The University of Manchester

Gas and Electricity Network Co-Optimisation considering Future Energy Net Zero Pathways Uncertainties in Northern Ireland (GeOpSySNI)

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Disclaimer

This report was prepared by Dr Dlzar Al Kez, a Research Associate in Net Zero Infrastructure at the University of Manchester, and Faraedoon Ahmed, PhD student at the University of Manchester, working under the supervision of Professor Aoife Foley, Chair in Net Zero Infrastructure at the School of Engineering, The University of Manchester. The work focuses on co-optimising gas and electricity network systems considering future energy net zero pathways and uncertainties in Northern Ireland. The information contained herein does not necessarily represent the views of the DfE.

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Executive Summary

The transition of the energy market to a renewable-dominated landscape presents several challenges, particularly in framing the system's marginal cost for diverse energy sources (i.e., wind, solar, fossil fuels, hydrogen, and ammonia). This shift requires all energy generators and storage solutions to cover capital and operational costs while achieving a fair profit without relying on subsidies. Additionally, the market must mitigate volatility, investor risk, and significant price fluctuations. As renewable energy grows in the energy system, optimizing plant and network operations will become more complex, especially in interconnected markets like Northern Ireland (NI).

An optimal strategy for integrated energy systems is crucial, considering the security constraints of both networks and future net-zero changes. The "Gas and electricity network co-optimisation considering future energy net zero pathways' uncertainties in Northern Ireland" (GeOpSySNI) project develops an integrated energy systems (IES) model that represents electricity and natural gas flows across all vectors and sectors as sources (generators) and sinks (demands) in a transmission network optimisation problem. In **Phase I**, the GeOpSySNI project establishes a baseline model representing the state of the NI's energy system as of 2022. This model accounts for the detailed operation of gas and electricity infrastructures at the transmission level, while acknowledging that increasing energy flows at the distribution level may become a significant factor in future analyses. The model is flexible enough to expand for 2030, 2040, and 2050 scenarios in **Phase II** and **Phase III**.

To analyse the transition to a net-zero power system, the GeOpSySNI project employs a gas and power unit commitment analysis using PLEXOS software, to evaluate impacts on carbon emissions, system marginal costs, and wholesale and retail prices as the Single Electricity Market (SEM) transitions to a net-zero power system. This analysis considers various fuel types (e.g., hydrogen, biomethane, ammonia, natural gas), storage solutions, and renewable generation levels while accounting for extreme weather events. Co-optimisation, in this context, involves simultaneously managing the generation, storage, and distribution of energy within these networks to minimise costs, reduce carbon emissions, enhance grid flexibility, and maintain system reliability. This integrated approach is essential in a transitioning energy market, where the interactions between gas and electricity systems are becoming increasingly

complex, particularly with the introduction of new renewable energy sources and changing demand patterns.

To further support this analysis, a targeted survey is conducted to gather insights and perspectives from experts on the current and future interactions between natural gas and electricity networks in NI. While the findings of the survey provide valuable insights into the challenges and opportunities for optimising the operation and integration of these energy systems, they represent just one aspect of the broader research framework. This work establishes a foundation for further studies aimed at deeper investigations into these interactions and the ongoing transition to a lower-carbon economy. The findings highlight the need for infrastructure upgrades and coordinated management across gas and electricity systems to achieve comprehensive network optimisation. Most respondents anticipate a declining role for natural gas as renewable energy sources become more prevalent. They emphasise that strategies such as long-term renewable energy contracts, market reforms to enhance grid flexibility and diversification of energy sources are crucial for ensuring market stability and reducing volatility.

Keywords: Renewable Energy, System Marginal Cost, Carbon Emissions, Net Zero, PLEXOS Energy Modelling, Energy Infrastructure, Integrated Energy Systems (IES), Natural Gas, Hydrogen, Biomethane, Wind Power, Demand Response, Energy Market Volatility

Nomenclature

Abbreviations

CCUS	Carbon capture and storage
EWIC	East-West interconnector
GFPP	Gas-fired power plants
GB	Great Britain
HVDC	High Voltage Direct Current
HG	High gas
I-SEM	Integrated Single Electricity Market
IoT	Internet of Things
IES	Integrated energy systems
RES	Renewable energy sources
RTP	Real-time pricing
ROI	Republic of Ireland
SEM	Single Electricity Market
SMP	System Marginal Price
SRMC	Short Run Marginal Cost
SEMO	Single Electricity Market Operator
SNIP	Scotland Northern Ireland Pipeline
TSO	Transmission system operators
LW	Low wind
MILP	Mixed-integer linear programming
NI	Northern Ireland
NWP	Northwest Pipeline
UCED	Unit commitment and economic dispatch
UK	United Kingdom

Units

kV	Kilovolt
MW	Megawatt
MWh	Megawatt hour
GW	Gigawatt
TWh	Terawatt hour

Symbols

€	Euro
£	Pound sterling
$	US dollar

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1. Introduction

Currently, wind power provides approximately 36% of electricity generation on the island of Ireland [1]. This percentage is expected to grow significantly in the coming decades due to planned expansions in both onshore and offshore wind capacities. The expansion plans for wind energy in Ireland are part of broader efforts to meet an increased overall 80% renewable electricity target by 2030 [2]. This initiative sets out ambitious objectives, to implement 9 GW of onshore wind power, 8 GW of solar energy, and a minimum of 5 GW through offshore wind projects [3]. These efforts are crucial not just for reducing emissions within the electricity sector, but also pave the way for the electrification of other sectors.

The transition to a lower-carbon economy drives significant changes in how gas supply and power systems are planned and optimised. There is a growing need for co-optimisation of gas and electricity systems, moving away from the legacy approach of planning these systems separately [4]. The co-optimisation of gas and electricity systems can enhance energy security by reducing reliance on imported fossil fuels and improving the resilience of the overall energy system [5]. This integrated approach allows for better coordination between gas-fired power plants and renewable energy sources (RES), enhancing overall system efficiency and reliability. By co-optimising gas and electricity systems, planners can create more robust and efficient energy systems that are better equipped to handle the challenges of the low-carbon transition. This approach provides new insights into system interactions, helps identify synergies between different energy vectors, and ultimately supports the development of a more sustainable and resilient energy infrastructure.

The integration of increased RES into the energy mix has profound implications for natural gas, affecting its demand, role, and infrastructure requirements. Existing gas infrastructure may need to be repurposed or adapted to support the energy transition [6]. This could include preparing pipelines for biomethane or hydrogen blending, options that are particularly relevant given the current capabilities of the NI gas network, which is already fit for biomethane blending and, to a degree, hydrogen readiness. Furthermore, carbon capture and storage (CCUS) capabilities for gas-fired power plants represent another adaptation pathway. These evolutions create new opportunities and insights compared to traditional approaches.

With the expansion of RES, the average annual demand for natural gas is expected to decrease. However, natural gas remains a crucial component of the energy mix, serving as a dispatchable backup power source. The demand on peak days, when renewable energy generation falls below full capacity, could increase significantly. This scenario necessitates a flexible and responsive natural gas infrastructure to meet the varying demand patterns effectively. Its flexibility allows it to quickly adjust to meet sudden spikes in demand or compensate for the intermittency of RES [7].

The variability of RES, primarily solar and wind, significantly affects the need for natural gas as a backup power source. The unpredictability of solar and wind energy generation necessitates a reliable backup power source to ensure continuous electricity supply. This relationship is shaped by the inherent intermittency of renewables, which depends on weather and environmental conditions, leading to fluctuations in output on hourly, daily, and seasonal timescales. Natural gas-fired power plants (GFPP) offer the flexibility and reliability needed to respond to the variable nature of RES [8]. The GFPP, in particular, play a crucial role in balancing grid fluctuations caused by intermittent RES. They can be started up or shut down rapidly, adjusted to match demand and provide consistent power output regardless of the availability of renewable energy. However, this role comes with challenges such as increased cycling and the need for greater operational flexibility [9].

Over time, the role of natural gas may evolve to support renewable energy more directly, possibly transitioning towards renewable gas options (i.e., biogas and hydrogen) [10]. This evolution acknowledges the decreasing reliance on fossil fuels while still utilising natural gas's advantages in the short to medium term. The evolving role of natural gas in a renewable-dominant grid necessitates upgrades to existing infrastructure, including pipelines and storage facilities. These improvements are essential to ensure that natural gas can be delivered efficiently and reliably to meet peak demand requirements. To facilitate access to natural gas during peak demand periods and support the transition to a renewable-dominant grid, new market mechanisms may be required. These could include pricing structures that incentivise the provision of natural gas during times of high demand and discourage its use during periods of abundant renewable energy generation.

To manage the delivery and pricing of natural gas in a renewable-dominant grid, several market mechanisms are currently in place or have been proposed. These mechanisms aim to ensure the reliability of the grid, accommodate the variability of RES, and facilitate the integration of GFPP as a flexible and responsive resource. Firstly, capacity markets are designed to ensure that sufficient generation capacity is available to meet peak demand, taking into account the variability and uncertainty introduced by RES [11]. These markets pay generators to keep their capacity ready to deliver electricity when needed, providing financial incentives for maintaining standby capacity. This mechanism helps maintain the reliability of the grid by compensating for the fact that RES cannot always generate power when most needed.

Furthermore, real-time pricing (RTP) mechanisms allow for the price of electricity to fluctuate throughout the day, reflecting the actual cost of generation at any given moment. This includes the cost of ramping up GFPP to meet peak demand or the cost savings from using excess renewable energy generation. The RTP encourages consumers and generators to adjust their behaviour to take advantage of lower prices during off-peak hours and avoid higher prices during peak demand periods. This mechanism can help balance the grid more efficiently, especially in a renewable-dominant scenario where renewable generation can vary widely.

Moreover, carbon pricing mechanisms (i.e., cap-and-trade systems or carbon taxes) can influence the economics of natural gas versus RES by assigning a cost to carbon emissions [12]. This can make natural gas more expensive relative to zero-emission RES, encouraging a shift towards cleaner energy technologies. However, in the short to medium term, natural gas can still play a crucial role as a transitional fuel, especially when paired with CCUS technologies to further reduce its emissions.

Additionally, demand response programs incentivise consumers to reduce their electricity consumption during peak demand periods or to increase their consumption during off-peak hours. This can help balance the load on the grid, reducing the need for GFPP during times of high renewable energy production. By participating in these programs, consumers can earn rewards (i.e., lower electricity bills or payments) thereby playing an active role in managing the grid's demand and supply balance

The planning process now needs to consider various decarbonisation scenarios, including the potential for natural gas to serve as a "bridge fuel" in the transition to a low-carbon economy [13]. This involves assessing the role of gas in different timeframes and its interaction with emerging technologies like energy storage and hydrogen. New market mechanisms are being developed to incentivise the necessary flexibility and capacity from GFPP while also promoting the growth of RES. The planning process now needs to account for emerging technologies (i.e., power-to-gas) which can convert excess renewable electricity into hydrogen or synthetic methane, providing a link between the electricity and gas systems.

1.1 Motivation

The increasing concern over climate change and the urgent need to reduce greenhouse gas emissions necessitates a shift towards RES. Northern Ireland, akin to many regions globally, faces the challenge of transitioning away from fossil fuels towards cleaner, more sustainable energy options. The influence of global trends and pricing on local energy policies and investments directly impacts the challenges faced in optimising the operation of gas and electricity systems in NI. Worldwide, there is a strong trend towards RES driven by environmental concerns and international agreements such as the Paris Agreement. This trend necessitates adjustments in local energy policies in NI to meet renewable energy targets and effectively integrate intermittent sources like wind and solar into the grid.

The motivation for researching and developing a comprehensive strategy for co-optimising gas and electricity networks in NI, especially in light of the transition towards a net-zero energy system, is deeply rooted in the pressing need to balance multiple critical factors. These factors include ensuring energy security, managing the intermittency of RES, modernising aging infrastructure, navigating a complex regulatory landscape, and building stakeholder confidence. Each of these aspects is interconnected and plays a crucial role in the successful transition to a sustainable and resilient energy system.

Maintaining a reliable and secure energy supply while significantly reducing the environmental impact is essential for avoiding energy shortages during the transition period and ensuring that the energy sector remains a cornerstone of NI’s economy. The integration of RES, despite their variable nature, is key to achieving this balance by providing a sustainable alternative to fossil fuels. The variable nature of wind and solar power generation introduces challenges that must be addressed through innovative solutions. These could include energy storage technologies, demand response mechanisms, and the integration of flexible loads to manage the variability and ensure a stable energy supply.

Upgrading the existing grid infrastructure is crucial for accommodating the integration of new technologies and a growing share of renewables. This involves enhancing the physical infrastructure, as well as implementing digital technologies to enable smarter, more responsive energy systems. Understanding and adapting to the rapidly evolving regulatory environment is vital for attracting investment and fostering innovation in the energy sector. This includes keeping pace with policy changes aimed at reducing emissions and supporting the transition to a low-carbon economy. The development of supportive policies and regulatory reforms is essential for creating an enabling environment that encourages investment in renewable energy and facilitates the necessary modernisation of energy networks.

Engaging consumers, industries, and policymakers is essential for fostering collaboration and support for the energy transition. This involves communicating the benefits of the transition, addressing concerns, and working together to overcome barriers. The successful implementation of new technologies and policies requires the active participation and support of various stakeholders, including industry players, policymakers, and consumers.

The environmental urgency behind this research is underscored by NI's commitment to achieving net-zero carbon emissions by 2050, as outlined by the Climate Change Act. This ambitious goal encompasses all sectors, not just those related to energy. While the Path to Net Zero Energy strategy provides a framework specifically for the energy sector, assessing electricity, heat, and other forms of energy use, the overall aim of the Climate Change Act is to achieve Net Zero emissions across all sectors.

The Greenhouse Gas Protocol categorises emissions into three scopes to provide a comprehensive view of carbon footprints: Scope 1 covers direct emissions from owned or controlled sources; Scope 2 involves indirect emissions from the generation of purchased energy; and Scope 3 accounts for all other indirect emissions. By addressing these scops, the research aligns with the broader climate goals and supports a holistic approach to reducing emissions across the entire economy.

Efforts to optimise energy systems are integral to achieving regional and global climate goals. NI journey towards net-zero emissions by 2050 necessitates a deep examination of the barriers hindering system optimisation, such as fluctuating renewable energy outputs, geopolitical influences on energy markets, and the integration of innovative technologies like smart grids and Internet of Things (IoT) devices.

1.2 Aim and Objectives

Phase I of the GeOpSySNI project aims to develop an IES model that represents the baseline state of NI's gas and electricity networks as of 2022. This focus on the baseline allows for a thorough understanding of the current system dynamics, operational challenges, and opportunities for improvement. By establishing this foundation, we can enhance the reliability and relevance of future projections.

In Phase II, this model will be extended to represent the IES scenario for 2030, with further extensions planned for 2040 and 2050 in Phase III. Using PLEXOS Energy Modelling software, this model will achieve high accuracy by incorporating detailed representations of all gas and electricity infrastructure, operational constraints, and various scenarios involving renewable penetration, fuel types, weather impacts, and infrastructure changes. The model will analyse changes in plant operations, system services, storage levels, emissions, and energy costs. Insights derived from the 2022 model will inform our assumptions and methodologies in developing these future scenarios, ensuring that they are robust and well-informed. Key objectives of the GeOpSySNI project include:

1. Replicating NI's 2022 Energy Position: Establishing a baseline model that accurately replicates the state of NI's gas and electricity networks as of 2022. This is crucial for validating the model's accuracy and building confidence in its ability to represent the current system.
2. Developing an IES Model: Creating a detailed model using PLEXOS software to represent the interaction between gas and electricity networks, incorporating infrastructure details, operational constraints, renewable energy penetration, fuel types, weather impacts, and potential infrastructure changes.
3. Evaluate the impacts of various scenarios on carbon emissions, system marginal costs, wholesale and retail prices, and energy security. This includes considering extreme weather events and their effects on both gas and power systems.
4. Conduct a targeted survey to gather insights and opinions from experts on the current and future interactions between natural gas and electricity networks in NI. The survey

assists in understanding the challenges, opportunities, and potential strategies for optimising the operation and integration of these energy systems.

By achieving these objectives, the GeOpSySNI project will provide critical insights and strategies for enhancing the sustainability and efficiency of NI's energy system, aligning with the region's emissions reduction targets and supporting economic stability.

1.3 Research Methodology

The research methodology utilises a four-step approach to investigate co-optimisation strategies for energy systems, especially focusing on the interaction between electricity and natural gas networks, as illustrated in Figure 1.

