right) \\ &= 5 \cdot (0.6 \cdot 0.25 + 0.4 \cdot 0.40) \\ &= 5 \cdot (0.15 + 0.16) \\ &= 5 \cdot 0.31 \\ &= \boxed{1.55} \end{aligned} \tag{8}$$

Local Transit Revenues (REV):

$$REV = \sum_{i=1}^{5}(0.3 \cdot 5 \cdot 10) = 5 \cdot 15 = \boxed{75 \text{ million USD/year}} \tag{9}$$

Degree of Gas Replacement (DGR):

$$DGR = \frac{25}{150} = \boxed{0.167} \tag{10}$$

Overall Objective Function Value:

$$\begin{aligned}\mathcal{F} &= 0.3 \cdot 1.55 + 0.4 \cdot 75 + 0.3 \cdot 0.167 \\ &= 0.465 + 30 + 0.0501 \\ &= \boxed{30.5151}\end{aligned} \tag{11}$$

4.3.3 Interpretation

The computed value of the overall objective function, $\mathcal{F} = 30.5151$, serves as a strategic indicator of the Africa Atlantic Gas Pipeline's (AAGP) potential impact by 2050. This value synthesizes the contributions of three critical policy dimensions: local economic development through transit revenues, enhancement of energy security for African transit countries, and support for Europe's diversification away from Russian gas. To better understand the strategic significance of this figure, each of the sub-objectives is examined in turn.

First, local transit revenues (REV) emerge as the most significant contributor to the total objective function. The AAGP is projected to generate an estimated $75 million USD annually in transit fees distributed across five West African countries. This revenue stream represents more than just a fiscal inflow—it also stimulates broader economic activity. The construction and operation of the pipeline are expected to catalyze job creation, stimulate investment in infrastructure, and trigger localized industrial development along the corridor. These economic spillovers may, in turn, contribute to long-term structural transformation in participating countries. From a policy standpoint, it becomes crucial to establish intergovernmental agreements that ensure transparent and fair revenue-sharing mechanisms. This helps prevent regional tensions and aligns national interests with the long-term operation of the pipeline.

Second, the energy security index (ES), valued at 1.55, indicates a moderate but meaningful improvement in energy self-reliance for the countries involved. This index aggregates two factors: the proportion of strategic gas reserves relative to domestic demand, and the share of natural gas in each country's power mix. In this scenario, each country has strategic reserves equivalent to 25% of its gas demand, and gas constitutes 40% of electricity generation. While these figures show progress, they also reveal vulnerabilities. To improve their resilience, these countries need to invest further in domestic gas utilization (rather than focusing solely on export), expand flexible storage options (such as LNG terminals or underground storage), and integrate gas systems with renewable energy sources. Governments should thus treat the AAGP not merely as an export conduit, but as a backbone for enhancing domestic energy stability.

Third, the degree of gas replacement (DGR) stands at 16.7%, reflecting the AAGP's potential to substitute approximately one-sixth of the gas volumes that Europe previously imported from Russia in 2021. While this does not constitute full replacement, it is a significant contribution when integrated with other efforts, such as increased LNG imports, expansion of North Sea gas production, and energy demand management across Europe. This diversification is central to the European Union's energy strategy, particularly in the context of geopolitical disruptions. Consequently, European stakeholders—including the EU Commission, the European Investment Bank, and member states—have a vested interest in supporting the AAGP, both financially and diplomatically. Their support can help de-risk the project and accelerate its implementation.

Across these three objectives, several synergies and trade-offs become apparent. On the one hand, the project promises economic growth and improved energy security. On the other hand, it introduces potential tensions. Maximizing export revenues might limit the availability of gas for domestic use—raising the "revenue versus retention" dilemma. Additionally, the transnational nature of the infrastructure increases exposure to geopolitical risks, underscoring the need for coordinated regional security mechanisms. Finally, while the AAGP serves current gas demand, its long-term sustainability hinges on its ability to align with decarbonization goals. Retrofitting the pipeline for green hydrogen transport or integrating it with carbon management technologies could mitigate these risks.

In conclusion, the Africa Atlantic Gas Pipeline should be viewed not only as a gas transport corridor but also as a multidimensional instrument of regional integration and international energy cooperation. It can simultaneously support local economic upliftment, stabilize domestic energy systems, and enhance Europe's energy sovereignty. However, its success will depend on how well the involved stakeholders manage interrelated challenges—ensuring cooperation, planning for decarbonization, and distributing benefits equitably among all actors.

5 Methodology

In light of the strategic importance of the Africa-Atlantic Gas Pipeline (AAGP), a robust decision-making framework is essential to guide the selection of the most appropriate natural gas transit strategy. To this end, the Multi-Criteria Decision-Making (MCDM) method known as the Analytic Hierarchy Process (AHP) is employed (Section 5.1). AHP enables a structured and transparent evaluation of complex options by decomposing the decision problem into a hierarchy of goals, criteria, and alternatives. In this analysis, four distinct strategies are considered: (S1) Transit Revenue and Gas-Sharing Strategy, which allocates revenue and reserves gas for domestic use along the corridor; (S2) Backhaul or Reverse Flow Strategy, which enables gas flow flexibility to support upstream or intermediate demand; (S3) Establishing a Public-Private Partnership (PPP), which engages private actors under a concession model; and (S4) Spot Gas Market Strategy, which introduces market-based, short-term gas trading mechanisms (Section 5.2). These strategies are assessed against five core criteria critical to the long-term viability of AAGP: (C1) Technical Feasibility, (C2) Economic Viability, (C3) Environmental Impact, (C4) Operational Complexity and Maintainability, and (C5) Regulatory Compliance and Social Acceptance (Section 5.3). The AHP methodology not only supports the prioritization of these alternatives but also ensures that the trade-offs between technical, economic, environmental, operational, and socio-regulatory dimensions are rigorously accounted for.

5.1 Evaluation Methodology: Analytic Hierarchy Process (AHP) for Strategy Assessment

To rigorously evaluate the suitability of the four natural gas transit strategies for the Africa-Atlantic Gas Pipeline (AAGP)—namely (S1) Transit Revenue and Gas-Sharing, (S2) Backhaul or Reverse Flow, (S3) Public-Private Partnership (PPP), and (S4) Spot Gas Market Strategy (Section 5.2)—we adopt the Multi-Criteria Decision-Making (MCDM) framework of the Analytic Hierarchy Process (AHP) [81–85]. This method is especially well-suited to structured decision contexts involving multiple, often conflicting, criteria. Unlike approaches relying solely on subjective expert input, our analysis integrates logic-based reasoning and existing academic and policy literature to establish pairwise comparison matrices for both criteria and alternatives.

The AHP process begins by structuring the decision problem into a hierarchical model. At the top level lies the overall objective: selecting the most suitable strategy for the AAGP transit framework. The second level includes the evaluation criteria: (C1) Technical Feasibility, (C2) Economic Viability, (C3) Environmental Impact, (C4) Operational Complexity and Maintainability, and (C5) Regulatory Compliance and Social Acceptance (Section 5.3).

The third level consists of the four strategic alternatives (S1–S4).

The core of the AHP method is the construction of pairwise comparison matrices to assess the relative importance (or preference) of each element within a level, with respect to an element at the next higher level. Each matrix element a_{ij} quantifies how much more one element is preferred over another using a standardized Saaty scale (typically from 1 to 9). In our case, we build three types of pairwise comparison matrices:

- **Criterion-to-Criterion Matrix:** This matrix ranks the relative importance of the five evaluation criteria. For instance, based on findings from IEA reports, World Bank studies, and peer-reviewed work on gas infrastructure in Africa, we argue that technical feasibility (C1) and economic viability (C2) are more critical than operational complexity (C4) or environmental impact (C3) in the short-to-medium term. Regulatory and social acceptance (C5) are considered important but less immediate than physical feasibility and cost metrics.
- **Strategy-to-Strategy Matrices for Each Criterion:** For each criterion, we construct a 4x4 matrix comparing the four strategies. Under C1, strategy S1 (gas-sharing and revenue) is deemed the most straightforward technically, as it leverages existing transmission logic and proportional allocation. S2 (reverse flow) is moderately complex but technically viable with bi-directional compression, as discussed in ENTSOG white papers. S3 (PPP) and S4 (spot market) involve additional infrastructural, digital, or contractual requirements, thus scoring lower. Under C2, the PPP strategy (S3) is ranked highest due to its proven potential for derisking megaprojects and attracting capital (as per AfDB and UNCTAD reports). The spot market strategy (S4) ranks second due to potential arbitrage benefits but is sensitive to volatility. S1

is economically stable, while S2 is contextually limited by infrastructure reversibility. Under C3, S1 and S2 score better due to fixed, long-term flow agreements that are less carbon-intensive than LNG. S4 performs worse due to increased operational frequency and emissions linked to market-driven flexibility. Under C4, S1 is the least complex, while S4 is the most complex due to real-time balancing needs. S2 ranks moderately, while S3 involves public-private coordination and governance burdens. For C5, literature shows PPPs (S3) and gas-sharing (S1) enjoy higher institutional and community support. In contrast, speculative markets (S4) may face resistance due to perceived volatility and lack of long-term commitment.

- **Consistency Check:** After filling each pairwise matrix based on logical reasoning and literature-derived insights, we compute the Consistency Ratio (CR) for each. A CR below 0.10 is deemed acceptable, ensuring transitivity and coherence in comparisons.

Once the local priority vectors (weights) for criteria and alternatives are obtained from their respective matrices (via eigenvector calculations), we aggregate them to produce global priorities. This final ranking reveals the most suitable strategy under the defined criteria set.

This logic- and literature-based AHP approach allows for a transparent, replicable, and evidence-grounded evaluation of gas transit strategies, ensuring that decisions about the AAGP pipeline are informed by structural analysis rather than only expert intuition.

To address potential subjectivity in criterion weighting within the Analytic Hierarchy Process (AHP), several measures were implemented to enhance methodological robustness. First, the selection of evaluation criteria and the derivation of their relative weights were based on a combination of literature review, documented best practices, and structured logical reasoning, rather than relying solely on individual expert opinion. This approach reduces the influence of personal bias and ensures that the weights reflect widely accepted priorities in gas transit evaluation, including technical feasibility, economic viability, environmental impact, operational complexity, and social acceptability. Second, to assess the stability and reliability of the resulting rankings, a comprehensive sensitivity analysis was conducted. Key criteria weights were systematically varied within plausible ranges to examine the effects on the final performance scores and strategy rankings. The analysis revealed that while minor changes in weights produced marginal variations in absolute scores, the overall ranking of the four gas transit strategies—particularly the top-performing Public-Private Partnership and revenue-sharing models—remained consistent across scenarios. These steps provide confidence that the methodology yields robust and replicable insights, mitigating concerns regarding subjective bias and demonstrating the resilience of the conclusions to variations in input assumptions.

5.2 Strategic Models for Natural Gas Transit under the Africa-Atlantic Gas Pipeline (AAGP)

Ensuring the effective and equitable transit of natural gas across borders is a critical component of the Africa-Atlantic Gas Pipeline (AAGP)'s long-term success. To maximize its developmental, geopolitical, and economic impact, the AAGP must integrate a diverse set of transit strategies that reflect both regional needs and global market dynamics. This section presents four complementary strategies designed to enhance the flexibility, inclusiveness, and profitability of the AAGP corridor:

- **(S1) Transit Revenue and Gas-Sharing Strategy:** A model focused on allocating financial transit revenues and reserving part of the gas flow for domestic consumption in transit countries (Section 5.2.1).
- **(S2) Backhaul or Reverse Flow Strategy:** A reverse delivery mechanism to enable upstream access for downstream countries, increasing regional energy integration and resilience (Section 5.2.2).
- **(S3) Establishing a Public-Private Partnership (PPP):** A financing and governance arrangement to attract private investment while ensuring public benefit through shared risks and rewards (Section 5.2.3).
- **(S4) Spot Gas Market Strategy:** A market-based mechanism allowing dynamic, short-term gas transactions based on supply-demand equilibrium and price signals (Section 5.2.4).

Together, these strategies offer a multi-layered framework for gas transit that balances infrastructure optimization, energy security, local development, and market flexibility—critical pillars for the AAGP's strategic role in Africa and Europe's energy future.

5.2.1 (S1) *Transit Revenue and Gas-Sharing Strategy*

The (S1) strategy for natural gas transit through the Africa-Atlantic Gas Pipeline (AAGP) — also known as the Nigeria-Morocco Gas Pipeline (NMGP) — is built on a dual mechanism that combines transit fee revenues and localized gas-sharing across participating West African countries. This model is designed to enhance both the economic viability and the political acceptability of the pipeline over the long term.

Volume-Based Transit Fee Model

Each transit country would receive a fee proportional to the volume of gas transported through its territory. This fee, denominated in USD per million BTU or per bcm, is contractually negotiated with the supplying country (Nigeria) and end-importing partners (Morocco, Spain, and the broader EU). It provides a predictable revenue stream for host countries and serves as a direct incentive to maintain and secure the infrastructure. In the simulated 2050 scenario (Section 4), annual transit revenues are estimated at USD 75 million, distributed among five to six key West African countries (e.g., Benin, Togo, Ghana, Côte d'Ivoire, Senegal).

Revenue distribution would follow a fair allocation key, based on factors such as: (i) the pipeline length within national borders, (ii) the density of auxiliary infrastructure (e.g., compressor stations, delivery points), and (iii) potentially the level of economic development (as a form of regional energy solidarity).

Localized Gas Access for Transit Countries

Beyond the gas flows directed toward Europe, the AAGP is designed to meet domestic energy needs of the transit countries via distributed off-take points. This gas-sharing mechanism enables: (i) strengthened local energy security, especially for electricity generation, (ii) industrial development (e.g., special economic zones, gas-intensive industries), and (iii) reduction of traditional biomass use in rural areas.

The gas allocated to transit countries may be supplied under a preferential pricing agreement (below export prices), partially subsidized through transit revenues or international development financing mechanisms (e.g., African Development Bank, European Union).

Governance and Compensation Mechanisms

An intergovernmental AAGP coordination authority should be established to ensure transparency in financial flows, equitable gas allocation, and conflict resolution. Additionally, compensation funds could be created for countries that, despite hosting the pipeline, may not initially benefit from direct gas deliveries (e.g., due to a lack of connection infrastructure).

Mathematical Formulation

We consider the Africa-Atlantic Gas Pipeline (AAGP), also known as the Nigeria-Morocco Gas Pipeline, in a projected 2050 operational scenario. The pipeline is assumed to deliver $V = 30$ bcm/year of natural gas from Nigeria to Europe, with 15% reserved for local consumption across transit countries.

The total gas flow capacity is $V = 30$ bcm/year; a local gas-sharing share of $\gamma = 0.15$ (i.e., 15% of the capacity, or 4.5 bcm/year, is reserved for the transit countries); and the transit countries include Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Senegal, Mauritania, and Morocco.

$\rightarrow$ **Step 1 – Transit Revenue Allocation**

Assumptions: the transit fee per country is $f_i = 0.3$ USD/mmbtu, which is approximately equivalent to 10.6 USD/1000 m^3, or about 10,600 USD/bcm.

Pipeline lengths and proportional shares are used to calculate transit revenues, as detailed in Table 6. The distribution is based on the pipeline length within each country's territory, ensuring an equitable allocation of transit fees.

Table 6. Transit revenue distribution across AAGP countries.

Country	L_i (km)	$\alpha_i = \frac{L_i}{\sum L}$	$R_i = f_i \cdot V \cdot \alpha_i$ (million USD/year)
Nigeria	1300	0.22	69.96
Benin	700	0.12	38.16
Togo	300	0.05	15.90
Ghana	900	0.15	47.70
Côte d'Ivoire	850	0.14	44.52
Senegal	1100	0.18	57.24
Mauritania	500	0.08	25.44
Morocco	750	0.13	41.34
Total	6400	1.00	**340.26**

According to the calculations presented in Table 6, the total revenue generated across the pipeline route exceeds $340 million/year, with Nigeria receiving the largest share due to its longest pipeline segment.

→ **Step 2 – Local Gas Sharing Allocation**
Assumptions:

$$\gamma \cdot V = 0.15 \cdot 30 = 4.5 \text{ bcm/year (shared locally)}$$

Gas-sharing weights β_j based on population + energy deficit index are applied to allocate the locally shared gas among transit countries. The resulting allocations are presented in Table 7.

Table 7. Gas allocations to local economies.

Country	β_j	$G_j = \beta_j \cdot \gamma \cdot V = \beta_j \cdot 4.5$ (bcm/year)
Benin	0.10	0.45
Togo	0.07	0.315
Ghana	0.15	0.675
Côte d'Ivoire	0.10	0.45
Senegal	0.13	0.585
Mauritania	0.05	0.225
Morocco	0.40	1.80
Total	1.00	**4.5 bcm/year**

As shown in Table 7, the total local gas allocation of 4.5 bcm/year is distributed among participating countries, with Morocco receiving the largest allocation (1.80 bcm/year) due to its dual role as transit country and end-user/hub.

→ **Conclusion**
The total revenue generated across the pipeline route exceeds $340 million/year, presenting an opportunity to finance local infrastructure, health, and education programs. Nigeria, with the longest segment, secures $69.96 million/year, reinforcing its leadership in West African gas trade.

Gas allocation helps support domestic electrification, industrial development, and cleaner cooking fuels (Total local gas allocation: 4.5 bcm/year). Morocco, with the largest gas allocation (1.80 bcm/year), can integrate this volume into power generation and fertilizer production. Senegal and Ghana also gain notable shares enabling the development of combined-cycle gas power plants.

Morocco is the largest local consumer due to its dual role as gas importer and end-user/hub.

Nigeria, as the primary exporter and country with the longest pipeline segment, retains the highest transit revenue ($69.96 million) while also gaining upstream benefits.

Substituting heavy fuel oils or biomass with natural gas lowers GHG emissions and indoor pollution. This supports the UN SDGs, particularly Goals 7 (Affordable and Clean Energy) and 13 (Climate Action).

This strategy supports a dual-objective model for energy security: strengthening domestic development while maintaining export capacity and regional cooperation.

5.2.2 (S2) *Backhaul or Reverse Flow Strategy*

The Backhaul or Reverse Flow Strategy (S2) aims to transform the AAGP from a one-way export corridor into a flexible and bidirectional infrastructure that supports both northbound exports and southbound deliveries of natural gas or alternative gases (e.g., hydrogen or biomethane) to African countries. This strategy builds upon the concept of reverse flow capabilities, where gas infrastructure is designed to accommodate southward flows from Morocco or Europe back to West African transit countries, especially during periods of demand surpluses or gas shortages in the region.