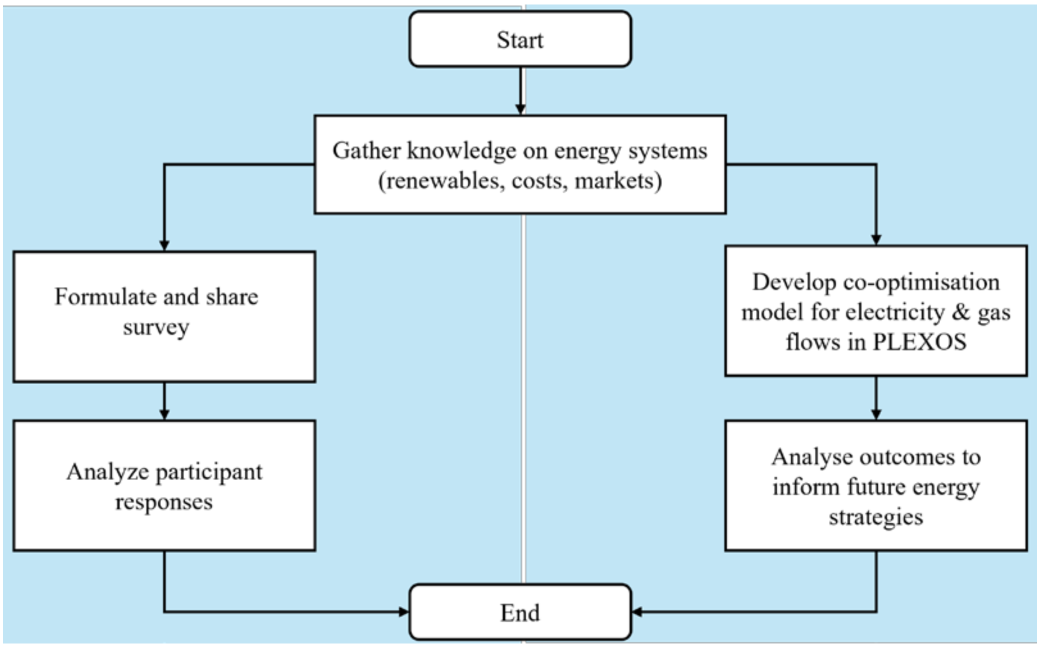


Figure 1 Research methodology flow chart

The **first step** involves a comprehensive literature review to establish a strong foundation in current energy system dynamics. This review focuses on key areas such as renewable energy integration, system marginal costs (the cost of supplying the last unit of electricity), and the intricacies of energy market dynamics, including the interactions between supply and demand, and the impact of regulatory frameworks on market performance.

Building on this knowledge, **Step 2** involves constructing a detailed co-optimisation model within the **PLEXOS** software. This model will simulate the interactions between electricity and natural gas flows within the energy transmission network. It will consider both the electricity grid and gas infrastructure, providing a comprehensive representation of the 2022 baseline model.

Once the model is built, **Step 3** focuses on running simulations under various scenarios. These scenarios will explore different levels of renewable electricity penetration, gas usage, and other factors affecting both electricity and gas networks. By analysing the outcomes of these simulations, valuable insights can be gained to inform the development of future energy strategies.

Finally, **Step 4** examines survey development. This step involves formulating and distributing a survey to participants to gather real-world perspectives on both electricity and gas network integration, followed by a thorough analysis of the collected responses.

1.4 Report Structure

This report is structured into five main sections. Section 2 explains the development of the PLEXOS model, detailing the constraints applied and presenting the model results to provide a thorough understanding of the system's capabilities and limitations. Section 3 focuses on the survey development, describing the methodology used and analysing the results to gather stakeholder insights. Section 4 discusses the findings in the context of the broader research questions, integrating insights from both the PLEXOS model and the survey. Finally, Section 5 concludes the report, summarising the key findings and offering suggestions for future work to further enhance the optimisation of gas and electricity systems.

2. PLEXOS Modelling

2.1 Introduction

The Single Electricity Market (SEM) on the island of Ireland streamlines electricity trading among generators and suppliers, particularly those generating 10 MW or more, through a mandatory gross pool. A mandatory gross pool is a market structure where all electricity generated must be sold into and bought from a central pool, rather than through bilateral contracts. This market operates under a day-ahead market mechanism, where generators submit their available capacity and desire to sell prices for each half-hour block of the next day.

The System Marginal Price (SMP), which determines the price paid to all generators, is established by sorting these bids from least to highest until the total expected demand is satisfied. The SMP corresponds to the cost of the last accepted bid. Additionally, a Capacity Market guarantees compensation for generators' availability and readiness to produce electricity. Bids are placed according to Short Run Marginal Cost (SRMC) in euros per megawatt-hour (€/MWh), reflecting operational costs. Generators with an SRMC exceeding the SMP may not be selected for dispatch due to their higher production costs.

The SEM is overseen by the Single Electricity Market Operator (SEMO) and operates in both euro and pound sterling currencies. It includes day-ahead and intraday trading frameworks to manage dispatch schedules, which are plans developed by market operators that determine which power plants will generate electricity and when based on demand forecasts and system constraints. These mechanisms consider system constraints and demand patterns, thereby enhancing grid stability and responsiveness to disturbances[1].

2.2 Baseline Modelling

This research employs PLEXOS software, specifically version 6.301 R03, to tackle the challenges of unit commitment and economic dispatch. The computational environment consists of a Dell Optiplex 7010 computer, powered by an Intel Core i7-3770 processor. The optimisation process relies on the Gurobi MP 11.0.1 solver from FICO, which is adept at handling mixed-integer problems.

[1] Examples of disturbances include sudden changes in demand, equipment failures, extreme weather events, and generator outage

The main objective of this study is to construct an IES for NI that focuses on the electricity and gas markets rather than covering all energy sectors. This system includes the domestic transmission networks for electricity and gas, along with interconnections with neighbouring countries. The development of this model utilises data from the Integrated Single Electricity Market (I-SEM) backcast and validation report covering the period from 2021 to 2029 [14]. Additionally, the methodology for integrating NI's gas and power energy models is adapted from official reports [15] [16].

The hardware setup and choice of software tools are crucial for the successful execution of the optimisation algorithms. PLEXOS, known for its robustness in modelling complex energy systems, is utilised here to simulate the operation of the energy market under various conditions. The integration of gas and power markets in NI, facilitated by PLEXOS, aims to provide a comprehensive view of the energy landscape, supporting decision-making processes related to energy policy and infrastructure planning.

2.2.1 Baseline Model Development

The I-SEM oversees the joint management of the electricity systems in both the Republic of Ireland (ROI) and NI. This market is supported by a sophisticated network of High Voltage Direct Current (HVDC) systems designed to facilitate efficient energy exchange across borders.

Key to this network is the Moyle interconnector, capable of transmitting up to 450 MW, linking NI's power system with Great Britain (GB). On the ROI side, three significant interconnectors are in place: the East-West interconnector (EWIC), which connects to GB with a capacity of 500 MW; the Greenlink interconnector, set to link to Wales with a capacity of 500 MW and expected to become operational by the end of 2024; and the Celtic interconnector, planned to connect to France with a capacity of 700 MW, aiming for completion by 2027 [14].

Additionally, the power systems of ROI and NI are directly connected via a 275 kV[2] double circuit with a capacity of less than 300 MW and two 110 kV[3] interconnectors with a maximum capacity of less than 30 MW. These connections form a critical component of the proposed model, designed to support long-term energy scenarios, a central focus of this project. A detailed energy system model for the entire island of Ireland, incorporating both ROI and NI, has been constructed using PLEXOS, as depicted in Figure 2. Data for this model, including supply and demand figures, were compiled from public I-SEM reports, ensuring transparency and reliability in the analysis [14] [17].

The model serves a dual purpose: first, it lays the groundwork for a foundational electricity market model specifically tailored for NI. This initial phase sets the baseline for understanding the current state of the electricity market in NI, focusing on the primary sources of power generation, including wind, solar, and storage technologies. Following this establishment, the model will be extended to forecast the state of the NI electricity market by 2030, 2040 and 2050 in Phase II and Phase III. This expansion is pivotal for aligning with the region's emissions reduction targets and for anticipating future energy landscapes [18]. It enables the identification of necessary adjustments and investments to meet environmental commitments effectively.

Furthermore, the model integrates with the gas market to analyse the intricate dynamics between the electricity and gas sectors. Given the continued significance of gas as a primary source of power generation in NI, this integration is crucial. Through this analysis, the model aims to develop co-optimisation strategies for gas and power, ensuring a balanced and sustainable energy mix that accommodates the increasing importance of RES like wind and solar, alongside traditional gas, ammonia, and hydrogen technologies. By focusing on both the electricity and gas markets, the model addresses the need for a comprehensive understanding of the energy landscape in NI. This holistic approach facilitates strategic planning and investment decisions that support the transition toward a more sustainable and efficient energy system.

[2] The Northern Ireland system connects to the Irish system through a 275 kV double-circuit line from the Tandragee substation in Co. Armagh to the Louth substation in Co. Louth. This tie line synchronises both power systems, enabling energy to flow freely between the two jurisdictions based on operational requirements and the generating plants in use.

[3] These 110 kV tie lines provide an AC connection between the two transmission systems, which allows emergency flows of active and reactive power for frequency and voltage support, increasing system stability.

In this context, the model places special emphasis on RES such as wind and solar, alongside energy storage solutions. It also focuses on traditional fossil fuels like natural gas, as well as low-carbon alternatives such as ammonia, and hydrogen. While natural gas remains significant in NI's current energy portfolio, there is an acknowledged need for a gradual transition towards cleaner and more sustainable energy options, including hydrogen and ammonia produced from renewable sources.

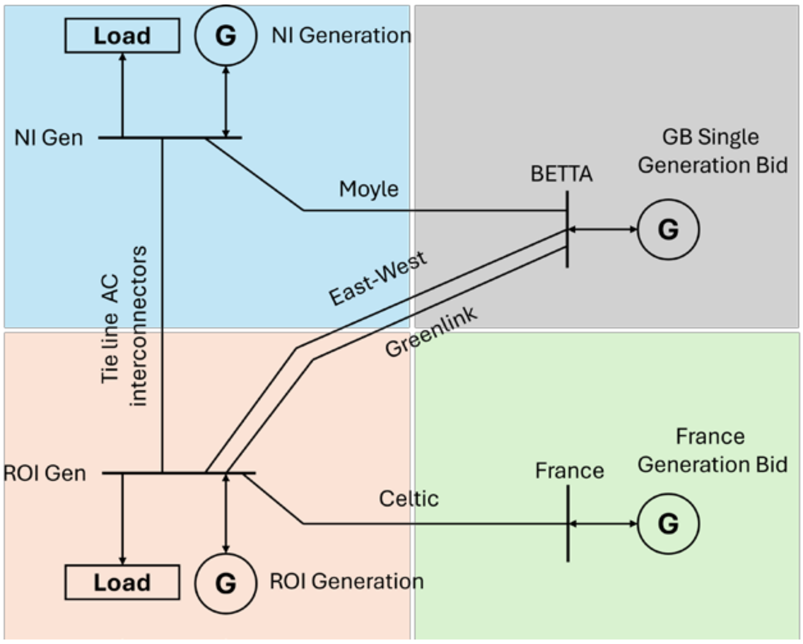


Figure 2 The developed I-SEM model in PLEXOS

Figure 2 illustrates the model, which was successfully executed for 2022. This year was specifically chosen because reliable, real-world data was publicly available from SONI and EirGrid, making 2022 the latest year for which network data could be used to cross-verify the model's outcomes. This ensures the model's accuracy and reliability, forming a robust baseline for future scenario development in Phase II and Phase III.

The model incorporates a comprehensive portfolio of all generation units, including their technical specifications. This information is derived from the validated-backcast SEM published model, which spans from 2021 to 2029 [14], and insights into the performance of the all-island transmission system [19]. This approach ensures that the model reflects the current state of the energy sector and is well-equipped to predict future trends.

The developed I-SEM PLEXOS optimisation model is meticulously configured to reflect the current operational realities of the electricity market. Key generation parameters are defined for all generators [14], including their maximum capacity, minimum stable output levels, heat rates, CO_2 pricing, startup costs, minimum uptime and downtime requirements, maximum ramp-up and ramp-down rates, and variable operation and maintenance expenses. Additionally, a marginal loss factor is incorporated for each generator to account for transmission losses from the generation site to the demand reference node.

Line wheeling charges, also known as megawatt flow charges, are fees applied to the use of transmission lines for transporting electricity across interconnectors between different market areas. These charges are intended to cover the costs associated with the maintenance and operation of the transmission infrastructure. To facilitate bi-directional power flows between the I-SEM area and external nodes, a consistent load of 1900 MW for the BETTA node and 900 MW for the France node is maintained. These settings are aligned with the latest I-SEM data, ensuring the model's alignment with real-world market conditions [14], [19]. Additionally, the study provides a summary of generation data for the I-SEM system in both 2022 and 2030, as outlined in Table 1.

Table 1 Installed generation, by fuel type, capacity in NI and ROI in 2022

Fuel type generators	Total installed capacity in NI (MW) 2022	Total installed capacity in ROI (MW) 2022
Gas	1,013	3,794
Coal	476	855
Oil		592
Peat	0	118
Distillate	369	324
Hydro	0	216
Pumped Storage	0	292
Waste	17.6	82
Onshore wind	1,350	4,483
Offshore wind	0	25
Solar	250	244

The GB IC Bid is assigned 4000 MW of gas-fired generators for all scenarios, as per the SEM Model. The France IC Bid is assigned 1800 MW of gas-fired generators for all scenarios, as per the SEM Model. The capacity of coal and oil is merged for NI because NI has a dual coal/oil power plant.

As of now, NI boasts 1350 MW of onshore wind and 250 MW of solar capacity [14]. Meanwhile, the ROI has a significantly larger installed capacity, with 4483 MW of onshore wind, 25 MW of offshore wind, and 244 MW of solar capacity. Hourly profiles for wind and solar generation have been generated based on historical data from 2014 to 2018. It is noteworthy that the System Non-Synchronous Penetration Limit (SNSP) is set to be 75% in 2022, set by SONI and EirGrid.

2.2.2 Co-optimisation Objective Function

This study leverages PLEXOS software to conduct the unit commitment and economic dispatch tasks within the model. The approach employs stochastic optimisation techniques coupled with mixed-integer linear programming (MILP) and utilises the Gurobi solver for computation. This methodological choice allows for the handling of complex scenarios and uncertainties inherent in energy system operations. Figure 3 visually represents the operational flow of the proposed model. It begins with the input parameters, which serve as the foundation for the model's calculations.

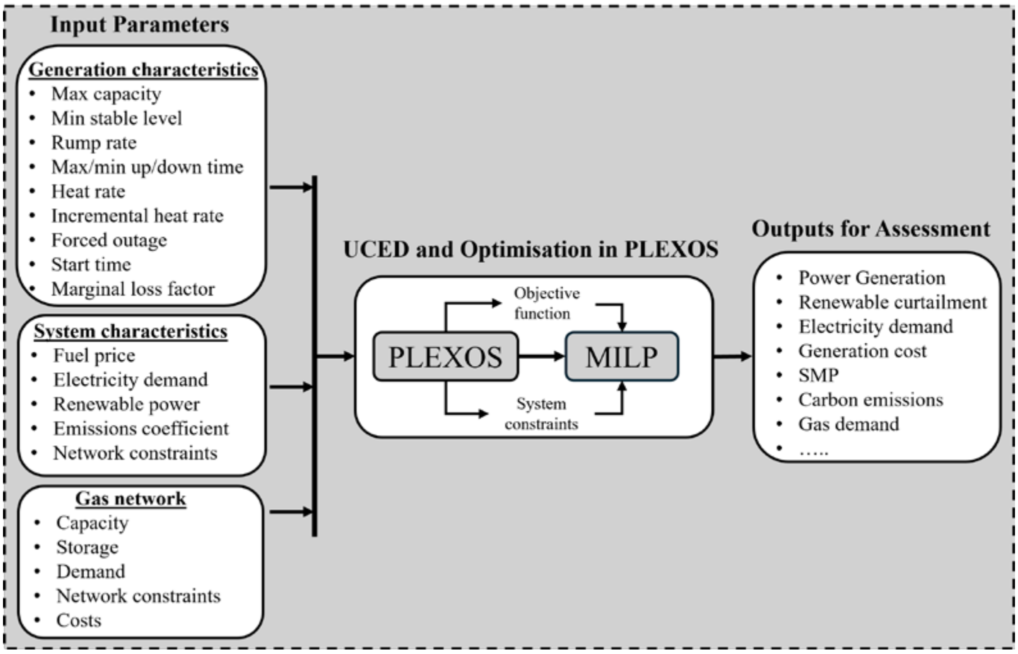


Figure 3 Gas and power system modelling using PLEXOS

These inputs are processed through the problem-solving solver, leveraging the advanced capabilities of PLEXOS and the Gurobi solver to optimise the unit commitment and economic dispatch decisions. The model then generates targeted output data, providing insights into the optimal operation of the energy system under various conditions. Unit commitment is a critical process in energy system management, aimed at determining the optimal generation mix[4] to

[4] The "optimal generation mix" refers to the combination of various energy sources (such as renewable and non-renewable) that provide the necessary electricity generation while considering cost efficiency, environmental

fulfil demand over a designated time frame. Mixed Integer Programming (MIP) is commonly employed in this context to either minimise or maximise a defined objective, subject to certain constraints represented by an objective function.