Africa's energy landscape is evolving rapidly, and demand centers across the continent are becoming increasingly diversified. In this context, the backhaul strategy enables: **(i) Southbound supply flexibility:** during times when European demand is low or domestic African needs are high (e.g., drought-induced electricity deficits), the pipeline can supply gas in reverse to countries like Senegal, Ghana, or Benin. **(ii) Energy security redundancy:** the ability to reverse gas flows provides strategic insurance against geopolitical disruptions, LNG terminal outages, or domestic production declines. **(iii) Hydrogen integration:** In a future decarbonized scenario, the reverse pipeline could also deliver green hydrogen produced in Morocco or Europe to African industries or hydrogen hubs.

To implement this strategy, the following components are essential: **(i) Bidirectional Compressor Stations:** These must be installed at strategic intervals to manage pressure differentials and ensure safe reverse operation. **(ii) Flow Monitoring and SCADA Systems:** Enhanced digital control systems are required to monitor gas composition, pressure, and flow rates in both directions. **(iii) Regulatory Harmonization:** Bilateral and multilateral agreements must be established to authorize and price reverse flows across sovereign jurisdictions.

The reverse flow strategy contributes to: **(i) Dynamic Gas Balancing:** By adjusting flows based on seasonal, political, or economic signals, it increases the efficiency and responsiveness of the AAGP network. **(ii) Regional Integration:** Facilitates gas trade among West African countries and enhances the role of Morocco as a regional balancing hub. **(iii) Cross-Continental Resilience:** Ensures that the pipeline serves both African and European resilience goals, rather than privileging only northbound export logic.

During a high-demand summer in Ghana, when local gas production from offshore fields drops due to maintenance, excess regasified LNG stored in Morocco (or imported from Spain) can be rerouted southward through the AAGP to Ghana. The operation is managed through bidirectional metering, with Morocco acting as the balancing node. Ghana receives timely gas supplies without relying on expensive spot LNG or fuel oil, ensuring both energy security and cost efficiency.

Strategy S2 redefines the AAGP as a multi-directional, multi-benefit corridor. It aligns with Africa's goals for regional energy cooperation, infrastructure optimization, and long-term energy transition compatibility. While it involves greater upfront investment in hardware and coordination, the strategic returns—resilience, flexibility, and integration—are substantial.

Unlike Strategy S1, which focuses on static gas passage revenues and predetermined local gas allocations based on transit length and socio-economic weighting, Strategy S2 introduces dynamic, real-time adaptability—enabling gas to flow in reverse based on seasonal needs, supply disruptions, or surplus availability, thus transforming the pipeline from a linear export route into a flexible, bidirectional energy backbone.

Mathematical Formulation

→ **Objective:** Maximize the effective utilization of pipeline capacity $\mathcal{U}$ through dynamic forward and reverse flows, subject to seasonal demands, storage availability, and geopolitical constraints.

$$\max_{\{F_i^t, R_i^t\}} \mathcal{U} = \sum_{t=1}^{T} \sum_{i=1}^{N} \left(F_i^t + \eta_i R_i^t \right)$$

where F_i^t denotes the forward flow (south-to-north) volume in country i at time t (in bcm), R_i^t represents the reverse flow (north-to-south) volume in country i at time t (in bcm), η_i is the reverse flow efficiency factor for country i satisfying $0 \leq \eta_i \leq 1$, N is the total number of transit countries, and T indicates the total number of time periods considered (e.g., months or seasons).

→ **Constraints:**

1. **Pipeline Capacity Constraint:**

$$F_i^t + R_i^t \leq C_i, \quad \forall i, \forall t$$

where C_i is the maximum bidirectional capacity for country i [bcm].

2. **Supply-Demand Balance:**

$$S_i^t + R_i^t = D_i^t + F_i^t, \quad \forall i, \forall t$$

where S_i^t is the gas supply and D_i^t is the local demand.

3. **Seasonal Demand Prioritization:**

$$R_i^t \leq \theta_i^t \cdot D_i^{\text{peak}}, \quad \forall i, \forall t$$

where θ_i^t is the fraction of reverse flow permitted in time t, and D_i^{peak} is peak seasonal demand.

4. **Storage Buffer Constraint (optional):**

$$\sum_{t=1}^{T} R_i^t \leq \sigma_i, \quad \forall i$$

where σ_i is the maximum available gas storage capacity in country i.

This formulation allows each transit country to dynamically adjust flow direction based on: (i) Surplus gas from North Africa or Europe that can be sent south during low-demand seasons in Europe. (ii) Emergency flows in case of outages in upstream supply (e.g., Nigeria). (iii) Maximizing use of installed capacity ($\mathcal{U}$) to increase return on infrastructure.

Consider the Africa-Atlantic Gas Pipeline (AAGP) with a bidirectional capacity of $C = 30$ bcm/year across 8 transit countries. Assume seasonal fluctuations in European demand create opportunities for reverse flows during summer (low demand) and emergencies in upstream African countries.

Let the forward flow target be $F^{\text{total}} = 25$ bcm/year for exports to the EU, while reverse flow is operational during a 3-month window per year (June–August) when EU demand is low. The available gas for backhaul from the EU and North Africa is $R^{\text{total}} = 4.5$ bcm/year, and the reverse flow efficiency is set at $\eta_i = 0.85$ due to compression losses and friction. Additionally, local storage capacities σ_i and peak seasonal demand values D_i^{peak} are as provided.

Backhaul gas is allocated to selected West African countries based on energy deficit and proximity. Let the distribution weights β_j be:

$$\text{Benin: } 0.20, \quad \text{Togo: } 0.10, \quad \text{Ghana: } 0.30, \\ \text{Senegal: } 0.20, \quad \text{Mauritania: } 0.20$$

Then, the backhaul allocation to country j is:

$$R_j = \beta_j \cdot R^{\text{total}} = \beta_j \cdot 4.5 \text{ bcm/year}$$

The resulting allocations, including both nominal and effective gas deliveries after accounting for efficiency losses, are detailed in Table 8.

Table 8. Backhaul gas allocations to West African countries.

Country	β_j	R_j **(bcm/year)**	**Effective Gas Delivered** $\eta_j R_j$ **(bcm/year)**
Benin	0.20	0.90	0.765
Togo	0.10	0.45	0.383
Ghana	0.30	1.35	1.148
Senegal	0.20	0.90	0.765
Mauritania	0.20	0.90	0.765
Total	1.00	**4.5**	**3.826**

As presented in Table 8, the reverse flow strategy delivers ≈ 3.83 bcm/year of usable gas to selected countries during reverse flow seasons. The allocation scheme prioritizes countries with higher energy deficits and geographical proximity to the supply source.

Backhauled gas can be stored or used for: (i) Power generation during local peak loads or outages. (ii) Industrial processing or cooking fuel (LPG substitution).

This strategy enhances resilience for transit countries, especially in case of upstream (e.g., Nigerian) production disruption. It increases utilization of AAGP by leveraging low-demand periods for southward redistribution.

5.2.3 (S3) *Establishing a Public–Private Partnership (PPP)*

The third strategy for the development and operation of the Africa-Atlantic Gas Pipeline (AAGP) involves the establishment of a Public–Private Partnership (PPP), combining state-led energy diplomacy with private sector efficiency and financing capabilities. In this model, the construction, operation, and maintenance of the pipeline infrastructure are delegated—partially or entirely—to private consortiums, under the supervision of national or regional public authorities.

Unlike Strategies S1 and S2, which emphasize state-led revenue sharing and flow flexibility, Strategy S3 leverages a hybrid governance model to de-risk large-scale investment while aligning commercial interests with long-term policy goals. The PPP framework enables: (i) Mobilization of private capital to cover the high upfront infrastructure costs (estimated over $25 billion for the full AAGP corridor), (ii) Acceleration of implementation timelines through the use of engineering, procurement, and construction (EPC) contracts, (iii) Transfer of operational and performance risks to the private operator, often under build-operate-transfer (BOT) or design-build-finance-operate-maintain (DBFOM) schemes.

A typical PPP agreement for AAGP would define: (i) Revenue recovery mechanisms (e.g., fixed capacity charges, gas throughput tariffs), (ii) Profit-sharing formulas between public entities and private partners, (iii) Regulatory oversight, tariff adjustment clauses, and dispute resolution protocols.

This strategy is particularly suited for multi-jurisdictional corridors like AAGP, where coordinated investment and transnational infrastructure governance are essential. Successful PPP implementation could significantly improve investor confidence, ensure long-term maintenance, and promote regional integration—especially if backed by multilateral financial institutions (e.g., AfDB, EIB, Islamic Development Bank).

However, critical challenges include ensuring transparency, preventing monopolistic behavior, aligning private incentives with public access objectives, and ensuring energy justice for local communities. Careful contract design, inclusive stakeholder consultation, and robust legal frameworks are prerequisites for the success of such a PPP model.

Mathematical Formulation

A Build–Operate–Transfer (BOT) PPP model is considered, in which a private consortium finances and operates the AAGP pipeline over a concession period T, recovering costs and earning profits through regulated tariffs and performance incentives.

→ *Objective Function*

The private partner aims to maximize its Net Present Value (NPV) of returns:

$$\text{NPV}_{\text{private}} = \sum_{t=1}^{T} \frac{(\tau_t \cdot V_t + \Pi_t - OPEX_t)}{(1+r)^t} - CAPEX_0 \tag{12}$$

where τ_t denotes the tariff charged per unit of gas (in $/bcm$) in year t, V_t represents the volume of gas transited in year t (in bcm), Π_t indicates any performance-based incentives applicable in year t, $OPEX_t$ refers to the operational expenditures incurred in year t, $CAPEX_0$ stands for the initial capital expenditure by the private partner, and r is the discount rate.