In this study, MIP is strategically applied to minimise the overall operational cost of power generation. This is achieved by considering the SRMC of the last generation unit required to meet demand. The objective function encapsulates the constraints that must be satisfied to ensure the feasibility and efficiency of the power production plan. PLEXOS optimisation is designed to minimise the objective function, as defined in Equation (1) while adhering to the constraints outlined in Equations (2) through (12). This process yields a dispatch strategy for both power and gas systems that achieves the minimum cost solution [16]. When the gas system is considered within the scope of the optimisation, the objective function is adjusted accordingly. The objective function including gas system is stated in Equation (1);

$$Minimum \sum_{t\in T}\sum_{i\in I}\begin{pmatrix} SC_{it}.US_{it} + NLC_{it}.UG_{it} + (VOM_{it} + UoS_{it}).P_{it} \\ PC_{it}.P_{it} + PenLL.UE_{it} + PenLL.RES_{it} + PD.Ex_t \end{pmatrix} + (GPC_{it} + GTC_{kt} + PenLLG.UGDt\ ) \quad (1)$$

where, t is the interval time until T, i is the index used for each generator unit until I units, SC_{it} is the startup cost of generator unit i at time t in (£), $US_{it}$is a binary number determining the unit commitment state (i.e., 0 or 1) of each unit, if unit i has been started at a time (t-1), NLC_{it} is a zero load cost of generation unit i (£), UG_{it} used as a binary number to represent the generator state of unit i, VOM_{it} is VOM cost of unit i (£), UoS_{it} is the generator unit i use of system cost (£), PC_{it} is the cost of production of unit i (£), P_{it} is the unit i power output (MW), $PenLL$ is a penalty set for loss load (£), UE_t is unserved energy by unit i (MWh), RES_t is reserve energy not fulfilled by unit i, PD is a penalty set for dump energy (£), and Ex_t is the excess energy of unit i over the period t. GPC_{it} is used to set a base price of gas in the model as a function of the production cost of each supply source field located at node i. GTC_{kt} represents gas pipeline transportation tariffs for pipeline k in the model. Similar to electricity

impact, and reliability to meet consumer demand. The objective function encapsulates the constraints that must be satisfied to ensure the feasibility and efficiency of the power production plan. These constraints include energy balance, maximum ramp rates, maximum and minimum capacity levels, gas production requirements, and flow constraints. Together, they balance the interplay between generation sources and operational requirements, ensuring a reliable and sustainable energy supply.

load loss, unserved gas demand ($UGDt$) penalised at the loss of load price ($PenLLG$). The objective function defined in (1) is subjected to the following constraints;

$$\sum_{t \in T} \sum_{i \in I} (P_{it} - PLoad_{it} + UE_{it} = D_t \quad \text{(Energy balance)} \quad (2)$$

$$P_{it} - P_{it-1} - MRU_{it}.UG_{it} \leq 0 \quad \text{(Maximum ramp up rate)} \quad (3)$$

$$P_{it} - P_{it-1} + MRD_{it}.UG_{it} \geq 0 \quad \text{(Maximum ramp down rate)} \quad (4)$$

$$(P_{it} - Pmax_{it}).UG_{it} \leq 0 \quad \text{(Maximum capacity)} \quad (5)$$

$$P_{it} - PMSL_{it}.UG_{it} \geq 0 \quad \text{(Minimum stable level)} \quad (6)$$

$$\sum_{i \in I} \sum_{t \in T} (GProd_{it}.UGD_t) = GD_t \quad \text{(Gas production constrraints)} \quad (7)$$

$$GFV_{it} - GFP_{it} \geq 0 \quad \text{(Volume flow constraints)} \quad (8)$$

$$GPV_{kt} - MaxPV_{kt} \geq 0 \quad \text{(Maximum volume)} \quad (9)$$

$$GPV_{kt} - MinPV_{kt} \geq 0 \quad \text{(Minimum volume)} \quad (10)$$

$$GPF_{kt} - MaxPF_{kt} \geq 0 \quad \text{(Maximum gas flow)} \quad (11)$$

$$GPF_{kt} - MinPF_{kt} \geq 0 \quad \text{(Minimum gas flow)} \quad (12)$$

where, $PLoad_{it}$ is the load of generator *i*, D_t represents energy demand over *t* period, MRU_{it} *and* MRD_{it} are maximum ramp-up/down rates of unit *i*, $Pmax_{it}$ is the maximum power generation of generator *i*, and $PMSL_{it}$ is the minimum stable generation level of unit *i*. $GProd_{it}$ represents gas production to meet the total system gas demand at time t (GD_t). GFP_{it} represents the production from each gas field, which will not violate the volume of the gas in that field (GFV_{it}). Equations (8) to (12) represent gas pipeline constraints.

2.2.3 Baseline System Constraints

Operational system constraints, as defined by transmission system operators (TSO), have been integrated into the model. This integration is crucial for maintaining the efficient and secure operation of the power systems, thereby avoiding potential issues related to voltage, frequency, and stability. These constraints are derived from authoritative sources, as referenced in [20] and [21], and include:

1. The SNSP plays a vital role in safeguarding the reliability of the power system by ensuring system frequency and dynamic stability. It is computed for each trading period, reflecting the proportion of non-synchronous generation allowed in the system. As of now, the SNSP is capped at 75%, but Ireland's TSOs aim to elevate this limit to 95% by 2030. This adjustment is intended to accommodate the increased reliance on RES across the I-SEM, aiming for an 80% RES contribution [22]. The current participation of the Moyle interconnector and the EWIC in electricity import and export activities will continue. By 2030, the Celtic and Greenlink interconnectors are also expected to be factored into the SNSP calculation, further enhancing the flexibility and resilience of the power system.

2. Operating reserves are essential for mitigating the impact of a generator's failure within the power system [23]. They are categorised into Primary Operating Reserve (POR), Secondary Operating Reserve (SOR), and two tiers of Tertiary Operating Reserve (TOR 1 and TOR 2) [24]. Specifically, POR and SOR together must constitute 75% of the capacity of the largest generator in-feed, whereas TOR 1 and TOR 2 collectively must match 100% of the largest generator's capacity. Notably, the largest synchronous generator, Poolbeg in the ROI, has a capacity of 466 MW, and the largest generator in-feed, the EWIC, boasts a capacity of 500 MW [7]. Furthermore, to prepare for unforeseen decreases in system demand, negative reserves of 100 MW in ROI and 50 MW in NI are mandated.

3. Ensuring system inertia and preventing voltage issues necessitates the presence of a minimum number of synchronous generation units across different segments of the power system. This requirement is crucial for maintaining system stability and reliability. The model incorporates the requirements for synchronous generation units in both the ROI and NI, as well as the inter-area flow units within these regions. It is important to note that the newly established HVAC interconnector between ROI and NI does not influence the inter-area flow constraint of existing transmission lines. Instead, these constraints are dictated by the technical limitations of the lines themselves. Currently, the minimum number of synchronous generation units required is set to 3 for NI and 5 for ROI, as per SONI and EirGrid's requirements [21].

2.3 Analysis and Results

This section contains the analysis and results, including the base model validation process and the gas network modelling results.

2.3.1 Baseline Model Validation

This section presents the PLEXOS model's outputs with actual data released by SONI and EirGrid for the year 2022. This comparative analysis serves as a critical step in validating the developed model, ensuring its accuracy and reliability. Upon successful validation, the model becomes a valuable tool for evaluating the effects of various technological options and TSO operational constraints on steering the NI power grid towards achieving net-zero emissions at the lowest possible cost.

Several key parameters are crucial for the validation process, particularly the electricity demand profile and generation mixes, which significantly influence broader electricity market dynamics. To effectively validate the PLEXOS model for optimising the integrated gas and electricity systems, several key data requirements must be met. First, actual generation data for 2022 from both the gas and electricity sectors is crucial, including metrics such as total generation in GWh, generation by fuel type, and renewable energy contributions. This includes parameters like GFPP, RES share, and curtailment figures. Additionally, detailed information about the gas pipeline infrastructure (i.e., diameter, length, and pressure specifications) must be incorporated to ensure realistic modelling of gas flows.

Validation also necessitates demand data, encompassing annual energy demands for both power and gas across NI, as well as the characteristics of the power system, including the total emissions, SMP, and total generation costs. This comprehensive dataset enables a robust comparison between actual performance and model outputs, ensuring the accuracy and reliability of the PLEXOS model in representing real-world scenarios.

As evidenced in Table 2, the PLEXOS model effectively captures the nuances of the NI power system, demonstrating its capability to serve as a robust representation of the system.

Table 2 Comparison of actual and PLEXOS dispatch data of NI electricity system in 2022

Generation parameter	Actual data 2022 in GWh	PLEXOS data 2022 in GWh	Error %*
Gas power	4,440.0	4,319.38	- 0.03
other non-RES	961	999.05	0.04
Wind	2905.4	2,953.49	0.02
NI other RES	406.5	360.71	- 0.11
Net import/export	-1111.2	-1078	- 0.03
Total generation	7,601.7	7,554.6	- 0.01
Total RES share	3,311.90	3,314.20	0.00
Wind curtailment	291	235	- 0.19
Solar curtailment	30	25	-0.17

* While there is no universal standard for acceptable error levels in model calibration, many practitioners consider a threshold of less than 5% as indicative of sufficient accuracy for most applications. This threshold may vary depending on the specific context, application, and acceptable margins of error within the energy sector.

2.3.2 Gas Network Modelling

The gas network on the island of Ireland is divided into two jurisdictions: NI and the ROI. The GB area is a separate jurisdiction with its own gas market operator. Currently, there are three different gas market operators: one for NI, one for ROI, and one for GB. In 2008, a significant milestone was reached when the Utility Regulator in NI and the Commission for Energy Regulation in the ROI signed a Memorandum of Understanding. This agreement aimed to unify the gas network, bringing it closer to the vision of the European Single Internal Energy Market.

The gas network analysed in this context encompasses major load centres and power stations, highlighting its integral role in supporting the energy demands of the region. The system is characterised by two principal entry points: the Inch terminal, which receives decreasing volumes from the Kinsale gas fields and serves as the sole gas storage facility, and the Moffat entry point. The latter is responsible for supplying over 95% of the island's gas demand through subsea interconnectors and the Scotland Northern Ireland Pipeline (SNIP).

Additionally, gas can flow between NI and the ROI via the South-North Pipeline (SNP), facilitating inter-jurisdictional trade [15]. Another notable feature is the Northwest Pipeline (NWP), which supplies gas to the Coolkeeragh Combined Cycle Gas Turbine (CCGT) plant. The NWP can receive gas directly from the SNP and indirectly from the SNIP via the Belfast Gas Transmission Pipeline (BGTP).

Table 3 presents the key characteristics of the importing gas pipelines utilised in this study, providing a detailed overview of their capacities, lengths, and other technical specifications. This comprehensive analysis underscores the complexity and interconnectedness of the gas network across the island of Ireland and its importance in meeting the region's energy needs.

In this study, the gas model is seamlessly integrated with the unit commitment and economic dispatch (UCED) model, employing a specialised gas transportation algorithm to manage demand and supply dynamics. This integration excludes direct modelling of pressure and pipeline hydraulics but incorporates line pack modelling to approximate pressure limitations. Data on non-power sector gas demand was obtained from Gas Networks Ireland and appropriately allocated to relevant nodes within the model. Importantly, compressors at above-ground facilities were not modelled in this study [16].

Table 3 Operational characteristics of gas transmission pipelines in this study [15] [16]

Gas pipeline	Diameter (mm)	Length (m)	Max Pressure (kPa Gauge)	Min Pressure (kPa Gauge)
IC1	600	204	14800	5000
IC2	750	195	14800	5000
SNP	450	156	8500	3000
ANIP	600	135	7500	5600
NWP	450	112	3500	2700
Inch	610	53	2950	1900

IC1 and IC2 refer to Interconnector No.1 and NO. 2, respectively. SNP is the South-North Pipeline. ANIP is the Antrim Pipeline, and NWP is the North-West Pipeline. Inch refers to the gas storage facility at Inch, which is used to store gas and manage supply during peak demand periods.

Figure 4 presents a simplified, single-line diagrammatic representation of the gas transmission networks utilised in this analysis. It is worth noting that the entire NI gas network is divided into 10 nodes and 12 pipelines, accounting for both power and non-power gas demands in 2022, based on the data provided in the references [15] [16]. NI's combined annual electricity and gas demand were 7.526 TWh for electricity and 739 TWh for gas.

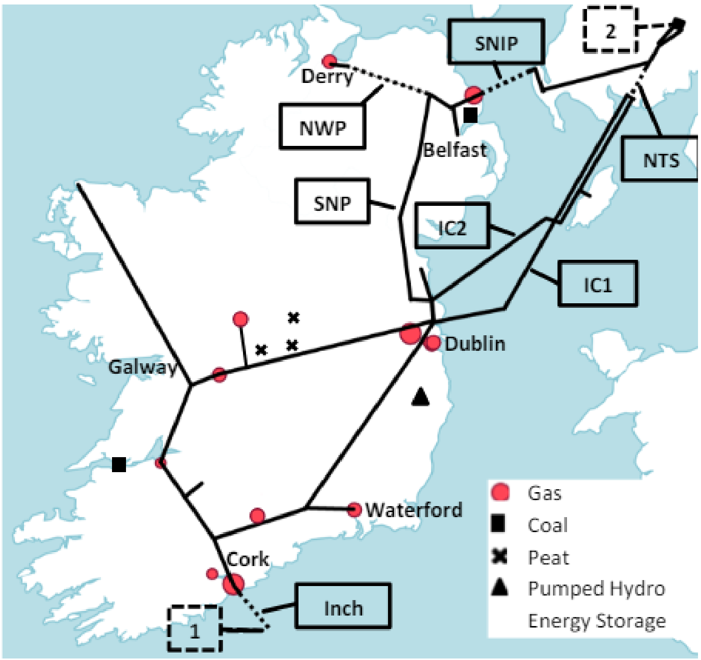


Figure 4 Single line diagram of gas transmission design of this analysis [16]

2.3.3 Gas and Power Interaction

The main aim of this analysis is to explore the intricate relationship between power and gas systems, facilitated by the integration of GFPP within both the UCED and gas models. This integration enables the co-optimisation of these systems, allowing for a more holistic view of their interdependencies and potential synergies [15].

Gas generators, which are integral components of both models, are connected to gas nodes. These generators draw their fuel supply from the gas model and contribute to electricity production within the UCED model. Each gas node is assigned a shadow price, which signifies the economic value of the next unit of gas supply available at that node. While this shadow price generally mirrors the fuel price, it can escalate substantially during periods of system stress, influenced by factors such as congestion or supply shortages.

This shadow price is instrumental in calculating the SRMC for GFPP when bidding into the UCED model. Consequently, constraints within the gas network directly influence the performance and decision-making processes of gas generators within the UCED model framework. Figure 5 provides a visual representation of the energy flow between the power and gas interaction models, illustrating how these systems dynamically interact and respond to each other through the medium of gas generators.

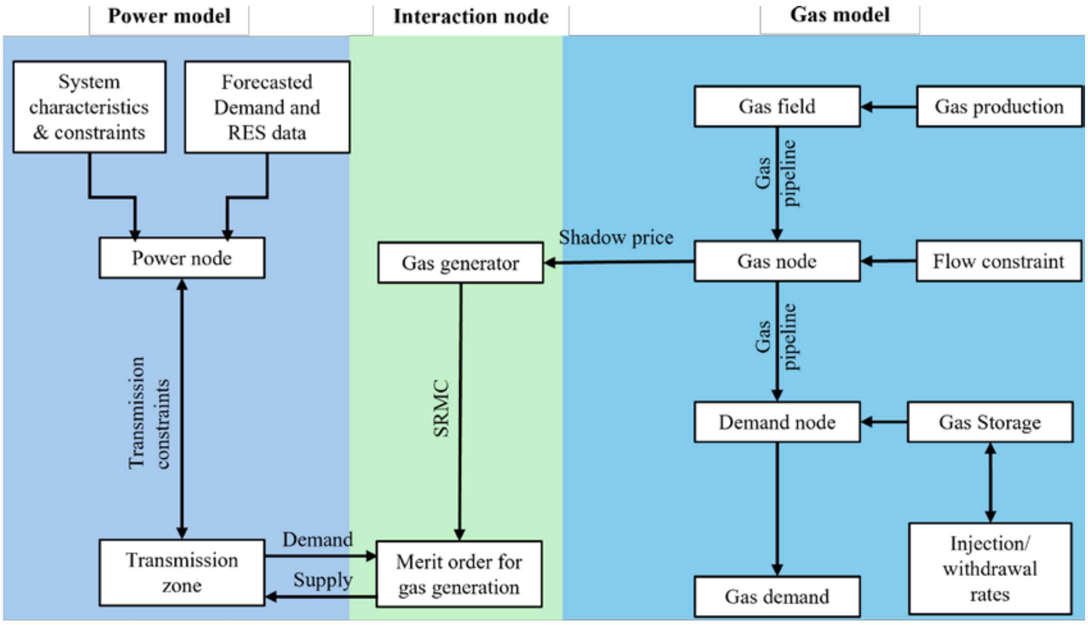


Figure 5 The flowchart representation of gas and power energy vector interaction

In the unit commitment and economic dispatch calculation, the generation cost of each thermal unit is determined based on its SRMC as per Equation (13);

$$SRMC\ (£) = Heat\ Rate\ x\ Fuel\ price + VO\&M \qquad (13)$$

where, VO&M is variable and maintenance cost (£). Considering the interaction between UCED and the gas model, Equation (14), is derived from Equation (13) to calculate the SRMC of each generator;

$$SRMC_i(£) = (SP_i * Heat\ rate_i) + VO\&M_i + UoS_i + \sum_{k=1}^{n} GTC_k + P_c \qquad (14)$$

where, SP_i is the shadow price of node i, UoS_i is a service charge introduced to supply to the grid, for unit i. $\sum_{k=1}^{n} GTC_k$ represents gas transportation costs for all pipelines to supply each generator, and P_c is a carbon price reflection in the market which can be included in the SRMC calculation.