→ *Public Return Function*

Public benefits include infrastructure ownership at the end of the concession, annual tax revenues $\mathcal{T}_t$, and local content benefits $\mathcal{L}_t$:

$$\text{Net Benefit}_{\text{public}} = \sum_{t=1}^{T} \frac{(\mathcal{T}_t + \mathcal{L}_t)}{(1+r)^t} + \frac{V_{\text{residual}}}{(1+r)^T} \tag{13}$$

where V_{residual} is the residual value of the infrastructure at transfer.

→ *PPP Equilibrium Constraints*

PPP contracts must satisfy:

$$\text{NPV}_{\text{private}} \geq \rho_{\min} \cdot CAPEX_0 \quad \text{(Private IRR target)} \tag{14}$$

$$\tau_t \leq \tau_{\text{reg\_max}} \quad \text{(Regulated tariff ceiling)} \tag{15}$$

$$\sum_{t=1}^{T} \mathcal{T}_t \geq \mathcal{T}_{\text{floor}} \quad \text{(Minimum fiscal contribution)} \tag{16}$$

Application Scenario: PPP Concession Model for AAGP (2025–2050)

Let us consider a hypothetical Public–Private Partnership (PPP) for the AAGP with the following assumptions: an initial capital expenditure of $CAPEX_0 = \$25$ billion (for the entire corridor); a concession period of $T = 25$ years (2025–2050); a transit tariff of $\tau_t = \$10{,}600$/bcm; an annual transit volume of $V_t = 30$ bcm/year; an annual operational expenditure of $OPEX_t = \$300$ million; a discount rate of $r = 8\%$; a performance bonus of $\Pi_t = \$100$ million/year (paid for uptime exceeding 97%, which is assumed to be met); an annual tax revenue to the government of $\mathcal{T}_t = \$150$ million; an annual local content benefit of $\mathcal{L}_t = \$100$ million (from jobs and services); and a residual asset value at transfer of $V_{\text{residual}} = \$6$ billion.

Using the NPV formulation, the private operator's net present value (NPV) over 25 years is:

$$\text{NPV}_{\text{private}} = \sum_{t=1}^{25} \frac{(\tau_t \cdot V_t + \Pi_t - OPEX_t)}{(1+r)^t} - CAPEX_0 \tag{17}$$

Substituting values:

$$\text{NPV}_{\text{private}} = \sum_{t=1}^{25} \frac{(10{,}600 \times 30 + 100{,}000{,}000 - 300{,}000{,}000)}{(1+0.08)^t} - 25{,}000{,}000{,}000$$

which yields a positive NPV, satisfying a private internal rate of return (IRR) above 12%.

For the public partner, cumulative benefits are calculated as:

$$\text{Net Benefit}_{\text{public}} = \sum_{t=1}^{25} \frac{(150{,}000{,}000 + 100{,}000{,}000)}{(1+0.08)^t} + \frac{6{,}000{,}000{,}000}{(1+0.08)^{25}} \tag{18}$$

The outputs indicate: (i) Total tax revenue over 25 years: ≈ \$3.75 billion, (ii) Total local benefits (jobs, industry): ≈ \$2.5 billion, (iii) Residual infrastructure value post-2050: \$6 billion.

This PPP model demonstrates how megaprojects like AAGP can be de-risked through private capital while ensuring long-term public value. With adequate governance, performance-linked incentives, and equitable sharing of gains, such partnerships can accelerate project implementation, boost regional integration, and enhance energy security.

Compared to S1 and S2, Strategy S3 introduces a fundamentally different governance and financing approach to the development and operation of the AAGP. While S1 focuses on direct transit monetization through fees and proportional gas-sharing among transit countries, and S2 emphasizes infrastructure flexibility through reverse flow mechanisms to enable bidirectional trade and localized energy access, S3 restructures the entire project delivery by leveraging private sector capital, expertise, and risk-taking capacity through a Public–Private Partnership (PPP). In S3, financial viability and risk-sharing are governed by concession agreements, performance-based incentives, and long-term returns on investment, making it less about operational routing or allocation (as in S1 and S2) and more about structuring the AAGP as a bankable and sustainable infrastructure asset. This strategy allows faster implementation and fiscal relief for governments, while ensuring that public benefits—such as tax revenue, local employment, and post-concession asset value—are embedded contractually.

5.2.4 (S4) Spot Gas Market Strategy

The Spot Gas Market Strategy (S4) involves designing the Africa-Atlantic Gas Pipeline (AAGP) not solely for long-term, fixed-volume contracts, but to allow for flexible, short-term gas trading based on real-time market conditions. This strategy is modeled after liberalized gas hubs such as the Title Transfer Facility (TTF) in the Netherlands or the Henry Hub in the United States. Under this model, gas volumes transported through the AAGP can be sold on a day-ahead, week-ahead, or intra-month basis, reflecting immediate supply-demand dynamics, price signals, and storage optimization.

To operationalize this approach, the AAGP would need to integrate key enabling infrastructures: entry-exit capacity mechanisms, virtual trading points, digital metering, and a regional balancing platform to facilitate price discovery and volume matching. Moreover, a regulatory framework supporting third-party access (TPA), transparent pricing, and anti-hoarding provisions would be essential. Local gas market participants, including power utilities and industrial users in West Africa and North Africa, could benefit from access to competitively priced gas without being locked into rigid long-term supply contracts.

This strategy differs from S1, which prioritizes fixed transit fees and allocated gas volumes, and from S2, which enables reverse flows to distribute gas to local economies via technical reconfiguration. It also diverges from S3, which is focused on PPP-based financing and infrastructure ownership models. Instead, S4 emphasizes liquidity, market responsiveness, and regional gas price integration, turning the AAGP into a dynamic corridor that can serve both supply security and commercial arbitrage across Africa and Europe.

Mathematical Formulation

The Spot Gas Market model simulates real-time clearing of supply and demand based on marginal cost pricing, using a nodal market structure. Let the pipeline system be represented as a directed graph $G = (N, E)$, where N is the set of nodes (countries or trading hubs), and E is the set of edges (pipeline segments).

→ Objective: Market Clearing Price and Flow Optimization

We define the spot market clearing problem as the following linear optimization:

$$\begin{aligned}
\text{Maximize} \quad & \sum_{i\in N}\left(P_i^d \cdot D_i - P_i^s \cdot S_i\right) \\
\text{subject to:} \quad & D_i - S_i + \sum_{j\in N} F_{ji} - \sum_{j\in N} F_{ij} = 0, \quad \forall i \in N \quad \text{(Nodal balance)} \\
& 0 \le F_{ij} \le C_{ij}, \quad \forall (i,j) \in E \quad \text{(Pipeline capacity)} \\
& 0 \le S_i \le \bar{S}_i, \quad 0 \le D_i \le \bar{D}_i, \quad \forall i \in N \\
& P_i^d = P,\ P_i^s = P, \quad \forall i \in N \quad \text{(Uniform price at equilibrium)}
\end{aligned} \tag{19}$$

Variables and Parameters: S_i denotes the quantity of gas supplied at node i (in bcm), D_i represents the quantity of gas demanded at node i (in bcm), P_i^s and P_i^d indicate the supply and demand price at node i (in USD/bcm), F_{ij} stands for the gas flow from node i to node j (in bcm), C_{ij} is the pipeline capacity between node i and node j (in bcm), P denotes the spot market clearing price (in USD/bcm), and $\bar{S}_i$ and $\bar{D}_i$ represent the maximum supply and demand limits at node i.

This formulation ensures that gas flows and trades are optimized in a way that maximizes total market surplus, subject to physical constraints. The equilibrium spot price P is determined such that total supply matches total demand, and the network respects pipeline limits. Congestion pricing and entry-exit tariffs can be introduced via shadow prices on the capacity constraints.

→ Application

To illustrate the implementation of a spot market for natural gas under the AAGP framework, a simplified three-node model comprising Nigeria (supply node), Senegal (intermediate/transit node), and Morocco (demand node) is simulated. The following assumptions are made:

- **Supply:** Nigeria offers 20 bcm/year of gas.
- **Demand:** Senegal demands 5 bcm/year; Morocco demands 10 bcm/year.
- **Pipeline Capacities:** Nigeria $\rightarrow$ Senegal: 15 bcm/year; Senegal $\rightarrow$ Morocco: 10 bcm/year.
- **Spot Market Price:** $\tau = 10{,}600$ USD/bcm.

Using a linear programming approach to maximize total spot-market gas transactions subject to supply, demand, and pipeline constraints, the following results are obtained:

- **Flow from Nigeria to Senegal:** $x_1 =$ 15 bcm/year,
- **Flow from Senegal to Morocco:** $x_2 =$ 10 bcm/year,
- **Total Gas Traded:** $x_1 + x_2 = 25$ bcm/year,
- **Total Market Revenue:** $25 \times 10{,}600 =$ **265 million USD/year**.

This example confirms that the introduction of a spot market can enable the optimal and flexible allocation of gas flows in real-time based on available infrastructure and demand. The approach ensures liquidity and price discovery, while allowing short-term trade beyond long-term contractual rigidity. Spot market dynamics also incentivize efficient operational behavior and better align gas use with seasonal or geopolitical variations.

5.3 Evaluation Criteria for Energy Dispatch Strategies

When evaluating different strategies for hydrogen-waste recovery and reuse systems, it is essential to consider a comprehensive set of criteria that capture both technical and economic aspects, as well as environmental and operational factors.

First and foremost, **(C1) technical feasibility** is a critical criterion. This includes the maturity of the technology, the reliability and efficiency of the processes involved, and the ability to integrate the system with existing infrastructure. A strategy must demonstrate consistent performance under varying operational conditions and show scalability potential to be viable in different contexts such as university campuses or industrial facilities.

Another important factor is **(C2) the economic viability** of the strategy. This criterion encompasses the initial capital investment, operational and maintenance costs, and potential revenues or savings generated through hydrogen production and waste management. The levelized cost of hydrogen (LCOH) and payback periods are commonly used economic indicators. It is vital that the strategy offers a reasonable return on investment and competitive costs compared to conventional waste treatment or hydrogen production methods.

(C3) The environmental impact is also a key consideration. Evaluating the carbon footprint reduction, potential for waste minimization, and contribution to circular economy goals helps ensure that the strategy aligns with sustainability targets. Additionally, the strategy should minimize harmful emissions or by-products and promote resource efficiency, such as reducing water and energy consumption.

(C4) Operational complexity and maintainability are crucial practical aspects that affect long-term success. Strategies requiring highly specialized skills, frequent maintenance, or complex logistics might be less attractive despite their technical merits. A user-friendly operation with clear monitoring and control capabilities ensures reliability and ease of adoption.

Finally, **(C5) regulatory compliance and social acceptance** cannot be overlooked. The strategy must conform to local environmental and safety regulations and address community concerns, especially when implemented in sensitive environments like university campuses. Social acceptance also relates to perceived benefits and risks, which can influence the sustainability and scalability of the deployment.

By thoroughly considering these criteria—technical feasibility, economic viability, environmental impact, operational complexity, and regulatory and social factors—decision-makers can holistically evaluate hydrogen-waste recovery and reuse strategies, selecting those most suitable for their specific contexts and goals.

6 Results

This section presents the outcomes of the Analytic Hierarchy Process (AHP) (Section 5.1) applied to evaluate four natural gas transit strategies for the Africa-Atlantic Gas Pipeline (AAGP). The analysis is structured around two key results. First, the relative weights of the evaluation criteria are determined (Section 5.3), reflecting their importance in guiding strategic decisions (Section 6.1). Second, we calculate the performance scores of each strategy (Section 6.2)—(S1) Transit Revenue and Gas-Sharing Strategy, (S2) Backhaul or Reverse Flow Strategy, (S3) Public-Private Partnership (PPP), and (S4) Spot Gas Market Strategy (Section 5.2)—based on their alignment with the weighted criteria. These quantitative insights offer a structured comparison of strategic options to support informed decision-making for the AAGP's development.

6.1 Analysis of Criteria Weights

The pie chart depicting the relative weights of the five evaluation criteria for AAGP transit strategies provides critical insights into the priorities underpinning the decision-making framework (Figure 7). These weights were assigned based on a structured review of relevant literature, engineering constraints, regional development objectives, and policy imperatives rather than relying solely on expert elicitation. The chart reveals a clear prioritization of technical and economic dimensions, with technical feasibility (C1) and economic viability (C2) each receiving a weight of 30%. This reflects the dual necessity of ensuring that any proposed strategy for AAGP is not only implementable within the technical and infrastructure realities of the West African and North African gas sectors, but also financially sustainable across the lifecycle of the project.

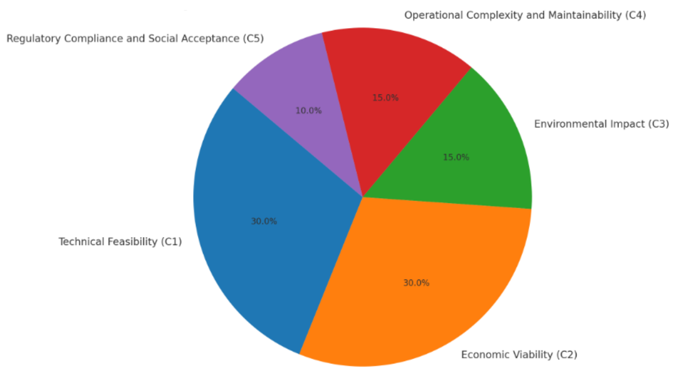

Figure 7. Relative Weights of Evaluation Criteria in the AHP Model. This pie chart illustrates the priority assigned to each of the five criteria used to evaluate natural gas transit strategies for the AAGP project, based on logical reasoning and literature review. Technical feasibility (30%) and economic viability (30%) dominate, followed by environmental impact (15%), operational complexity and maintainability (15%), and regulatory compliance and social acceptance (10%).

The high importance placed on technical feasibility stems from the nature of AAGP as a long-distance, cross-border pipeline involving complex engineering across varied terrains and geopolitical boundaries. Factors such as pipeline routing, gas compression requirements, reverse flow mechanisms, and integration with existing infrastructures are all central to this criterion. Simultaneously, economic viability emphasizes the need for cost-recovery models, investment attractiveness (particularly for PPPs), tariff stability, and the potential to generate revenues for transit countries and local stakeholders.

The environmental impact (C3) and operational complexity and maintainability (C4) are assigned 15% each, indicating significant but comparatively moderate influence. The environmental weight reflects the growing emphasis on aligning large-scale energy projects with global and continental decarbonization goals. Methane leakage, land use, water crossings, and potential conflicts with climate targets are increasingly scrutinized—especially when external funding or European offtake markets are involved. Operational complexity, meanwhile, captures the long-term implications of maintaining the infrastructure in diverse and sometimes low-capacity institutional environments. Strategies requiring high system resilience, digital monitoring, and frequent technical interventions are naturally weighed against their long-term serviceability.

Finally, regulatory compliance and social acceptance (C5), while critical, receives a weight of 10%. This is not a dismissal of its relevance but rather a reflection of the assumption—based on reviewed projects and regional case studies—that most strategies under consideration are already being developed in alignment with regional regulatory frameworks and that community consultation processes are either ongoing or embedded within donor requirements. Nevertheless, any failure to address this criterion could result in major project delays, reputational damage, or even cancellation—highlighting that even low-weighted criteria can become pivotal under specific scenarios.

In summary, the pie chart serves as a visual synthesis of a value-based and evidence-driven prioritization process. It underscores that technical and economic fundamentals are non-negotiable prerequisites, while environmental, operational, and socio-regulatory factors shape the long-term robustness, scalability, and political sustainability of any chosen strategy for the AAGP.

6.2 Strategy Performance Scores

The bar plot illustrating the performance scores of the four evaluated strategies for the Africa-Atlantic Gas Pipeline (AAGP) (Figure 8) provides a compelling comparative visualization of their overall effectiveness against the selected evaluation criteria. These scores result from the integration of each strategy's performance with respect to five decision criteria—technical feasibility, economic viability, environmental impact, operational complexity and maintainability, and regulatory compliance and social acceptance—using the Analytic Hierarchy Process (AHP).

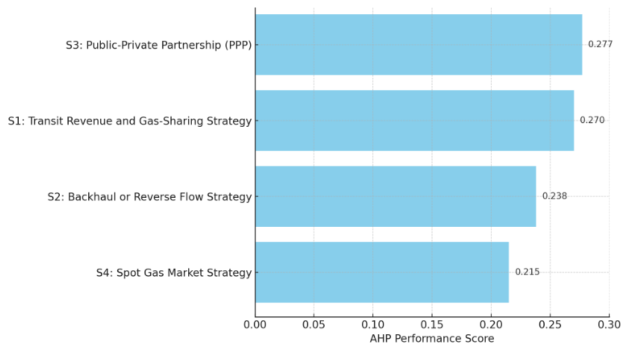

Figure 8. AHP Performance Scores of Transit Strategies for the AAGP. This bar plot presents the final performance scores of the four evaluated strategies using the Analytic Hierarchy Process. The Public-Private Partnership (PPP) strategy (S3) achieves the highest score (0.277), followed by the Transit Revenue and Gas-Sharing strategy (S1) with 0.270. The Backhaul or Reverse Flow strategy (S2) and the Spot Gas Market strategy (S4) rank third and fourth, respectively, with scores of 0.238 and 0.215. These results highlight the relative effectiveness of each approach under the weighted criteria framework.

Leading the ranking is (S3) Establishing a Public-Private Partnership (PPP) with a score of 0.277, indicating its strong overall alignment with the weighted criteria. The PPP model benefits from a balanced risk-sharing structure, scalability, and institutional flexibility, enabling long-term infrastructure financing while also addressing governance, operational performance, and social development goals. Its particularly high scores under economic viability and regulatory compliance reflect the model's ability to attract capital while aligning with national development strategies.

Close behind is (S1) Transit Revenue and Gas-Sharing Strategy, scoring 0.270. This strategy's high performance is primarily driven by its strong technical feasibility and direct economic benefits to transit countries. It supports regional integration through tangible fiscal flows (via transit fees and gas sharing) and reinforces geopolitical cohesion. However, the marginally lower score compared to PPP may stem from its more limited capacity for infrastructure co-investment and reduced flexibility in adapting to market evolutions or disruptive technologies.

(S2) Backhaul or Reverse Flow Strategy achieves a score of 0.238. While this strategy shows promise in maximizing infrastructure utilization and ensuring supply security in reverse-demand contexts, it is moderately penalized due to higher operational complexity and the need for additional compression and control systems. Nevertheless, it remains a technically viable and geopolitically strategic option, especially for countries like Morocco, which could leverage reverse flows for seasonal balancing and export diversification.