2.3.4 Gas and Electricity Characteristics

The integrated gas and power energy vectors, thoroughly developed for this study, have been simulated for the year 2022. The outcomes for NI, are systematically compiled and displayed in Table 4. This table encapsulates the findings from the simulation, offering annual power and gas demand in 2022.

Table 4 Combined gas and electricity network demands by 2022 across NI

Energy vector	Demand	NI
Power	Annual (GWh)	7.526
Gas	Annual (TJ)	70,500

The central theme of this report is to explore the interaction and co-optimisation of the gas and power systems within NI. Detailed insights into the performance of NI's gas and power systems are presented in Table 5 and Table 6, respectively. The data reveals that RES generation accounted for over 76% of electricity demand, despite approximately 3 TWh of RES-generated electricity being curtailed due to system constraints such as the SNSP, minimum stable level requirements, and the necessity for a certain number of thermal units to operate for stability.

Table 5 NI’s power system characteristics in 2022

Generators	Generation (GWh)
Gas NI	4,319
Coal NI	999
Distillate NI	173
Renewables NI	3086
Renewables NI curtailment	293
Waste NI	9.04
Electricity Demand (GWh)	7,526
SMP (£/MWh)	37
Total Generation cost (£000)	366,377
Emissions (tonne)	2,070,371

Table 6 Gas demand in NI in 2022

Gas nodes	Demand (GWh)
10_Lurgan	2040
3_Ballylumford	4900
32_West	1988.221
4_Carrickfergus	0.00
5_Belfast	12,450
6_Ballyalbannagh	0.00
7_Coolkeragh	0.00
8_Derry	9122
9_Gormanstown	0.00
ISML	0.00

It is feasible to incorporate this curtailed generation back into the system by improving system flexibility, thereby augmenting the overall RES generation. This enhancement supports the ambitious goal of achieving a 75% RES share as facilitated in the current NI’s electricity market operation. It is important to note that the base model discussed herein reflects the NI gas and power system for 2022. This model provides a foundational understanding that can be built upon through further analysis, exploring various scenarios to equip NI's decision-makers with valuable insights into the dynamics between the gas and power systems.

2.3.5 Scenario Development

To gain deeper insights into the co-optimisation and interaction between the gas and power systems in NI, three distinct scenarios were constructed alongside the base scenario for the year 2022. These scenarios include:

1. **Low Wind Scenario (LW)**: This scenario assumes that wind generation capacity is reduced to 70% of its original capacity.
2. **High Gas Demand Scenario (HG)**: This scenario considers an increase in gas demand.
3. **Low Wind High Gas Demand Scenario (LWHG)**: Combining elements of the LW and HG scenarios, this scenario accounts for both reduced wind generation and increased gas demand.

Results for these scenarios were specifically recorded for January 2022, providing a monthly snapshot of how variations in wind generation and gas demand could impact the system. The analysis shows that under the LW scenario, an increase in gas-powered generation was observed to compensate for the reduced availability of wind energy. Furthermore, there was a notable increase in the SMP due to the decrease in wind generation in NI.

These results are shown in Table 7, Table 8, and Table 9, offering an overview of the impacts of these scenarios on the NI gas and power systems. Through this comparative analysis, stakeholders can better understand the dynamics of the system under different conditions and plan accordingly to achieve optimal performance and reliability.

Table 7 Scenario comparative analysis of developed scenarios against base model for the power system in the first week of January 2022

Generators	Base Scenario Generation (GWh)	LW Scenario Generation (GWh)	HG Scenario Generation (GWh)	HGLW Scenario Generation (GWh)
Gas NI	467.51	552.47	467.97	552.92
Distillate NI	19.99	38.19	19.76	37.79
RES NI	522.42	267.57	523.90	267.10
Waste NI	1.90	4.99	2.07	5.10
RES NI Curtailment	36.6	11.9	35	12.4

Table 8 Developed scenarios against base model for the power system in January 2022

System Characteristics	Base Scenario	LW Scenario	HG Scenario	HGLW Scenario
Electricity Demand (GWh)	701.65	701.65	701.65	701.65
SMP (£/MWh)	54.39	82.34	58.76	90.80
Generation cost (£000)	42,056.64	51,911.68	42,379.55	52,112.07
CO_2 Emissions (tonne)	195,455.09	240,209.26	197,559.76	241,786.44

Table 9 Developed scenarios against baseline model for gas network in January 2022

Gas nodes	Demand (Baseline)	Demand (TJ) LW	Demand (TJ) HG	Demand (TJ) LWHG
10_Lurgan	203.69	203.69	254.00	254.00
3_Ballylumford	477.86	493.22	429.91	443.01
32_West	210.55	210.55	262.56	262.56
4_Carrickfergus	0.00	0.00	0.00	0.00
5_Belfast	1,442.13	1,442.13	1,798.33	1,798.33
6_Ballyalbannagh	0.00	0.00	0.00	0.00
7_Coolkeragh	0.00	0.00	0.00	0.00
8_Derry	990.34	990.34	1,234.95	1,234.95
9_Gormanstown	0.00	0.00	0.00	0.00
ISML	0.00	0.00	0.00	0.00

3. Survey Analysis

The purpose of this survey is to gather insights and opinions from experts on the current and future interactions between natural gas and electricity networks in NI. We aim to understand the challenges, opportunities, and potential strategies for optimising the operation and integration of these energy systems to support the transition towards a lower-carbon economy. This survey is designed to collect qualitative and quantitative data through a series of structured questions. The target respondents are industry experts, policymakers, researchers, and stakeholders involved in NI's energy sector. The results from this survey will be incorporated into the PLEXOS sensitivity analysis in Phases II and III, providing valuable insights for scenario modelling. Currently, the model addresses only the baseline scenario for 2022, but these survey results will help refine and expand future scenarios, considering renewable penetration, fuel types, and operational constraints.

3.1 Survey Round One Design and Implementation

The survey questions were carefully developed to address key aspects of the interaction between natural gas and electricity networks in NI. The questions are structured to cover current conditions, mid-term future expectations, and long-term projections, ensuring a comprehensive understanding of the topic. Input from industry experts and academic researchers was considered to ensure the relevance and clarity of the questions.

The remote survey was conducted using an English language online form designed with QualtricsXM and distributed by email to a hand-picked recipient list. The survey was distributed through various channels, including email invitations, and professional networks to reach a diverse group of respondents. Target respondents included policymakers, industry experts, researchers, and stakeholders from the energy sector. This approach ensures a wide range of opinions and expertise is captured, reflecting the perspectives of key players in the energy field.

The data collection process commenced on [17/06/2024] and continued until [01/07/2024]. A total of 67 people participated in this survey. However, not all participants responded to every question, resulting in some questions receiving more feedback than others. Respondents completed the survey online, ensuring ease of access and convenience. The collected data are anonymised and analysed to identify trends, challenges, and opportunities in the integration and optimisation of gas and electricity networks in NI.

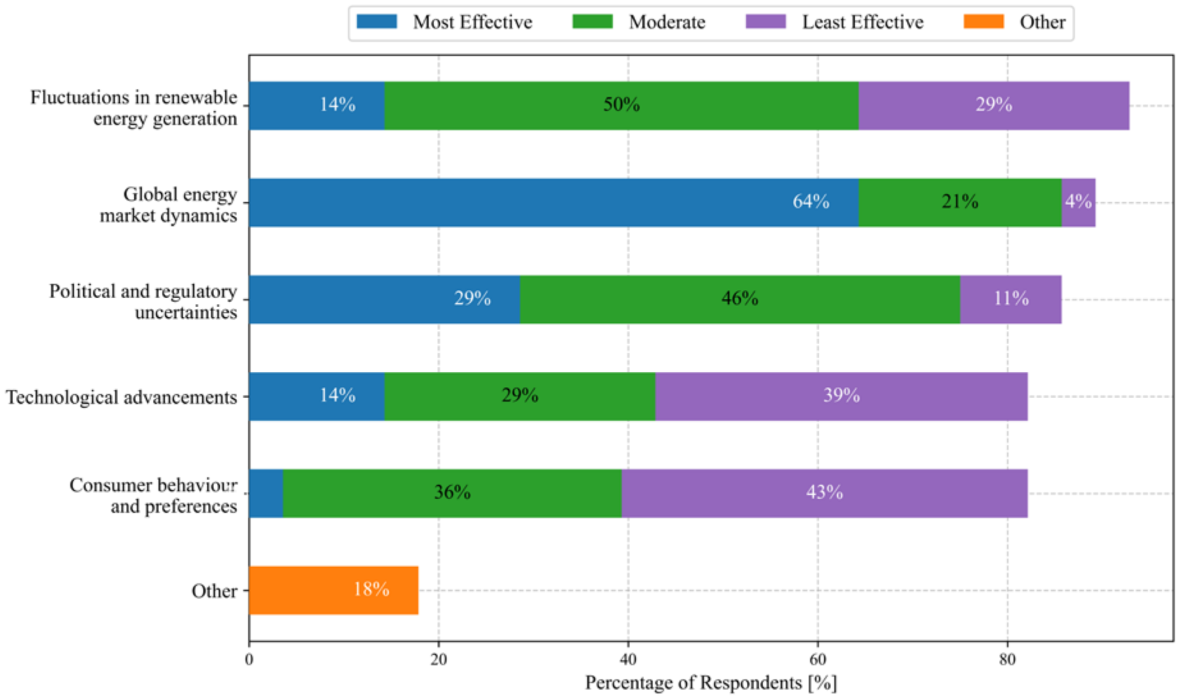
3.2 Survey Results

3.2.1 Challenges Limiting Optimisation of Gas and Electricity Systems

The variability of RES, particularly solar and wind, poses significant challenges to the optimisation of gas and electricity systems. The intermittent nature of solar and wind power can lead to rapid fluctuations in electricity supply, making it difficult to maintain grid stability [24]. This requires more sophisticated forecasting, monitoring, and control systems to balance supply and demand in real time. Additionally, renewable energy generation may not align with periods of peak demand, creating supply-demand mismatches that strain existing transmission infrastructure and necessitate flexible backup generation. The unpredictability of renewable energy generation can create scheduling challenges for generation assets. Accurately predicting power demand and renewable energy output is crucial for efficient scheduling and operation of the power system. Uncertainty in forecasting can lead to inefficiencies in asset utilisation and may necessitate the use of backup generation to compensate for the variability of renewable sources.

The first survey question asks respondents to identify the biggest obstacles preventing NI from optimising its gas and electricity systems. In this context, 'optimising' is defined as achieving a balance across multiple criteria, including balancing supply and demand, minimising costs, and reducing carbon emissions. For each factor listed, respondents are asked to rate how effective they believe it is in managing energy consumption on a scale of 1 (most effective) to 3 (least effective) and the results are plotted in Figure 6.

The survey results indicate a clear consensus among respondents regarding the main challenges facing the optimisation of gas and electricity systems in NI. The most frequently cited challenges, particularly fluctuations in renewable energy generation and global energy market dynamics, highlight the interconnectedness of local energy systems with broader environmental and economic forces. This aligns with the broader discussion on the energy transition and the increasing reliance on variable RES such as wind and solar power [25]. The intermittency of these sources poses technical challenges for system stability and requires sophisticated management and storage solutions to balance supply and demand effectively.



Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective

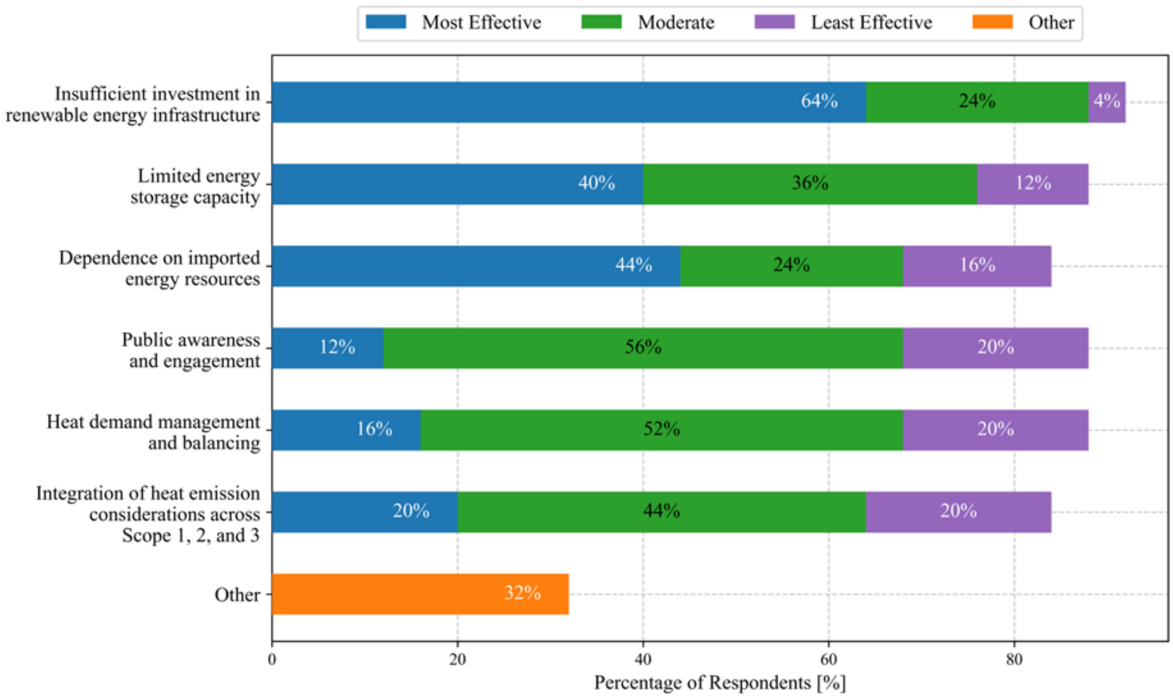
Figure 6 What are the main challenges limiting the optimisation of the operation of gas and electricity systems in NI?

Furthermore, global energy market dynamics significantly impact the optimisation of gas and electricity systems in regions like NI due to several interconnected reasons. These dynamics encompass many factors, including the cost and availability of energy resources, technological advancements, policy changes, and market trends. Understanding these dynamics is crucial for formulating effective local energy policies and investments that can navigate the challenges and capitalise on the opportunities presented by the global energy landscape. The impact of global energy market dynamics reflects the interconnectedness of local energy systems with broader economic and geopolitical forces. The volatility of global energy markets can affect the cost and availability of energy resources, influencing investment decisions and operational strategies in the energy sector. The reliance on GFPP for flexibility and the increasing intimacy between electricity supply security and natural gas deliverability is central to this challenge. These findings underscore the complexity of managing renewable energy variability and adapting to global market trends, which are critical for the sector's resilience and efficiency.

Political and regulatory uncertainties also emerge as significant challenges, reflecting concerns over the stability and predictability of the regulatory environment. This suggests that stakeholders perceive a need for a stable and supportive regulatory framework to facilitate investment and operational strategies in the energy sector.

3.2.2 Factors Influencing Energy Market Volatility

Energy market volatility, characterised by rapid price swings, is a complex issue driven by a confluence of factors. The results revealed that insufficient investments in renewable energy infrastructure and limited energy storage capacity were identified as the most significant factors contributing to market volatility, as shown in Figure 7. This suggests that a lack of diversification away from traditional energy sources and challenges in managing the variability of renewable energy production are seen as key drivers of price fluctuations in the NI context. While the baseline PLEXOS model does not specifically optimise the amount and duration of energy storage, these aspects will be addressed in more detail in Phase II of the project.



Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective.

Figure 7 In your opinion, what are the main factors influencing the volatility of energy markets, particularly concerning natural gas and electricity?

The survey reveals that insufficient investment in renewable energy infrastructure is perceived as a major barrier to energy transition. An overwhelming majority of 64% of respondents rated this factor as the most effective barrier, while another 24% considered it moderately effective.

This strong consensus underscores the critical role of investment in renewable energy technologies for achieving sustainable energy goals. The IEA's projection that annual clean energy investment needs to triple to around $4 trillion by 2030 to reach net-zero emissions by 2050 further emphasises the scale of this challenge [26]. This widespread recognition among experts highlights the urgent need for increased financial commitments to renewable infrastructure development. The significant gap between current investment levels and required amounts suggests that addressing this barrier will be crucial for meeting climate targets and ensuring a smooth transition to cleaner energy sources. Policymakers and investors should take note of this strong consensus, prioritising strategies to boost renewable energy investments and overcome the associated barriers.

Several factors contribute to insufficient investment in renewables. Renewable energy projects often require significant initial capital, which can deter investors due to the high upfront costs and long payback periods [27]. Inconsistent or unclear government policies regarding renewable energy create additional investment risks, making it difficult for investors to commit to long-term projects. Furthermore, continued subsidies for fossil fuels in many countries skew the market, making it harder for renewables to compete on a level playing field. Additionally, the need for grid upgrades and energy storage solutions to accommodate variable renewable sources increases the overall cost, further complicating the investment landscape for renewables.

The survey revealed a strong consensus among experts regarding the impact of limited energy storage capacity on energy market volatility. An impressive 40% of respondents rated this factor as most effective in contributing to market volatility, while another 36% considered it moderately effective. These combined totals indicate that a significant majority of 76% perceive limited energy storage capacity as having either a high or moderate influence on market dynamics. Only 12% of respondents viewed this factor as less effective, suggesting a relatively minor dissenting opinion. This widespread agreement underscores the critical role that energy storage plays in managing supply-demand imbalances and smoothing out fluctuations in renewable energy generation. The strong emphasis placed on this factor by experts highlights the urgent need for investments in advanced energy storage technologies to stabilise the grid and support the integration of intermittent renewable sources. As the energy sector continues to transition towards cleaner, more variable power sources, addressing limitations in energy storage capacity emerges as a crucial priority for maintaining market stability and reliability.

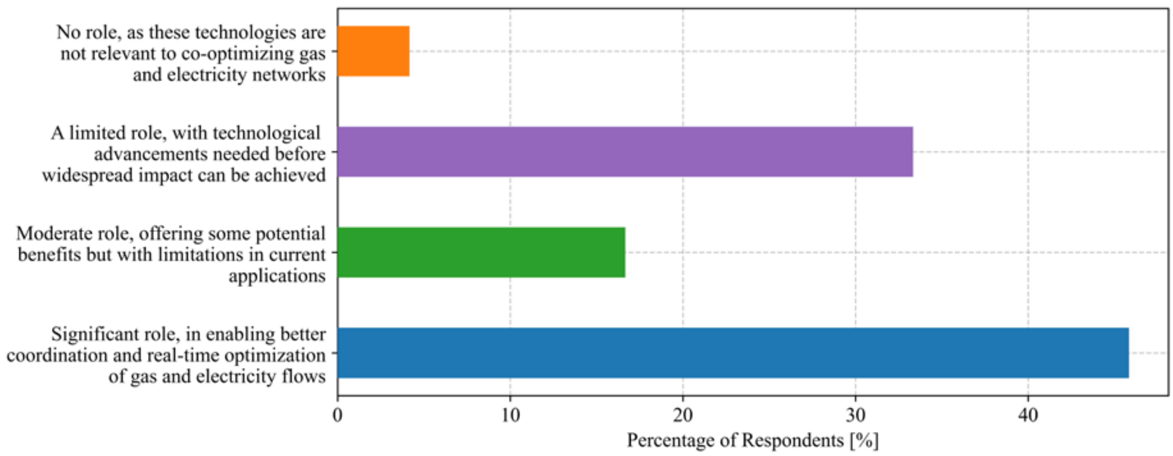
Furthermore, a heavy dependence on imported energy resources creates a precarious situation for a nation's energy security and sustainability goals. International price fluctuations, often triggered by geopolitical tensions or economic changes, can cause dramatic swings in the cost of imported energy, inflicting economic hardship. This vulnerability extends beyond price, as countries relying heavily on imports lack control over the supply chain itself. Disruptions caused by political disputes or infrastructure issues can leave a nation struggling to meet its energy demands. Moreover, imported energy sources may not be derived from sustainable practices, hindering progress towards clean energy goals. The environmental impact can extend beyond the source, as transportation and processing of imported energy often generate additional burdens. The recent global energy crisis, fuelled by the war in Ukraine, serves as a stark reminder of these vulnerabilities. To achieve a more stable, secure, and sustainable energy future, nations must take action. Investing in domestic energy production, particularly from RES, can reduce dependence on imports and bolster energy security. Additionally, improving energy efficiency through infrastructure upgrades and promoting responsible consumer behaviour can minimise overall energy needs. Finally, diversifying import sources can mitigate the risks associated with relying on a single supplier. By addressing these challenges, countries can pave the way for a more resilient and sustainable energy landscape.

Finally, Figure 7 shows that factors related to public awareness, heat demand management, and the integration of heat emission considerations were deemed less impactful compared to primary challenges. While these aspects are important, they were considered secondary to the main issues facing energy markets and received lower rankings for their influence on market volatility. Despite this, these factors play crucial roles in overall energy system efficiency and sustainability.

3.2.3 Role of Technological Innovations in Co-optimisation

Technological innovations, particularly smart grids, and IoT devices, offer significant potential for improving the co-optimisation of gas and electricity networks. Smart grids integrate ICT with traditional power systems, enabling real-time control and optimisation of energy distribution, allowing for more efficient allocation of resources between gas and electricity systems [28]. The IoT devices provide granular data on consumption patterns and network performance, facilitating predictive maintenance and optimised resource utilisation [29]. These technologies can help synchronise gas and electricity supply chains, enhance grid resilience, and optimise energy storage and dispatch. By leveraging advanced analytics and machine learning algorithms applied to IoT-generated data, utilities can better manage peak demand periods, reduce energy waste, and create more flexible, responsive energy systems [30].

Technological innovations, specifically smart grids and IoT devices, hold considerable promise for enhancing the co-optimisation of gas and electricity networks in NI. The survey results indicate a nuanced perspective on this matter with approximately 46% of respondents recognising the potential of smart grids and IoT technologies to significantly contribute to the better coordination and real-time optimisation of gas and electricity flows, as illustrated in Figure 8. This group acknowledges the value these technologies bring to balancing supply and demand across both networks, highlighting their understanding of the transformative potential of such innovations. Conversely, 33% of respondents express scepticism about the extent to which these technologies can impact network optimisation, suggesting that current technological capabilities might not be sufficient or that further advancements are required to achieve meaningful improvements. However, the responses do not explicitly differentiate between current and future capabilities, leaving room for interpretation of whether these views pertain to existing technological limitations or anticipated future developments.



Please choose the option that best fits your perception.

Figure 8 To what extent do you believe technological innovations, such as smart grids and IoT devices, can play a role in improving the co-optimisation of gas and electricity networks in NI at present?

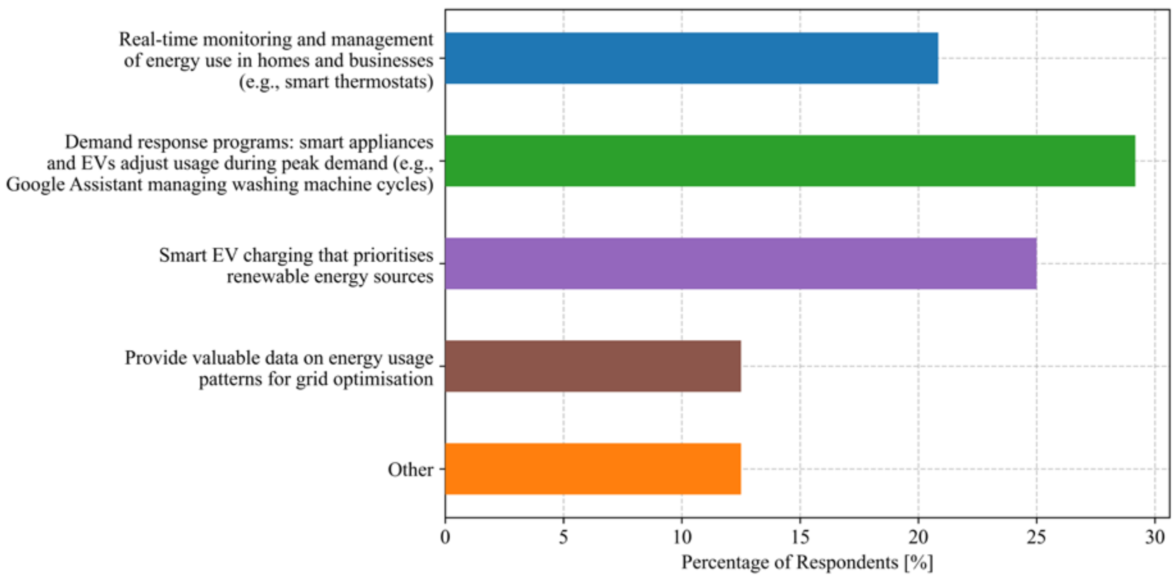
As noted by the IEA, many of the technologies involved in smart grids have already reached maturity, indicating that the focus should now shift towards widespread deployment and integration into existing systems [31]. This implies that while the foundational technologies may be ready, their application and optimisation in specific contexts, such as NI's gas and electricity networks, could still benefit from further development and customisation.

The integration of IoT devices into the electric grid brings increased connectivity and, consequently, new vulnerabilities. Ensuring the security of these devices and protecting against potential cyber threats is crucial for maintaining the integrity and reliability of the grid [32]. Addressing these challenges requires a multi-faceted approach involving technological solutions, robust policies and procedures, ongoing training, and collaboration between utilities, device manufacturers, regulators, and cybersecurity experts. As the grid becomes increasingly connected and reliant on IoT devices, maintaining a strong security posture will be essential to ensure the reliability, integrity, and resilience of our energy infrastructure. This is not a one-time effort but an ongoing process that must evolve as new threats emerge and technologies advance.

Smart grids and IoT devices offer significant potential to improve the management of both gas and electricity networks. For example, sensors and meters in smart grids can provide real-time data on energy consumption and generation, which can help optimise flows within the electricity grid and manage the gas grid more efficiently. This data can be used to minimise imbalances, reduce operational costs, and ensure efficient use of resources within each network. Furthermore, smart grids enable better management of consumer demand through dynamic pricing or automated controls, potentially reducing peak loads and improving grid stability. While these technologies can significantly improve the efficiency of individual networks, further integration and coordination would be required to achieve true co-optimisation of both gas and electricity networks, beyond merely connecting large gas pipelines to thermal generators.

The successful implementation of smart grids and IoT devices requires not only technological readiness but also effective deployment strategies and integration with existing infrastructure. This involves addressing logistical, regulatory, and compatibility issues to ensure that these technologies can seamlessly interact with and enhance the functionality of the gas and electricity networks. Furthermore, implementing smart grid technologies requires significant investment in upgrading network infrastructure and communication systems. Secure data management and communication are crucial to ensure the integrity and reliability of the system. The effectiveness of some approaches might rely on consumer adoption of smart meters or participation in demand-side management programs.

Furthermore, based on the survey results in Figure 9, smart technologies such as Google appliances and electric vehicles are perceived to have a moderate impact on co-optimising gas and electricity networks in NI. The concept of real-time monitoring and management aligns well with these technologies, as smart appliances and electric vehicles can provide real-time data on energy consumption, enabling adjustments to optimise energy use efficiently. The survey indicates a positive impact on this aspect. Moreover, smart appliances and electric vehicles can participate in demand response programs, contributing to grid stability by adjusting energy consumption in response to grid conditions, as indicated by the survey's findings. Additionally, smart electric vehicle charging systems that prioritise RES can reduce reliance on gas networks during peak demand periods. The survey results affirm a positive impact of these technologies on integrating renewables into the energy mix. Together, these insights highlight the potential of smart technologies to enhance the co-optimisation of gas and electricity networks in NI by improving efficiency, grid responsiveness, and renewable energy integration.



Please choose the option that best fits your perception.

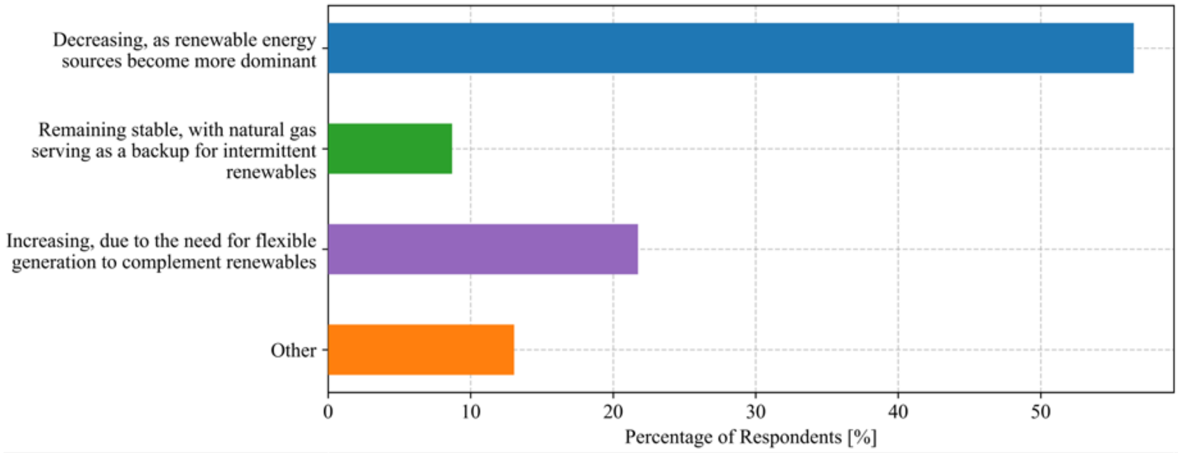
Figure 9 How can smart technologies like Google appliances and electric vehicles help co-optimise gas and electricity networks in NI?

The survey results include an interesting perspective from some participants who selected the “other” option but did not always provide detailed justification for their responses. Only a few participants offered explanations, which were included in *italics* to highlight their viewpoints. One participant noted that while the listed options (i.e., smart appliances and electric vehicles (EV)) represent forms of "demand shift," this might not directly translate to network co-optimisation “*some of these options are examples of demand shift, which has value in peak shaving and network optimisation, but has little value in co-optimisation of multiple networks*”. Co-optimisation goes beyond just demand shifting; it involves the integrated management of supply and demand across both the gas and electricity networks simultaneously. The aim is to maximise overall system efficiency, minimise costs, and reduce carbon emissions by optimising how these networks operate together, rather than in isolation.

3.2.4 Future Natural Gas and Power Sector Interactions

Figure 10 shows that over 50% of the survey respondents anticipate a decrease in the role of natural gas over the next decade as wind power and other RES become more dominant in NI's power sector, reflecting a strong expectation that renewables will significantly displace natural gas in the energy mix. This majority view underscores a growing confidence in the capability of renewables to meet energy demands and a shift towards a more sustainable energy landscape. Conversely, approximately 25% of respondents believe the role of natural gas will increase, emphasising the ongoing necessity for flexible generation capacity to balance the variable output from wind power and other renewables. This minority perspective highlights the critical role that natural gas could continue to play in ensuring grid stability and reliability as the energy transition progresses. The coexistence of these views illustrates the complex dynamics of energy system optimisation, and the multifaceted approach required to integrate RES effectively.

The survey results also highlighted a range of perspectives on the future role of natural gas in the power sector, particularly in relation to the increasing presence of wind power generation. Respondents offered insights that suggest a nuanced outlook on the future of natural gas, emphasising its potential roles and limitations in the evolving energy landscape. One perspective suggested that natural gas might become a "*secondary energy vector for hard/impossible to electrify processes*." This viewpoint underscores the potential for gas in specific sectors even as its role in electricity generation might decline, highlighting the versatility of natural gas as an energy carrier, capable of serving various needs beyond electricity generation.



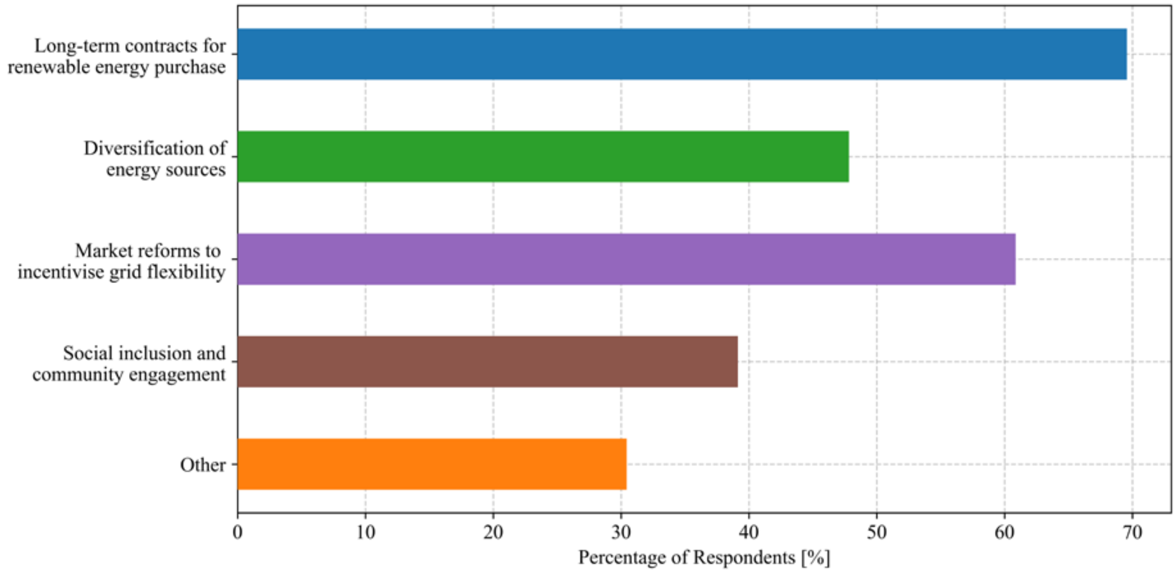
Please choose the option that best fits your perception.

Figure 10 How do you anticipate the role of natural gas evolving in the power sector over the next decade in NI, considering the projected increase in wind power generation?