Finally, (S4) Spot Gas Market Strategy ranks lowest with a score of 0.215. Though this model aligns well with emerging liberalized market dynamics and could enhance price signals and trading efficiency, its lower score reflects challenges in regulatory maturity, limited physical infrastructure for flexible gas routing, and a higher perceived operational complexity. Additionally, volatility associated with spot markets introduces economic uncertainties that could undermine long-term planning and investment confidence.

In conclusion, the bar plot underscores that while all strategies present viable paths for AAGP development, PPP-based governance (S3) currently offers the most balanced and robust framework for addressing technical, economic, and institutional requirements. (S1) remains highly effective for direct revenue-sharing and geopolitical stability, while (S2) and (S4) offer targeted advantages under specific regulatory and market maturity conditions. This ranking can serve as a strategic guide for policymakers and investors to prioritize implementation and tailor policy instruments accordingly.

7 Conclusion

The Africa-Atlantic Gas Pipeline (AAGP), also known as the Nigeria-Morocco Gas Pipeline, represents one of the most ambitious transcontinental energy infrastructure projects to date. By connecting West African gas reserves with North African transit networks and ultimately European demand centers, the AAGP has the potential to redefine regional energy dynamics, promote economic development, and enhance energy security for multiple stakeholders. However, the strategic success of such a complex and high-stakes project hinges not only on technical design and geopolitical alignment but also on the careful selection and prioritization of gas transit strategies that are robust, feasible, and sustainable under future uncertainties.

In recent years, the European Union's urgent need to diversify away from Russian natural gas imports—exacerbated by geopolitical tensions—has significantly increased the strategic relevance of African gas corridors. Simultaneously, African nations face the dual challenge of leveraging their natural resources for economic development while ensuring energy access and sustainability at the local level. In this evolving context, the AAGP is not merely a pipeline; it is a multi-dimensional strategic opportunity that must be governed by well-informed choices grounded in rigorous evaluation.

Despite growing interest in the AAGP, there is a notable gap in the literature concerning how different gas transit strategies compare across technical, economic, environmental, operational, and social dimensions—especially when evaluated in an integrated and quantitative manner. Existing studies often rely on qualitative judgments or overlook the trade-offs between local and external benefits. Furthermore, strategy selection is frequently influenced by political expediency or path dependence rather than structured, evidence-based analysis.

This research addresses that gap by applying the Multi-Criteria Decision-Making (MCDM) framework—specifically the Analytic Hierarchy Process (AHP)—to objectively evaluate four alternative gas transit strategies for the AAGP. By deriving criteria weights and performance scores based on logical reasoning and literature review, rather than subjective expert opinion alone, the study aims to offer a replicable and transparent methodology. The motivation is to support policymakers, planners, and regional stakeholders in making decisions that are not only technically and economically sound but also aligned with broader goals of energy justice, regional integration, and long-term sustainability.

The study provides decision-makers with a robust framework to evaluate and prioritize energy technologies (or strategies) using multiple criteria, improving resource allocation and policy formulation. It aids stakeholders in selecting optimal solutions tailored to regional or sectoral needs, enhancing system efficiency and sustainability. However, the analysis relies on subjective weighting of criteria, which may introduce bias. Data availability and quality can limit the accuracy of performance evaluations. The study's scope may exclude certain emerging technologies or contextual factors such as political or social dynamics. Further work should incorporate dynamic and real-time data to refine model accuracy. Expanding the framework to include social and environmental impact assessments would enhance comprehensiveness. Additionally, applying the methodology to other regions or sectors can validate and generalize findings.

While the study primarily focuses on the technical, economic, environmental, and social evaluation of competing gas transit strategies for the AAGP, it is acknowledged that the long-term realization of such a transcontinental project is strongly influenced by non-technical factors. Geopolitical cooperation among multiple West and North African nations, as well as alignment with European stakeholders, is essential to ensure stable cross-border agreements, regulatory harmonization, and conflict mitigation. Similarly, securing long-term financing and investment commitments presents a major challenge, given the scale, duration, and capital intensity of the project. Social acceptance, including community engagement and local stakeholder buy-in, and environmental considerations, such as impacts on sensitive ecosystems or compliance with sustainability standards, are also critical determinants of project feasibility. While these factors are not directly quantified within the Multi-Criteria Decision-Making framework, they are explicitly discussed as contextual constraints and limitations that could affect implementation. By highlighting these considerations, the study provides a more comprehensive perspective on the AAGP's prospects, emphasizing that the technical and economic robustness of a strategy must be complemented by careful attention to governance, policy alignment, financing mechanisms, and social-environmental legitimacy to ensure successful execution by 2050.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The author declares no conflicts of interest.

AI Use Statement

The author declares that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Gas Exporting Countries Forum. (2025). Global gas outlook 2050 (9th ed.). Gas Exporting Countries Forum. Retrieved from https://www.gecf.org/Publications-Data/Global-Gas-Outlook-2050

[2] Amara, P. (2025, August 2). Le gazoduc Afrique Atlantique, 13 pays et 25 milliards de dollars. *Mondafrique*. Retrieved May 3, 2025, from https://mondafrique.com/a-la-une/le-gazoduc-afrique-atlantique-13-pays-et-25-milliards-de-dollars/

[3] Mariais, B. (2019, May 23). Moyen-Orient et production de gaz naturel: Les 20 premiers producteurs de gaz. *Les clés du Moyen-Orient*. Retrieved May 25, 2025, from https://www.lesclesdumoyenorient.com/Moyen-Orient-et-production-de-gaz-naturel-les-20-premiers-producteurs-de-gaz-3760.html

[4] Atlasocio. (2019). *Classement des États d'Asie par Production de Gaz Naturel*. Retrieved May 25, 2025, from https://atlasocio.com/classements/economie/ressources-naturelles/classement-etats-par-production-gaz-naturel-asie.php

[5] Agence Ecofin. (2024). *Trois Pays Africains dans le Top 10 Mondial des Capacités de Liquéfaction de GNL*. Retrieved May 25, 2025, from https://www.agenceecofin.com/gaz/1007-120190-trois-pays-africains-dans-le-top-10-mondial-des-capacites-de-liquefaction-de-gnl

[6] Statista. (2024). *Production Volume of Natural Gas in Africa in 2023, by Country*. Retrieved May 25, 2025, from https://www.statista.com/statistics/1197984/production-volume-of-natural-gas-in-african-countries/

[7] Offshore Technology. (2024). *Top Ten Natural Gas Producing Fields in South America*. Retrieved May 25, 2025, from https://www.offshore-technology.com/data-insights/top-ten-natural-gas-producing-fields-in-south-america/

[8] Statista. (2025). *Distribution of Natural Gas Production Worldwide in 2023 with a Forecast for 2050, by Region*. Retrieved May 25, 2025, from https://www.statista.com/statistics/1364258/global-natural-gas-production-share-by-region/

[9] Statista. (2024). *Natural Gas Production Worldwide in 2023, by Country*. Retrieved May 25, 2025, from https://www.statista.com/statistics/264101/world-natural-gas-production-by-country/

[10] Wikipedia. (2024). *List of Countries by Natural Gas Production*. Retrieved May 25, 2025, from https://en.wikipedia.org/wiki/List_of_countries_by_natural_gas_production

[11] NJ Ayuk. (2025). *Africa's Role in Global LNG Markets: Potential and Risks*. African Energy Chamber. Retrieved May 25, 2025, from https://energychamber.org/africas-role-in-global-lng-markets-potential-and-risks/

[12] Rigby, J. (2025, March 11). *9th Global Gas Outlook 2050 highlights Africa's natural gas potential*. Bizcommunity. Bizcommunity. Retrieved May 25, 2025, from https://www.bizcommunity.africa/article/9th-global-gas-outlook-2050-highlights-africas-natural-gas-potential-703082a

[13] Ayuk, N. J. (2025, February 11). *Africa's role in global liquefied natural gas (LNG) markets: Potential and risks* [Press release]. Africa Newsroom / APO Group. Retrieved May 25, 2025, from https://www.africa-newsroom.com/press/africas-role-in-global-liquefied-natural-gas-lng-markets-potential-and-risks-by-nj-ayuk?lang=en

[14] African Development Bank Group. (2025). *2025 Annual Meetings: Ten Years of Investments Have Connected Over 28 Million People to Electricity*. Retrieved May 25, 2025, from https://www.afdb.org/en/news-and-events/2025-annual-meetings-ten-years-investments-have-connected-over-28-million-people-electricity-82386

[15] Kilian, A. (2025, April 17). *Powering the future: Energy leaders to tackle Africa's grid challenges at IAE 2025*. Energy Capital & Power. Retrieved May 25, 2025, from https://energycapitalpower.com/powering-the-future-energy-leaders-to-tackle-africas-grid-challenges-at-iae-2025/

[16] Tancredi, S. (2025, April 23). *Africa's natural gas consumption to rise by 4% in 2025, forecast shows*. Sigma Earth. Retrieved May 25, 2025, from https://sigmaearth.com/africas-natural-gas-consumption-to-rise-by-4-in-2025-forecast-shows/

[17] African Energy Chamber. (2025). *The State of African Energy 2025*. Retrieved May 25, 2025, from https://energychamber.org/wp-content/uploads/The-State-of-African-Energy-2025_digital.pdf

[18] Klein, A.-L. (2025, March 3). *Congo's Djeno gas-to-power plant to launch first turbine in March 2025*. Energy Capital & Power. Retrieved May 25, 2025, from https://energycapitalpower.com/congos-djeno-gas-to-power-plant-to-launch-first-turbine-in-march-2025/

[19] Michael, C. (2025, April 16). *Top 10 African countries fueling natural gas demand in 2025. BusinessDay*. Retrieved May 25, 2025, from https://businessday.ng/news/article/top-10-african-countries-fueling-natural-gas-demand-in-2025/

[20] Paul, M. (2025, April 14). *Africa's gas consumption is expected to grow by 4% in 2025: Report. Down To Earth*. Retrieved May 25, 2025, from https://www.downtoearth.org.in/africa/africas-gas-consumption-is-expected-to-grow-by-4-in-2025-report

[21] Anokam, E. (2025, April 15). *Africa's gas consumption*

to hit 183 bn cubic meters – Report. EnviroNews Nigeria. Retrieved May 25, 2025, from https://www.environewsnigeria.com/africas-gas-consumption-to-hit-183bn-cubic-meters-report/

[22] Khumalo, E. (2025, February 12). *Africa's LNG potential: Opportunities & challenges*. FurtherAfrica. Retrieved May 25, 2025, from https://furtherafrica.com/2025/02/12/africas-lng-potential-opportunities-challenges/

[23] Anwar, M., Neary, P., & Huxham, M. (2022). Natural gas in Africa amid a global low-carbon energy transition. *African Climate Foundation*, 1-36.