Another respondent emphasised the importance of defining the term "*role" when discussing natural gas, stating that "total natural gas consumption will decrease*," and the influence of natural gas on wholesale energy costs may decrease, especially if electricity market costs are decoupled from gas prices. This suggests that the role of natural gas extends beyond its direct contribution to electricity generation, influencing broader energy market dynamics and consumer costs. Yet another perspective suggests that gas usage will likely "*decrease overall as wind displaces traditional generation, but gas-fired power plants might still be crucial for backup during peak demand periods,*" leading to increased gas reliance on those specific days. This insight reflects the changing landscape of energy generation, where natural gas remains a key player in ensuring grid stability despite the growing dominance of RES.

These nuanced views collectively paint a picture of a dynamic future for natural gas in NI's power sector. As the region transitions towards greater reliance on wind power, the role of natural gas is expected to evolve, potentially becoming more specialised in areas where it offers distinct advantages, such as providing backup power during peak demand or serving as a secondary energy source for hard-to-electrify processes. At the same time, the influence of natural gas on wholesale energy costs may diminish, reflecting the broader shifts in the energy market driven by the integration of RES.

Furthermore, the responses to the question: "*In your view, what strategies could be implemented to ensure energy market stability and reduce volatility as NI moves towards net-zero emissions by 2030?"* highlight a multifaceted approach, combining financial, technical, and social strategies, to ensure a stable and resilient energy market as NI aims for net-zero emissions by 2030. As shown in Figure 11, respondents proposed several strategies with varying levels of support. We asked participants to "*tick all applicable options*," which allowed for a comprehensive understanding of the preferred strategies.



Please select all applicable options.

Figure 11 In your view, what strategies could be implemented to ensure energy market stability and reduce volatility as NI moves towards net-zero emissions by 2030?

Long-term contracts for renewable energy purchases stood out as the most favoured strategy, garnering nearly 70% support from respondents. This preference is rooted in the contracts' ability to safeguard renewable energy projects through guaranteed demand and financial stability, thereby catalysing investments in renewable energy infrastructure. Approximately 60% of respondents backed market reforms aimed at boosting grid flexibility, acknowledging its indispensable role in smoothly integrating variable RES like wind and solar into the grid. These reforms pave the way for more agile and responsive energy systems.

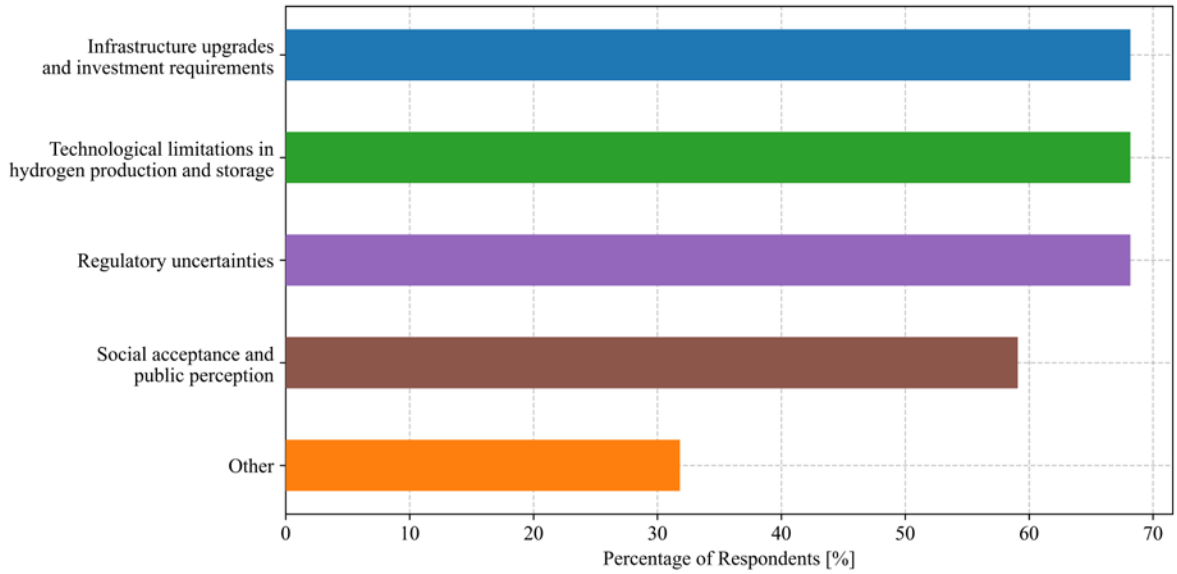
Moreover, the importance of diversifying energy sources was recognised by about 45% of respondents. This strategy not only bolsters energy security and resilience by mitigating risks associated with over-reliance on a single energy type but also ensures a more balanced and reliable energy supply. Finally, the emphasis on social inclusion and community engagement resonated strongly, underlining the necessity of an equitable and widely supported transition to net-zero emissions. These strategies foster community involvement and acceptance of new energy projects, ensuring that the energy transition benefits all segments of society.

The survey results highlighted a range of strategies that respondents believe could be implemented to stabilise the energy market and mitigate volatility as NI progresses towards its goal of achieving net-zero emissions by 2030. These strategies reflect a multifaceted approach to addressing the challenges of transitioning to a more sustainable energy system. Several respondents emphasised the importance of establishing a "*renewable generation support scheme*." This strategy recognises the need for incentives and subsidies to encourage the development and deployment of renewable energy technologies, which are crucial for reducing carbon emissions and achieving the net-zero target.

Another common theme was the call for "*delivering overall infrastructure and upgrading the grid*." This suggests a recognition that the existing energy infrastructure may need significant upgrades to accommodate the integration of RES and to ensure the grid can handle the variability and intermittency of these sources. Moreover, the idea of adopting a "*competitive allocation model for biomethane production*" was also raised. This strategy could incentivise innovation and efficiency in the production of biomethane, a RES that can be used in place of natural gas, thus contributing to the decarbonisation of the energy sector. Respondents also highlighted the potential of "*incentives to promote energy savings, including insulation/retrofit and electric heat pumps*." These measures aim to reduce energy demand through energy efficiency improvements, which can lower overall energy consumption and the associated carbon emissions.

Furthermore, there was a call for "*policy certainty and development of long-duration storage markets, including power to X solutions*." This strategy acknowledges the need for stable policy frameworks to support the development of energy storage technologies and innovative energy solutions, such as power-to-gas (power to X), which can store excess renewable energy for later use. Collectively, these strategies underscore a comprehensive approach to achieving energy market stability and reducing volatility in the transition to net-zero emissions. They emphasise the importance of supportive policies, infrastructure upgrades, and innovative technologies in facilitating a smooth and efficient energy transition.

Turning now to Figure 12, which encapsulates the responses to the question about the prospective difficulties in integrating green hydrogen into the existing energy infrastructure by 2030, a variety of critical challenges surface, each eliciting differing levels of concern from participants. The participants were asked to "*tick all applicable options*," which allowed for a comprehensive understanding of the potential challenges. The primary obstacle, acknowledged by nearly 70% of respondents, revolves around the necessity for considerable infrastructure upgrades and investment. The seamless integration of green hydrogen necessitates comprehensive enhancements and financial dedications across production, storage, and distribution networks, thereby introducing significant financial and logistical hurdles.



Please select all applicable options.

Figure 12 What potential challenges might arise in integrating green hydrogen into the existing energy infrastructure by 2030?

Simultaneously, regulatory ambiguities were pinpointed as a concern by approximately 60% of respondents. The establishment of a clear and consistent regulatory framework is essential for laying a solid groundwork for investment and expansion within the green hydrogen sector; the lack of such clarity can indeed obstruct progress. Furthermore, technological limitations in hydrogen production and storage, flagged by about 55% of respondents as a significant challenge, underscore the urgency of overcoming current technological impediments to efficient hydrogen production and storage. This is crucial for advancing green hydrogen as a prominent energy solution on a large scale.

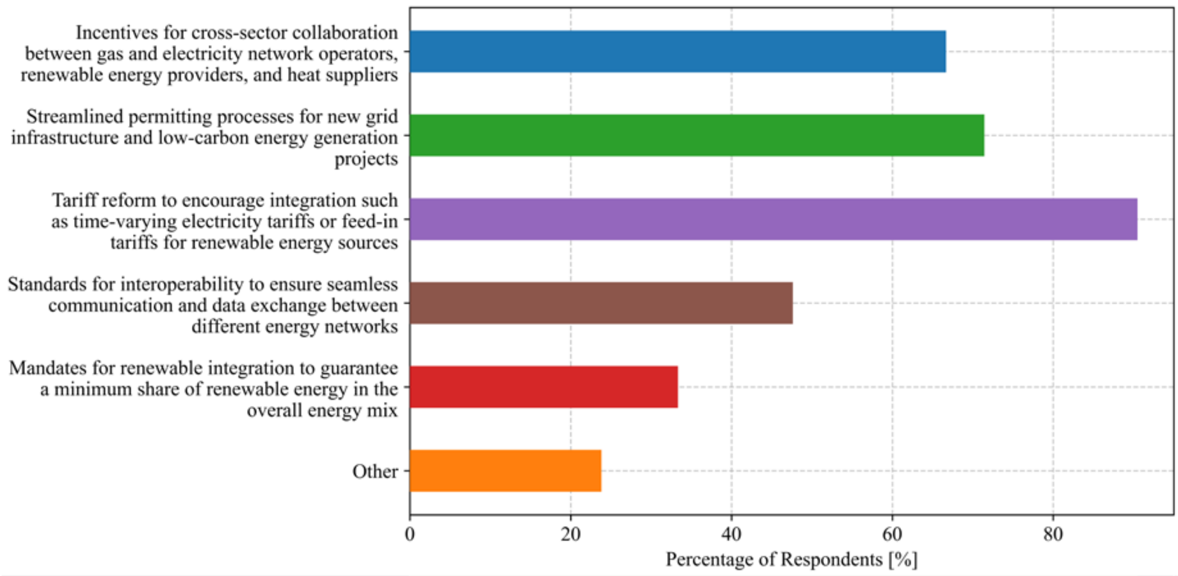
Additionally, social acceptance and public perception, considered challenges by roughly 50% of respondents, highlight the critical need for securing public support and understanding for the successful integration of green hydrogen. Navigating resistance or scepticism represents a substantial barrier. Collectively, these insights illuminate a broad array of financial, technological, regulatory, and social challenges that must be skilfully managed to effectively incorporate green hydrogen into NI's energy infrastructure by 2030.

Roughly 25% of respondents highlighted a variety of additional concerns that could impact the integration of green hydrogen into the energy infrastructure, indicating a broad spectrum of issues beyond the primary challenges already discussed. Among these, efficiency emerged as a significant concern, with some respondents arguing that "*utilising hydrogen for demand that can be met through electrification is inefficient.*" This sentiment was echoed by others who asserted that "hydrogen should not be utilised where electrification can be employed instead," suggesting a preference for electrification over hydrogen in certain applications due to its perceived efficiency.

Cost-effectiveness, safety, and planning were also cited as critical considerations. The cost of hydrogen itself was identified as a barrier, with economic viability being a related concern. Some respondents pointed out that "*green hydrogen can be uneconomical when compared to alternatives such as heat from heat pumps*," particularly in contexts where the latter offers a more cost-effective solution. These insights underscore the complexity of integrating green hydrogen into the energy mix, highlighting the need for careful consideration of both the technical and economic aspects of its application.

3.2.5 Policy and Regulatory Changes for Effective Sector Coupling

The survey results, shown in Figure 13, offer valuable insights into stakeholder perspectives on policy and regulatory changes necessary for effective sector coupling in NI. The participants were asked to "*tick all applicable options*," from a list of potential changes aimed at integrating electricity, heating/cooling, and transportation sectors. These options included incentives for cross-sector collaboration, streamlined permitting processes, tariff reforms, interoperability standards, and mandates for renewable integration.



Please select all applicable options.

Figure 13 What policy or regulatory changes do you believe are necessary to facilitate effective sector coupling, integrating electricity, heating/cooling, and transportation sectors, in NI?

The drive towards a more efficient, secure, and sustainable energy future in NI hinges on the electrification of the heating and transportation sectors, alongside their effective integration with the electricity sector, a concept known as sector coupling. The goals of sector coupling are to optimise the use of renewable energy across sectors, enhance energy efficiency, and reduce greenhouse gas emissions. This integrated approach not only promotes the optimal use of renewable energy but also significantly reduces reliance on fossil fuels. However, achieving this vision requires a comprehensive strategy that includes technological advancements, supportive policy changes, and targeted regulatory reforms.

While the survey results do not directly address specific policy changes, they offer valuable insights into stakeholder perspectives on the challenges and opportunities. A recurring theme is the need for streamlined permitting processes for new grid infrastructure and low-carbon energy generation projects. Lengthy bureaucratic hurdles can hinder progress and delay the implementation of crucial upgrades needed for sector coupling. Additionally, fostering cross-sector collaboration between gas and electricity network operators, renewable energy providers, and heat suppliers is likely essential for effective integration.

The concept presented in the figure complements these findings and delves deeper into specific policy and regulatory reforms. One key area highlighted is tariff reform. Implementing time-varying electricity tariffs, where prices fluctuate based on demand, could incentivise consumers to shift their energy use to off-peak periods. This aligns perfectly with sector coupling goals, as it allows for better utilisation of available resources across the integrated system. Additionally, feed-in tariffs could play a vital role by incentivising renewable energy generation, which is a cornerstone of a sustainable and decarbonised energy future.

Furthermore, the figure emphasises the importance of standards for interoperability. Standardised communication protocols would allow for real-time data exchange between different parts of the energy system, facilitating coordination and optimisation. This coordination would enable different energy sources and networks (e.g., gas, electricity, heating) to work together more efficiently, balancing supply and demand dynamically and minimising operational costs. Optimisation would involve adjusting generation, storage, and distribution in real-time to maximise efficiency, reduce energy losses, and enhance grid stability. Additionally, some stakeholders might support mandates for a minimum share of renewable energy in the overall energy mix. While the survey does not address this directly, increasing renewable energy integration is crucial for achieving long-term sustainability goals, and mandates could catalyse this transition.

The survey responses under the "Other" category suggest additional policy ideas worthy of consideration. For instance, the widespread deployment of “*smart meters*” could provide invaluable data on energy consumption across all sectors (i.e., residential, commercial, industrial, and transportation), thereby informing strategies for optimising energy use and facilitating sector coupling. Furthermore, revising and strengthening the “*existing mandate for renewable heat*” could significantly accelerate the transition away from fossil fuels in the heating sector, aligning perfectly with the goals of sector coupling and decarbonisation. Finally, “*implementing heat metering for consumers, similar to what exists for electricity*,” would empower consumers with greater transparency into their heating energy use. This transparency can encourage informed choices and potentially reduce overall heating demand, contributing significantly to sector coupling efforts.

3.3 Limitations

As part of the survey, the integration of natural gas and electricity networks in NI is being assessed using PLEXOS for modelling. While PLEXOS provides valuable insights, it is crucial to acknowledge several limitations in our study. Firstly, the scope and methodology may not encompass all factors influencing network integration, potentially overlooking nuanced interactions or dependencies such as localised infrastructure constraints, varying regulatory impacts, or specific technological limitations. Secondly, data constraints and model assumptions could introduce biases, affecting the accuracy of our findings. To address these limitations in future research, we recommend expanding data sources to enhance model robustness, refining assumptions based on real-world scenarios, and conducting sensitivity analyses to gauge the impact of varying inputs. These steps aim to improve the reliability and comprehensiveness of our evaluations, ensuring a more informed approach to integrating and optimising gas and electricity networks in NI. Finally, this includes not only the use of gas and electricity as fuels but also their roles in broader energy system management and integration.

4. Discussion

The integration of GFPPs into the NI energy landscape represents a critical strategy for addressing the inherent intermittency of RES such as wind and solar. These GFPPs facilitate rapid response capabilities, essential for effectively balancing the dynamic fluctuations between supply and demand. However, this integration of electricity and natural gas systems introduces unique challenges, including the potential for infrastructure strain and operational inefficiencies due to the variability of RES output. Moreover, issues such as gas supply shortages or pipeline congestion could limit GFPP output, thereby impacting system reliability and operational costs.

The PLEXOS modelling conducted as part of this study corroborates these observations. Scenarios simulating reduced wind generation capacity (LW scenario), or increased gas demand (HG scenario) reveal significant impacts on electricity prices, generation costs, and CO_2 emissions. Specifically, the combined effect of decreased wind generation and heightened gas demand (LWHG scenario) underscores the interconnectedness of energy systems and the potential repercussions of strategic energy policy decisions.

Furthermore, the modelling underscores the central role of renewable energy, particularly wind power, in gradually displacing natural gas within NI's power sector. Despite this trend, natural gas remains a crucial component, providing essential flexibility during peak demand periods and low renewable output scenarios. This dual role of natural gas highlights a transitional phase, where GFPPs act as vital bridging assets, ensuring grid stability as NI transitions towards a more sustainable energy mix.

Beyond GFPPs, our analysis, based on survey responses, identifies several emerging flexibility options to address the challenges posed by high levels of RES penetration. Power-to-gas (P2G) technologies, in particular, stand out as innovative solutions. By converting surplus renewable energy into hydrogen or synthetic natural gas (SNG), P2G technologies enhance energy storage capabilities within the existing natural gas infrastructure, thereby supporting system flexibility and maintaining grid stability amidst fluctuating RES generation.

The survey analysis complements these findings, providing nuanced stakeholder perspectives on technological innovations and future energy strategies. While 46% of respondents recognise the potential of smart grids and IoT devices in enhancing network co-optimisation, 33% express scepticism, underscoring the need for ongoing education and demonstration projects to address concerns about technological maturity and integration challenges, including cybersecurity risks associated with IoT devices.

Stakeholders also acknowledge the impact of smart appliances and electric vehicles on co-optimising networks, particularly through demand response programs and renewable energy integration. However, broader strategies, including infrastructure upgrades and coordinated management across gas and electricity systems, are deemed necessary for achieving comprehensive network optimisation.

Most respondents anticipate a decrease in the role of natural gas as renewables become more prevalent, reflecting a shifting energy landscape where natural gas serves as a backup to renewable energy and storage solutions. Strategies such as long-term renewable energy contracts, market reforms for grid flexibility, and diversification of energy sources are identified as critical for ensuring market stability and reducing volatility. These strategies underscore the need for a multifaceted approach, combining financial incentives, regulatory reforms, and technological advancements to create a resilient and stable energy market in NI.

Lastly, the integration of green hydrogen into NI's energy infrastructure faces challenges identified through survey responses, including the need for infrastructure upgrades, regulatory ambiguities, and technological limitations. Additionally, public perception and social acceptance pose significant barriers, underscoring the need for comprehensive outreach and education efforts to garner support for green hydrogen initiatives.

5. Conclusions

In conclusion, this report highlights the crucial importance of a comprehensive and coordinated strategy to optimise gas and electricity networks within NI's dynamic energy sector. Based on PLEXOS modelling and stakeholder feedback, our analysis underscores the need to adopt technological innovations, engage stakeholders effectively, and establish supportive policy and regulatory frameworks.

Smart grids, energy storage systems, and IoT technology are foundational in managing the inherent variability of RES and enhancing grid flexibility. Equally essential is the active participation of stakeholders across the spectrum, from industry leaders and policymakers to consumers, to build trust and facilitate the seamless adoption of advanced technologies. Furthermore, creating an enabling environment through strategic policies, financial incentives, and regulatory adjustments is crucial for attracting investment and driving the necessary grid modernisation.

Looking ahead, NI must prioritise targeted initiatives to address challenges posed by renewable energy variability, market volatility, and political uncertainties. By emphasising resilience and sustainability, we can strengthen grid stability, integrate RES more deeply, and achieve net-zero carbon emissions targets. Continuous learning and adaptation are also key to navigating the evolving energy landscape and ensuring sustained success in transitioning to a renewable-centric energy system.

By adopting a holistic approach encompassing these critical elements, NI can fully harness its RES, enhance energy security, and chart a sustainable course towards a prosperous energy future. This comprehensive strategy not only serves as a beacon of hope and innovation in the global energy transition but also sets a precedent for other regions grappling with similar challenges.

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Appendix A Blank Survey Questions

This appendix includes the survey questions.

<u>Questions Regarding Current Power and Gas Networks</u>

1. What are the main challenges limiting the optimisation of the operation of gas and electricity systems in NI? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Fluctuations in renewable energy generation	☐ ☐ ☐
Global energy market dynamics	☐ ☐ ☐
Political and regulatory uncertainties	☐ ☐ ☐
Technological advancements	☐ ☐ ☐
Consumer behaviour and preferences	☐ ☐ ☐
Other (Please provide your opinion if you see other factors affecting the energy market)	☐
2. In your opinion, what are the main factors influencing the volatility of energy markets, particularly concerning natural gas and electricity? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Insufficient investment in renewable energy infrastructure	☐ ☐ ☐
Limited energy storage capacity	☐ ☐ ☐
Dependence on imported energy resources	☐ ☐ ☐
Public awareness and engagement	☐ ☐ ☐
Heat demand management and balancing	☐ ☐ ☐
Integration of heat emission considerations across Scope 1, 2, and 3	☐ ☐ ☐
Other (Please provide your additional obstacles or concerns)	☐
3. What do you see as the primary obstacles in achieving a secure and economically viable transition to a lower-carbon economy in NI at present? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Insufficient investment in renewable energy infrastructure	☐ ☐ ☐
Limited energy storage capacity	☐ ☐ ☐
Dependence on imported energy resources	☐ ☐ ☐
Public awareness and engagement	☐ ☐ ☐
Heat demand management and balancing	☐ ☐ ☐
Integration of heat emission considerations across Scope 1, 2, and 3	☐ ☐ ☐
Other (*Please provide your additional obstacles or concerns*)	☐

4. To what extent do you believe technological innovations, such as smart grids and Internet of Things (IoT) devices, can play a role in improving the co-optimization of gas and electricity networks in NI at present? ***<u>Please choose the option that best fits your perception</u>***	
Significant role, in enabling better coordination and real-time optimization of gas and electricity flows	☐
Moderate role, offering some potential benefits but with limitations in current applications	☐
A limited role, with technological advancements needed before widespread impact, can be achieved	☐
No role, as these technologies are not relevant to co-optimizing gas and electricity networks	☐
5. How can smart technologies like Google appliances and electric vehicles help co-optimise gas and electricity networks in NI? ***<u>Please choose the option that best fits your perception</u>***	
Real-time monitoring and management of energy use in homes and businesses (e.g., smart thermostats)	☐
Demand response programs: smart appliances and EVs adjust usage during peak demand (e.g., Google Assistant managing washing machine cycles)	☐
Smart EV charging that prioritises renewable energy sources	☐
Provide valuable data on energy usage patterns for grid optimisation	☐
Other (*please specify in the space below*)	☐

<u>Questions Regarding Mid-Term Future Power and Gas Networks</u>

6. How do you anticipate the role of natural gas evolving in the power sector over the next decade in NI, considering the projected increase in wind power generation? ***<u>Please choose the option that best fits your perception</u>***	
Decreasing, as renewable energy sources become more dominant	☐
Remaining stable, with natural gas serving as a backup for intermittent renewables	☐
Increasing, due to the need for flexible generation to complement renewables	☐
Other (*Please specify*)	☐
7. In your view, what strategies could be implemented to ensure energy market stability and reduce volatility as NI moves towards net-zero emissions by 2030? ***<u>Please select all applicable options</u>***	
Long-term contracts for renewable energy purchase	☐
Diversification of energy sources	☐
Market reforms to incentivise grid flexibility	☐
Social inclusion and community engagement	☐
Other (*Please provide any additional strategies or considerations you believe could contribute to ensuring energy market stability*)	☐

8. What potential challenges might arise in integrating green hydrogen into the existing energy infrastructure by 2030? ***Please select all applicable options***	
Infrastructure upgrades and investment requirements	☐
Technological limitations in hydrogen production and storage	☐
Regulatory uncertainties	☐
Social acceptance and public perception	☐
Other (*Please share any additional challenges or considerations you foresee*)	☐
9. How effective do you perceive each of the listed factors will be in addressing the challenges in Q8? ***Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective***	
Infrastructure upgrades and investment requirements	☐ ☐ ☐
Technological limitations in hydrogen production and storage	☐ ☐ ☐
Regulatory uncertainties	☐ ☐ ☐
Social acceptance and public perception	☐ ☐ ☐
10. How do you perceive the integration of heat, gas, and power sectors (sector coupling) influencing the energy landscape of NI in the medium term? ***Please choose the option that best fits your perception***	
Significant Transformation	☐
Moderate Impact	☐
Incremental Change	☐
Limited Effect	☐
Negligible Influence	☐
11. What policy or regulatory changes do you believe are necessary to facilitate effective sector coupling, integrating electricity, heating/cooling, and transportation sectors, in NI? ***Please select all applicable options***	
Incentives for cross-sector collaboration between gas and electricity network operators, renewable energy providers, and heat suppliers	☐
Streamlined permitting processes for new grid infrastructure and low-carbon energy generation projects	☐
Tariff reform to encourage integration such as time-varying electricity tariffs or feed-in tariffs for renewable energy sources	☐
Standards for interoperability to ensure seamless communication and data exchange between different energy networks	☐
Mandates for renewable integration to guarantee a minimum share of renewable energy in the overall energy mix	☐
Other (*do you suggest additional policy changes not listed*)	☐

12. How effective do you perceive each of the listed policy or regulatory changes will be in facilitating effective sector coupling in NI? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Incentives for cross-sector collaboration between gas and electricity network operators, renewable energy providers, and heat suppliers	☐ ☐ ☐
Streamlined permitting processes for new grid infrastructure and low-carbon energy generation projects	☐ ☐ ☐
Tariff reform to encourage integration such as time-varying electricity tariffs or feed-in tariffs for renewable energy sources	☐ ☐ ☐
Standards for interoperability to ensure seamless communication and data exchange between different energy networks	☐ ☐ ☐
Mandates for renewable integration to guarantee a minimum share of renewable energy in the overall energy mix	☐ ☐ ☐
13. How do you see the role of technological innovations, such as advanced smart grids, smart metering, AI and the integration of Internet of Things (IoT) devices, evolving in facilitating the co-optimization of gas and electricity networks in NI by 2030? ***<u>Please choose the option that best fits your perception</u>***	
Significant impact	☐
Incremental impact	☐
Moderate impact	☐
Limited impact	☐
Not sure	☐
14. As NI transitions towards a net-zero energy system, how can the co-optimization of gas and electricity networks better integrate considerations for heat emission across Scopes 1, 2, and 3 of the Greenhouse Gas Protocol? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Develop clear and concise labels or reports outlining the carbon footprint of the heating service (e.g., breakdown of Scope 1, 2, and 3 emissions)	☐ ☐ ☐
Explore opportunities to utilise behavioural nudges to encourage energy-efficient heating practices	☐ ☐ ☐
Implement online tools or calculators that allow users to estimate their related emissions based on usage data	☐ ☐ ☐
Integrate information about the carbon footprint into online billing statements or user portals	☐ ☐ ☐
Offer educational resources and awareness campaigns to explain the concept of Scope 1, 2, and 3 emissions and their connection to heating systems	☐ ☐ ☐
Partner with consumer support groups to promote transparency and empower consumers to make informed choices about heating options	☐ ☐ ☐
Partner with technology companies to develop user-friendly apps or dashboards for real-time monitoring of heat consumption and associated emissions	☐ ☐ ☐
Other (P*lease specify in the space below*)	☐

15. How can heat suppliers (e.g., district heating providers) in NI better inform end users (households and businesses) about the associated Scope 1, 2, and 3 emissions of their heating services? ***Please choose the option that best fits your perception***	
Develop clear and concise labels or reports outlining the carbon footprint of the heating service (e.g., breakdown of Scope 1, 2, and 3 emissions)	☐
Integrate information about the carbon footprint into online billing statements or user portals	☐
Offer educational resources and awareness campaigns to explain the concept of Scope 1, 2, and 3 emissions and their connection to heating systems	☐
Implement online tools or calculators that allow users to estimate their related emissions based on usage data	☐
Partner with consumer support groups to promote transparency and empower consumers to make informed choices about heating options	☐
Explore opportunities to utilise behavioural nudges to encourage energy-efficient heating practices	☐
Partner with technology companies to develop user-friendly apps or dashboards for real-time monitoring of heat consumption and associated emissions	☐
Other (*please specify*)	☐

Questions Regarding Long-Term Future Power and Gas Networks

16. What role do you foresee natural gas play in the energy mix of NI in the year 2050, given the targets for net-zero emissions? ***Please choose the option that best fits your perception***	
Phased out entirely, replaced by renewable energy sources	☐
A limited role, primarily serving as backup generation	☐
Significant role, in providing flexibility and reliability in the energy system	☐
Other (*Please share your insights or concerns regarding the future role of natural gas in NI*)	☐

17. How would you rate the effectiveness of the following in shaping the cooperation of gas and power systems to accommodate higher penetration of renewable energy sources by 2050? ***Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective***	
Improved grid energy management and coordination	☐ ☐ ☐
Expansion of energy storage capacity	☐ ☐ ☐
Integration of smart technologies for demand response	☐ ☐ ☐
Heat demand management and balancing	☐ ☐ ☐

18. What challenges do you anticipate in maintaining energy security and reliability as the energy system transitions towards net-zero emissions by 2050? ***Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective***	
Intermittency of renewable energy sources	☐ ☐ ☐
Dependence on imported energy resources	☐ ☐ ☐
Ageing infrastructure	☐ ☐ ☐
Increased frequency and severity of extreme weather events	☐ ☐ ☐
Other (*Please provide your insights*)	☐
19. How do you rate the co-optimization of gas and electricity systems can contribute to the affordability of energy for consumers in NI by 2050? ***Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective***	
By reducing operational costs through efficient resource allocation	☐ ☐ ☐
By minimising reliance on expensive imported fuels	☐ ☐ ☐
By enabling greater integration of low-cost renewable energy sources	☐ ☐ ☐
By ensuring equitable access to energy services	☐ ☐ ☐
Energy efficiency improvements in buildings	☐ ☐ ☐
Other (*Please provide your insights or expectations*)	☐
20. What policy measures do you believe will be essential for supporting the successful transition to a net-zero emissions energy system in NI by 2050? ***Please select all applicable options***	
Carbon pricing mechanisms	☐
Subsidies for renewable energy development	☐
Regulatory mandates for emissions reductions	☐
Social policies to address energy poverty	☐
Integration of policies addressing heat emissions across sectors and scopes, including Scope 1, 2, and 3 considerations	☐
Other (*Please suggest additional policy measures you believe are important*)	☐
21. How effective do you perceive each of the listed policy measures will be in supporting the transition to a net-zero emissions energy system by 2050 in NI? ***Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective***	
Carbon pricing mechanisms	☐ ☐ ☐
Subsidies for renewable energy development	☐ ☐ ☐
Regulatory mandates for emissions reductions	☐ ☐ ☐
Social policies to address energy poverty	☐ ☐ ☐
Integration of policies addressing heat emissions across sectors and scopes, including Scope 1, 2, and 3 considerations	☐ ☐ ☐

22. What potential advancements in smart technology do you foresee significantly impacting the co-optimization of gas and electricity systems in the next decade? ***<u>Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective</u>***	
Implementation of advanced demand response systems for real-time load management	☐ ☐ ☐
Integration of AI and machine learning algorithms for predictive maintenance and optimization of gas and power infrastructure	☐ ☐ ☐
Deployment of smart grid technologies for enhanced grid flexibility and resilience	☐ ☐ ☐
Adoption of IoT devices and sensors for granular monitoring and control of energy consumption	☐ ☐ ☐
Development of blockchain-based platforms for transparent and efficient energy trading and billing	☐ ☐ ☐

23. Looking towards 2030 and beyond, how can the potential integration of new fuel sources like ammonia, hydrogen, and biogas contribute to the co-optimization of gas and electricity networks in NI? ***<u>Please select all applicable options</u>***	
Fuel Blending: Explore the feasibility of blending these new fuels (ammonia, hydrogen) with existing natural gas supplies to reduce carbon emissions in the gas network.	☐
Dedicated Infrastructure: Develop dedicated infrastructure for new fuel transportation and distribution, potentially creating separate networks for ammonia, hydrogen, and biogas.	☐
Power-to-X Technologies: Utilise renewable electricity to produce hydrogen (through electrolysis) or synthetic methane (through methanation) for integration into existing gas networks.	☐
Sector Coupling: Integrate these new fuel sources with other sectors like transportation and industry, potentially using hydrogen for fuel cell vehicles or biogas for industrial processes.	☐
Strategic Storage: Develop storage solutions for these new fuels (e.g., ammonia storage tanks, underground hydrogen storage) to manage seasonal variations and ensure grid flexibility.	☐
Regulatory Frameworks: Establish clear and supportive regulatory frameworks that incentivise the production, transportation, and utilisation of these new low-carbon fuel sources.	☐
Public Awareness and Consumer Adoption: Raise public awareness and encourage consumer adoption of technologies that utilise these new fuel sources (e.g., hydrogen fuel cell vehicles, biogas boilers).	☐
Other (*please specify in the space below*)	☐

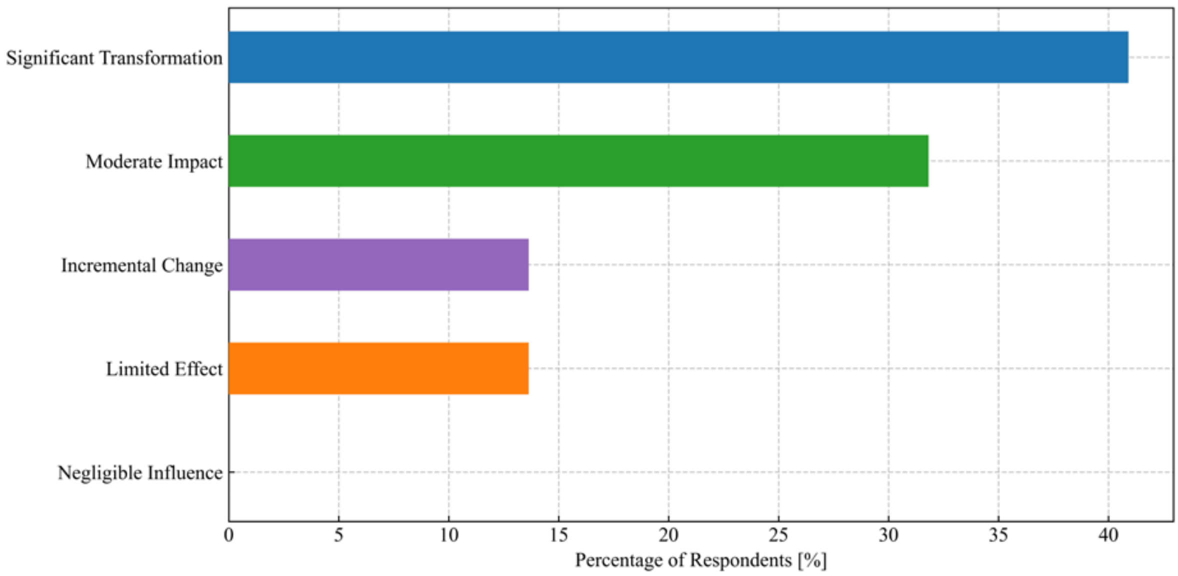
24. Looking towards 2030 and beyond, how can the potential integration of new fuel sources like ammonia, hydrogen, and biogas be facilitated while considering future taxation policies aimed at reducing carbon emissions in NI? ***Please select all applicable options***	
Develop carbon pricing mechanisms that incentivise the production and use of low-carbon fuels like hydrogen and biogas, potentially with tax breaks or rebates	☐
Design a tax framework for new fuels (ammonia, hydrogen) that reflects their lifecycle carbon emissions, potentially with higher taxes for more carbon-intensive options	☐
Explore revenue-neutral tax reforms, where any new taxes on low-carbon fuels are offset by reductions in existing energy taxes, ensuring overall cost neutrality for consumers	☐
Implement a combination of carbon pricing, infrastructure investment, and research & development initiatives to support the cost-effective integration of these new fuels	☐
Include lifecycle assessments in tax policy design to account for the full environmental impact of each fuel source, from production to consumption	☐
Other (*Please comment in the space below*)	

Appendix B Survey Question Results

This annexe contains the results of the questions answered by participants that are not included in the main body of the report.