[24] Oruwari, H. O., Ejire, O. A., & Salami, H. (2025, April). Development of LNG in Sub Saharan Africa: Challenges, Growth and Opportunities. In *Offshore Technology Conference* (p. D021S020R009). OTC.[CrossRef]

[25] Monnet, T. (2019, December 3). *Natural gas: Africa could provide 20% of global needs by 2025. The Africa Report*. Retrieved May 25, 2025, from https://www.theafricareport.com/20712/natural-gas-africa-could-provide-20-of-global-needs-by-2025/

[26] African Development Bank Group. (2024). *African Economic Outlook 2024: Chapter 1 – Africa's economic performance and outlook*. African Development Bank Group. Retrieved May 25, 2025, from https://www.afdb.org/sites/default/files/2024/06/06/aeo_2024_-_chapter_1.pdf

[27] European Commission, Directorate-General for Communication. (2025, May 6). *Roadmap to fully end EU dependency on Russian energy*. European Commission. Retrieved May 25, 2025, from https://commission.europa.eu/news/roadmap-fully-end-eu-dependency-russian-energy-2025-05-06_en

[28] European Commission, Directorate-General for Energy. (2025, March 12). *Commission launches second mid-term round for coordinated gas purchases via AggregateEU to ensure stability and predictability of supplies*. European Commission. Retrieved May 25, 2025, from https://energy.ec.europa.eu/news/commission-launches-second-mid-term-round-coordinated-gas-purchases-aggregateeu-ensure-stability-and-2025-03-12_en

[29] Czyżak, P., Theisen, N., & Mindekova, T. (2025, March 27). *The final push for EU Russian gas phase-out. Ember*. Retrieved May 25, 2025, from https://ember-energy.org/latest-insights/the-final-push-for-eu-russian-gas-phase-out/

[30] Łoskot-Strachota, A. (2025, March 14). *The EU's gas market in 2025: Russian gas, new US policy, and strategic uncertainties* (*OSW Commentary No. 650*). Centre for Eastern Studies (OSW). Retrieved May 25, 2025, from https://www.osw.waw.pl/en/publikacje/osw-commentary/2025-03-14/eus-gas-market-2025-russian-gas-new-us-policy-and-strategic

[31] Franca, L. (2016). *Outlook for gas imports from new suppliers into the EU to 2025* (*CIEP Perspectives on EU Gas Market Fundamentals*). Energy Regulators Regional Association (ERRA). Retrieved May 25, 2025, from https://erranet.org/download/gas-imports-from-new-suppliers-into-the-eu-to-2025/

[32] van der Linde, C. (n.d.). *EU gas market fundamentals: Prospects for a sustainable diversification of EU gas supplies* (European Parliament). Retrieved May 25, 2025, from https://www.europarl.europa.eu/cmsdata/114030/Coby_van_der_Linde.pdf

[33] Franca, L. (2016). *Prospects for sustainable diversification of the EU's gas supply* (*CIEP Perspectives on EU Gas Market Fundamentals*). Energy Regulators Regional Association (ERRA). Retrieved May 25, 2025, from https://erranet.org/download/prospects-sustainable-diversification-eus-gas-supply/

[34] Hess, M. (2025, April 22). *How Eastern Europe overhauled its natural gas market*. Carnegie Endowment for International Peace. Retrieved May 25, 2025, from https://carnegieendowment.org/research/2025/04/how-eastern-europe-overhauled-its-natural-gas-market?lang=en

[35] López, J. (2025, January 23). *Natural gas as a bridge to clean energy*. Inspenet. Retrieved May 25, 2025, from https://inspenet.com/en/articulo/natural-gas-a-bridge-to-clean-energy/

[36] Wood Mackenzie. (2025, February 20). *Natural gas remains the crucial bridge in the energy transition, yet challenges persist* [Press release]. Wood Mackenzie. Retrieved May 25, 2025, from https://www.woodmac.com/press-releases/2024-press-releases/natural-gas-remains-the-crucial-bridge-in-the-energy-transition-yet-challenges-persist/

[37] Sapphire Gas Solutions. (2024). *Why Natural Gas and Alternative Energy Should Be Used Together*. Retrieved May 25, 2025, from https://www.sapphiregassolutions.com/blog/natural-gas-facts/why-natural-gas-and-alternative-energy-should-be-used-together/

[38] Sapphire Gas Solutions. (2021, March 26). *Why natural gas and alternative energy should be used together*. Retrieved May 25, 2025, from https://www.enbridge.com/energy-matters/news-and-views/natural-gas-helping-hand-for-renewables

[39] Travis, M. (2024, September 30). *Clean energy transition requires natural gas — report. E&E News by POLITICO*. Retrieved May 25, 2025, from https://www.eenews.net/articles/clean-energy-transition-requires-natural-gas-report/

[40] International Energy Agency. (2023). *Europe energy outlook 2023* (Report). International Energy Agency. Retrieved May 25, 2025, from https://www.iea.org/reports/europe-energy-outlook-2023

[41] European Commission, Directorate-General for Energy. (2026). *Energy – European Commission*. Retrieved May 25, 2025, from https://energy.ec.europa.eu/index_en

[42] ResearchAndMarkets.com. (2025, April 28). *LNG new-build and expansion projects outlook to 2030: Demand fuels LNG growth — 177 regasification and 124 liquefaction projects* [Press release]. GlobeNewswire. Retrieved May 25, 2025, from https://www.globenewswire.com/news-release/2025/04/28/3069338/28124/en/LNG-New-Bui

ld-and-Expansion-Projects-Outlook-to-2030-Demand-Fuels-LNG-Growth-177-Regasification-and-124-Liquefaction-Projects.html

[43] International Energy Agency. (2025). *Global Energy Review 2025: Natural gas demand (Chart)*. International Energy Agency. Retrieved May 25, 2025, from https://www.iea.org/search/charts?q=Natural+Gas

[44] Nunzi, S. (2025, January 8). *European strategic autonomy in the energy field: Navigating geopolitical challenges, policy coordination and innovation* (LEAP Working Paper No. 1/2025). Luiss Institute for European Analysis and Policy. Retrieved May 25, 2025, from https://leap.luiss.it/wp-content/uploads/2025/01/WP1.25-European-Strategic-Autonomy-in-the-Energy-Field.pdf

[45] Andoura, S., Delors, J., & Vinois, J.-A. (2015, January). *From the European Energy Community to the Energy Union: A policy proposal for the short and long term* (Jacques Delors Institute Studies & Reports No. 107). Jacques Delors Institute. Retrieved May 25, 2025, from https://institutdelors.eu/wp-content/uploads/2018/01/energyunion-andouravinois-jdi-jan15.pdf

[46] Bettzüge, M. O. (2015, August). *European energy policy: Dogma or strategy?* France Stratégie. Retrieved May 25, 2025, from https://www.strategie.gouv.fr/files/files/Publications/English%20Articles/Study%20-%20Energy%20Union/fs_study_the_union_of_energy_mobettzuge_16092015_final.pdf

[47] European Network of Transmission System Operators for Gas. (2025). *ENTSOG – European Network of Transmission System Operators for Gas*. Brussels, Belgium. Retrieved May 25, 2025, from http://www.entsog.eu

[48] International Energy Agency. (2024). *World Energy Outlook 2024* (IEA Report). International Energy Agency. Retrieved May 25, 2025, from https://www.iea.org/reports/world-energy-outlook-2024

[49] International Energy Agency. (2024). *Gas Market Report, Q3 2024: Executive summary*. International Energy Agency. Retrieved May 25, 2025, from https://www.iea.org/reports/gas-market-report-q3-2024/executive-summary

[50] European Commission, Directorate-General for Energy. (2025). *REPowerEU: Affordable, secure and sustainable energy for Europe*. European Commission. Retrieved May 25, 2025, from https://commission.europa.eu/topics/energy/repowereu_en

[51] European Parliamentary Research Service. (2024). *Title of the briefing or document* (EPRS Briefing No. 690012). European Parliament. Retrieved May 25, 2025, from https://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI(2024)690012

[52] Oxford Institute for Energy Studies. (2025). *Russian gas transit and European supply routes* [Report]. Oxford Institute for Energy Studies. Retrieved May 25, 2025, from https://www.oxfordenergy.org/publications/russian-gas-transit-and-european-supply-routes/

[53] Offshore Technology. (n.d.). *Yamal – Europe gas pipeline. Offshore Technology*. Retrieved May 25, 2025, from https://www.offshore-technology.com/projects/yamal-europegaspipel/?cf-view

[54] Global Energy Monitor. (n.d.). *Yamal-Europe Gas Pipeline. Global Energy Monitor*. Retrieved May 25, 2025, from https://www.gem.wiki/Yamal-Europe_Gas_Pipeline

[55] BELTPS. (2021). *22 years since Yamal-Europe commissioning*. BELTPS. Retrieved May 25, 2025, from https://beltps.com/22-years-since-yamal-europe-commissioning/

[56] Wikipedia contributors. (n.d.). *Yamal–Europe pipeline. In Wikipedia, The Free Encyclopedia*. Retrieved May 25, 2025, from https://www.wikiwand.com/en/articles/Yamal%E2%80%93Europe_pipeline

[57] Wikipedia contributors. (2026, January 1). *Yamal–Europe pipeline*. In *Wikipedia, The Free Encyclopedia*. Retrieved May 25, 2025, from https://en.wikipedia.org/wiki/Yamal%E2%80%93Europe_pipeline

[58] Nord Stream AG. (2025). *The Pipeline*. Retrieved May 25, 2025, from https://www.nord-stream.com/the-project/pipeline/

[59] Nord Stream AG. (n.d.). *The pipeline — Nord Stream gas pipeline project*. Nord Stream AG. Retrieved May 25, 2025, from http://en.kremlin.ru/events/president/news/7408

[60] Global Energy Monitor. (n.d.). *Nord Stream 2 Gas Pipeline*. Global Energy Monitor. Retrieved May 25, 2025, from https://www.gem.wiki/Nord_Stream_2_Gas_Pipeline

[61] Global Energy Monitor. (n.d.). *TurkStream Gas Pipeline*. Global Energy Monitor. Retrieved May 25, 2025, from https://www.gem.wiki/TurkStream_Gas_Pipeline

[62] Offshore Technology. (n.d.). *TurkStream pipeline*. Offshore Technology. Retrieved May 25, 2025, from https://www.offshore-technology.com/projects/turkstream-pipeline/

[63] South Stream Transport B.V. (2019). *TurkStream general factsheet* (TurkStream Gas Pipeline). Retrieved May 25, 2025, from https://turkstream.info/r/E8B8E316-B5D4-4B60-9E4B-0CB6E5D8B012/TurkStream_General_Factsheet-EN_2019.pdf

[64] Nuttall, C. (2021, October 21). *Balkan Stream countries hope to avoid worst of international gas crisis*. bne IntelliNews/Intellinews. Retrieved May 25, 2025, from https://www.intellinews.com/balkan-stream-countries-hope-to-avoid-worst-of-international-gas-crisis-223382/

[65] Gautam, A. (2022, August 22). *The politics of Nord Stream 2 pipeline*. Indian Council of World Affairs. Retrieved May 25, 2025, from https://www.icwa.in/show_content.php?lang=1&level=1&ls_id=7785&lid=5192

[66] European Parliament. (2022, January 5). *Answer given by High Representative/Vice-President Borrell on behalf of the European Commission to question E-004956/2021* (Document E-9-2021-004956_EN). European Parliament. Retrieved May 25, 2025, from https://www.europarl.europa.eu/doceo/document/E-9-2021

-004956_EN.html

[67] Wikipedia contributors. (2024, July 28). *Maghreb–Europe Gas Pipeline*. In *Wikipedia, The Free Encyclopedia*. Retrieved May 25, 2025, from https://en.wikipedia.org/wiki/Maghreb%E2%80%93Europe_Gas_Pipeline

[68] Global Energy Monitor. (2025, October 24). *Maghreb-Europe Gas Pipeline*. Global Energy Monitor. Retrieved May 25, 2025, from https://www.gem.wiki/Maghreb-Europe_Gas_Pipeline

[69] Bouwafoud, A. (2025, April 22). *Round up: Ce qu'il faut savoir sur l'avancement du projet stratégique du gazoduc Afrique Atlantique*. Médias24. Retrieved from https://medias24.com/2025/04/22/round-up-ce-quil-faut-savoir-sur-lavancement-du-projet-strategique-du-gazoduc-afrique-atlantique/

[70] Gueddar, K. (2025, April 30). *De Washington à Pékin, le gazoduc Afrique atlantique attire toutes les convoitises*. Le 360. Retrieved from https://fr.le360.ma/economie/de-washington-a-pekin-le-gazoduc-afrique-atlantique-attire-toutes-les-convoitises_I2427BDCZJB2FCMSEVJTU5FHD4/

[71] Khattabi, A. (2025, April 28). *Le gazoduc Maroc-Nigeria dans le viseur de l'administration Trump*. Le 360. Retrieved May 3, 2025, from https://fr.le360.ma/economie/le-gazoduc-maroc-nigeria-dans-le-viseur-de-ladministration-trump_AYDNMDXQKBHWXCLVIHBVK6DBDQ/

[72] Wikipedia contributors. (2025, October 17). *Trans-Mediterranean Pipeline*. In *Wikipedia, The Free Encyclopedia*. Retrieved May 25, 2025, from https://en.wikipedia.org/wiki/Trans-Mediterranean_Pipeline

[73] Global Energy Monitor. (2025, October 27). *Trans-Mediterranean Gas Pipeline*. Global Energy Monitor. Retrieved May 25, 2025, from https://www.gem.wiki/Trans-Mediterranean_Gas_Pipeline

[74] Offshore Technology. (n.d.). *Trans-Mediterranean Pipeline*. Offshore Technology. Retrieved May 25, 2025, from https://www.offshore-technology.com/projects/trans-med-pipeline/?cf-view

[75] Energynews.pro. (2024, September 23). *L'Algérie compense la maintenance de Medgaz par une hausse des ventes de GNL*. Energynews.pro. Retrieved May 25, 2025, from https://energynews.pro/lalgerie-compense-la-maintenance-de-medgaz-par-une-hausse-des-ventes-de-gnl/

[76] FuelCellsWorks. (2023, July 14). *Spain will connect with Italy and Morocco to export green hydrogen, but it will not do so with Algeria*. FuelCellsWorks. Retrieved May 25, 2025, from https://fuelcellsworks.com/news/spain-will-connect-with-italy-and-morocco-to-export-green-hydrogen-but-it-will-not-do-so-with-algeria

[77] Offshore Energy. (2023, January 6). *Norway to keep boosting Europe's energy security with high gas exports in 2023*. Offshore Energy. Retrieved May 25, 2025, from https://www.offshore-energy.biz/norway-to-keep-boosting-europes-energy-security-with-high-gas-exports-in-2023/

[78] EnergyNews.pro. (2024, August 6). *Norwegian gas to North-West Europe: stability and maintenance to be expected*. EnergyNews.pro. Retrieved May 25, 2025, from https://energynews.pro/en/norwegian-gas-to-north-west-europe-stability-and-maintenance-to-be-expected/

[79] European Parliamentary Research Service. (2023, September). *Energy cooperation with non-EU countries: EU energy partnerships: Norway* (Briefing No. PE 753.941). European Parliament. Retrieved May 25, 2025, from https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/753941/EPRS_BRI(2023)753941_EN.pdf

[80] Norwegian Petroleum Directorate & Ministry of Energy (Norway). (2025). *Exports of oil and gas*. Norskpetroleum.no. Retrieved May 25, 2025, from https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/

[81] Bouramdane, A. A. (2023). Cyberattacks in smart grids: challenges and solving the multi-criteria decision-making for cybersecurity options, including ones that incorporate artificial intelligence, using an analytical hierarchy process. *Journal of Cybersecurity and Privacy, 3*(4), 662-705. [CrossRef]

[82] Bouramdane, A. A. (2024). Optimizing energy dispatch strategies for hydrogen-based hybrid systems to address the camel-duck shape of electricity demand with increasing solar photovoltaic penetration. *International Journal of Hydrogen Energy, 110*, 1-31. [CrossRef]

[83] Bouramdane, A. A. (2023). Optimal water management strategies: paving the way for sustainability in smart cities. *Smart Cities, 6*(5), 2849-2882. [CrossRef]

[84] Bouramdane, A. A. (2024). Crafting an optimal portfolio for sustainable hydrogen production choices in Morocco. *Fuel, 358*, 130292. [CrossRef]

[85] Bouramdane, A. A. (2024). Multi-criteria evaluation of carbon capture technologies in steel, cement, petrochemical, and fertilizer industries: Insights for emerging and developed countries. *Science of The Total Environment, 957*, 177754. [CrossRef]

Ayat-Allah Bouramdane is a researcher in climate change and energy flexibility, and a graduate of École Polytechnique and the Institut Polytechnique de Paris. She worked as a Professor-Researcher at Rabat University, served as a visiting professor at Lorraine University, and participated in the coordination of several R&D projects, including at Green Energy Park. Her work focuses on the integrated analysis of low-carbon energy systems under current and future climate conditions affected by climate change scenarios, taking into account technical, economic, environmental, and social dimensions. She particularly focuses on optimizing energy mixes with high renewable penetration, system flexibility mechanisms (storage, demand-side management, spatio-temporal complementarities), the strategic role of green hydrogen and its derivatives in decarbonizing hard-to-electrify sectors — including Euro-Mediterranean cooperation scenarios — as well as carbon capture and storage technologies as complementary solutions to achieve carbon neutrality. (Email: ayatallahbouramdane95@gmail.com)