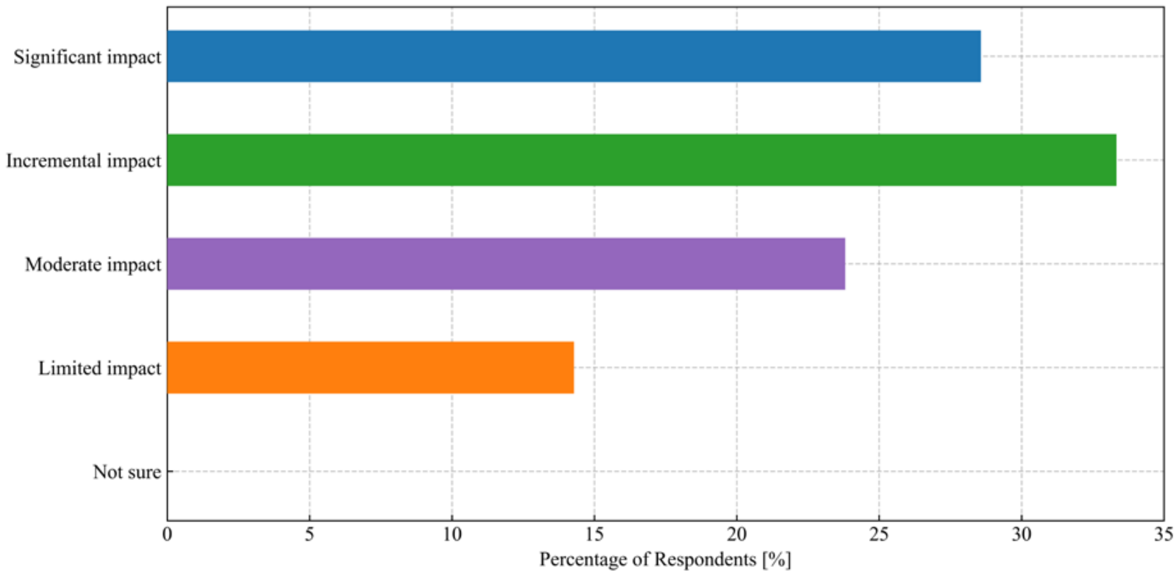
Q10: How do you perceive the integration of heat, gas, and power sectors (sector coupling) influencing the energy landscape of NI in the medium term?

Please choose the option that best fits your perception



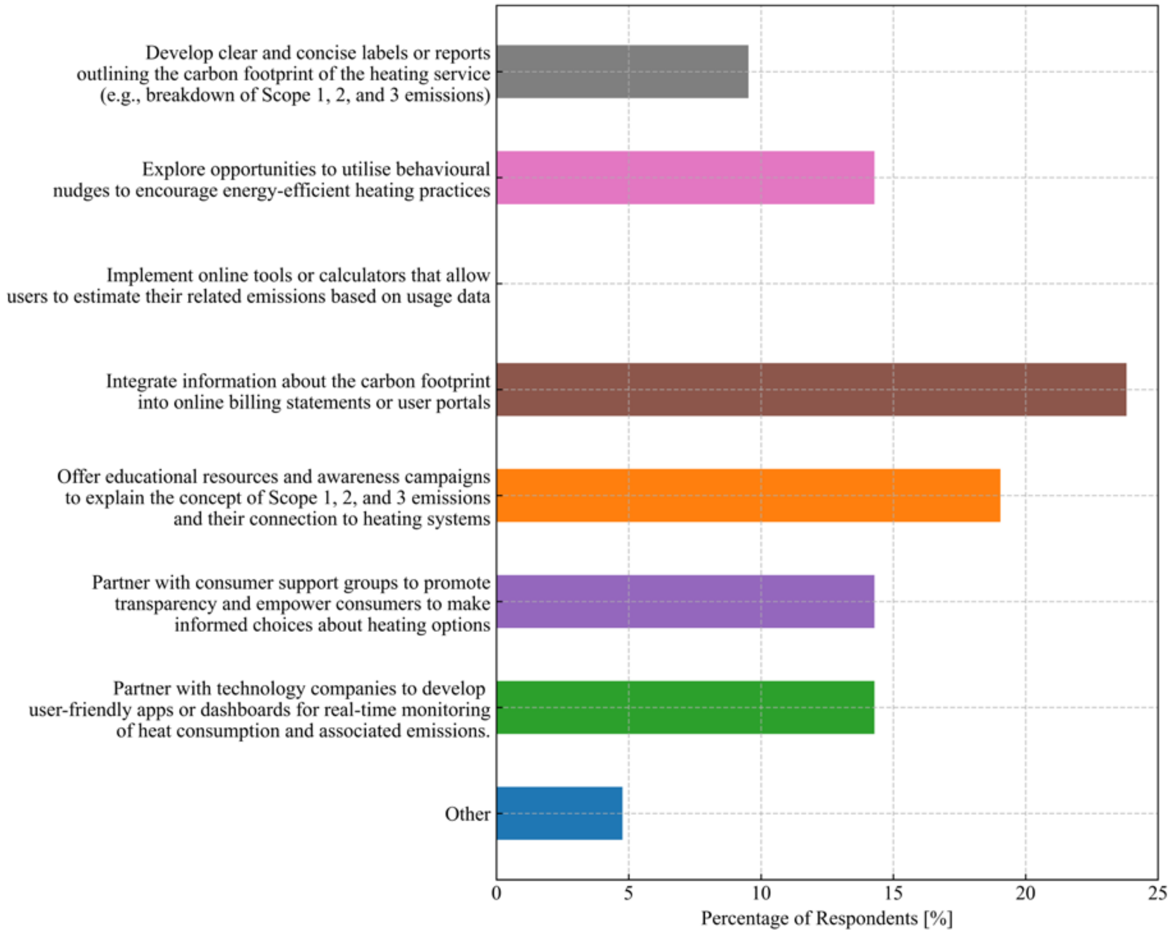
Q14: How do you see the role of technological innovations, such as advanced smart grids, smart metering, AI and the integration of IoT devices, evolving in facilitating the co-optimization of gas and electricity networks in NI by 2030?

Please choose the option that best fits your perception



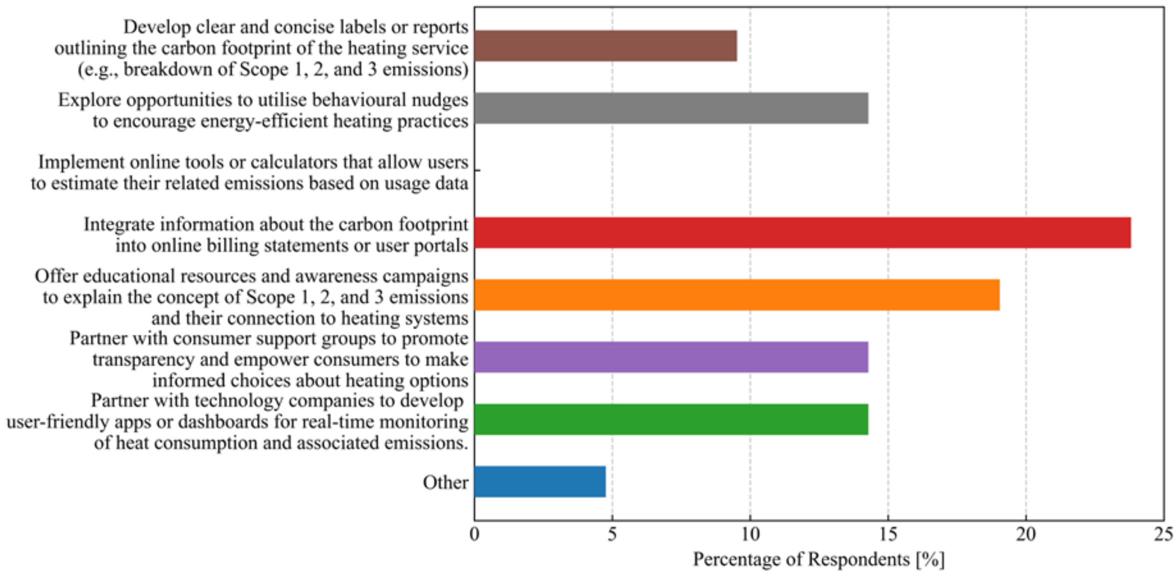
Q14: As NI transitions towards a net-zero energy system, how can the co-optimization of gas and electricity networks better integrate considerations for heat emission across Scopes 1, 2, and 3 of the Greenhouse Gas Protocol?

Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective



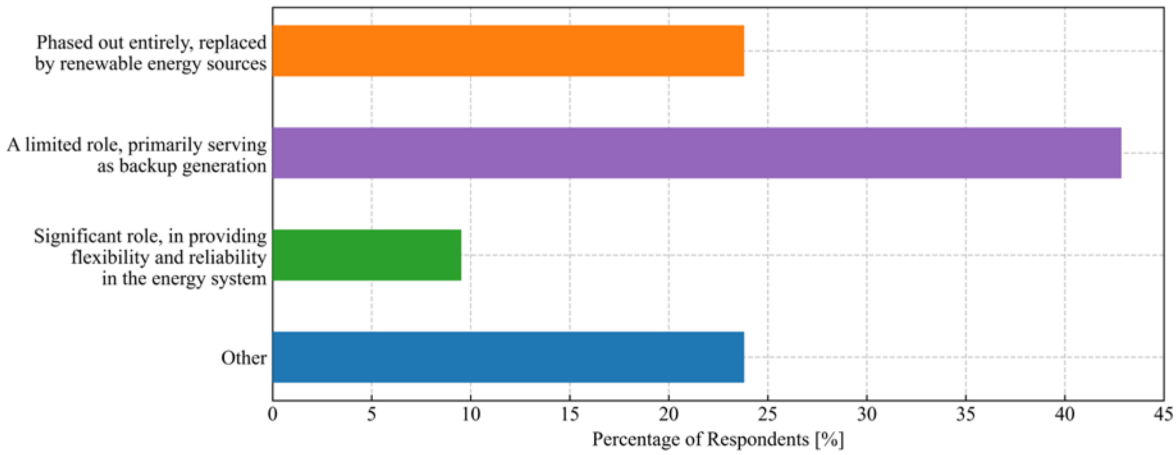
Q15: How can heat suppliers (e.g., district heating providers) in NI better inform end users (households and businesses) about the associated Scope 1, 2, and 3 emissions of their heating services?

Please choose the option that best fits your perception



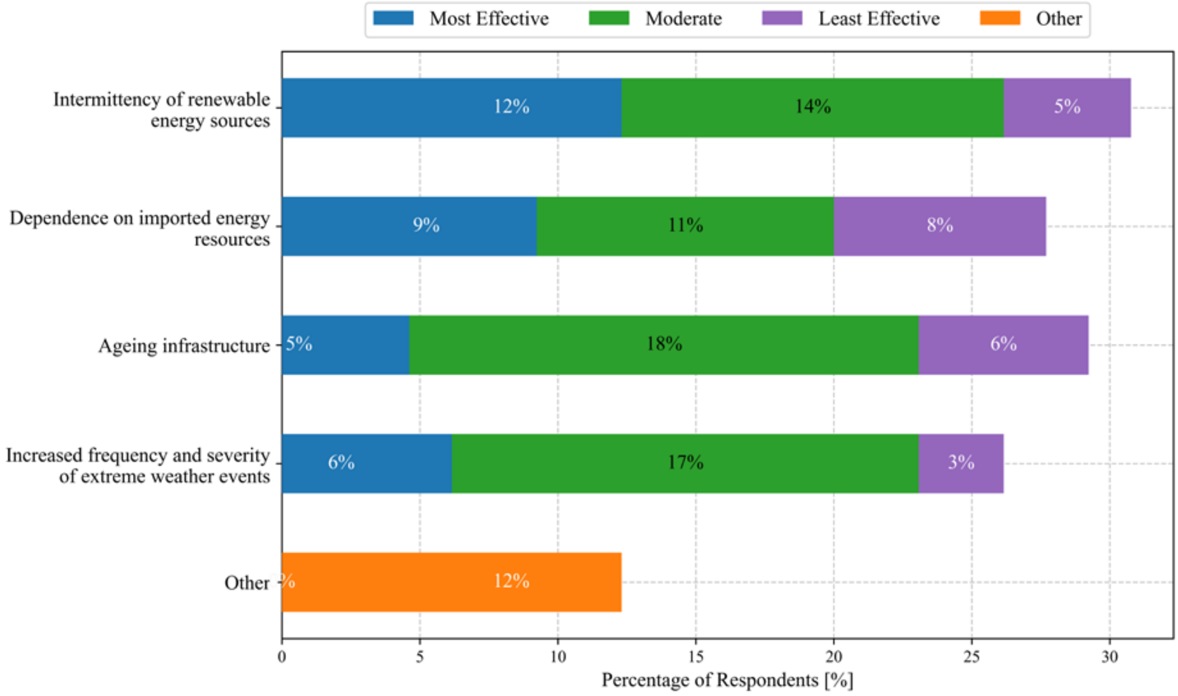
Q16: What role do you foresee natural gas play in the energy mix of NI in the year 2050, given the targets for net-zero emissions?

Please choose the option that best fits your perception



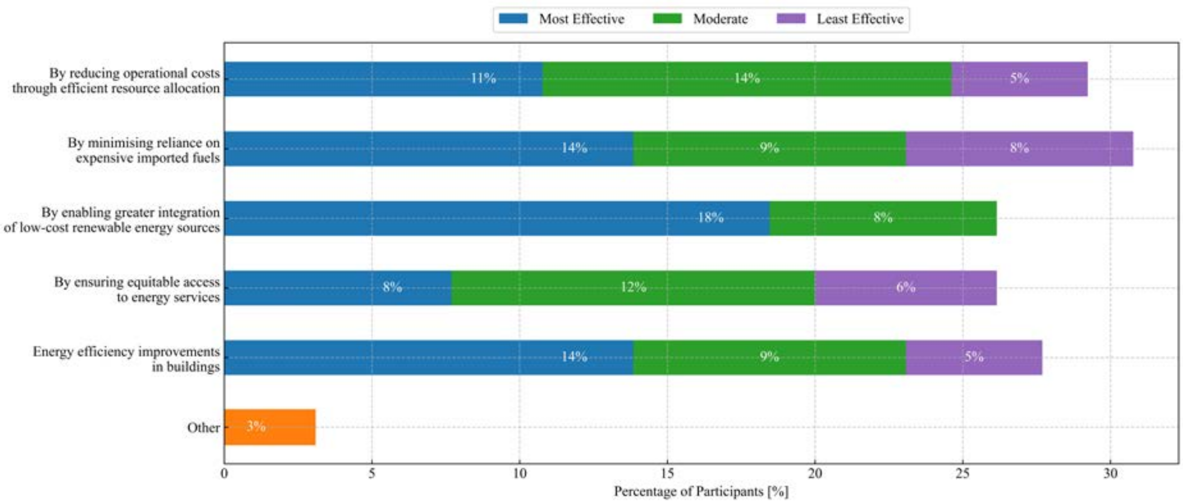
Q18: What challenges do you anticipate in maintaining energy security and reliability as the energy system transitions towards net-zero emissions by 2050?

Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective



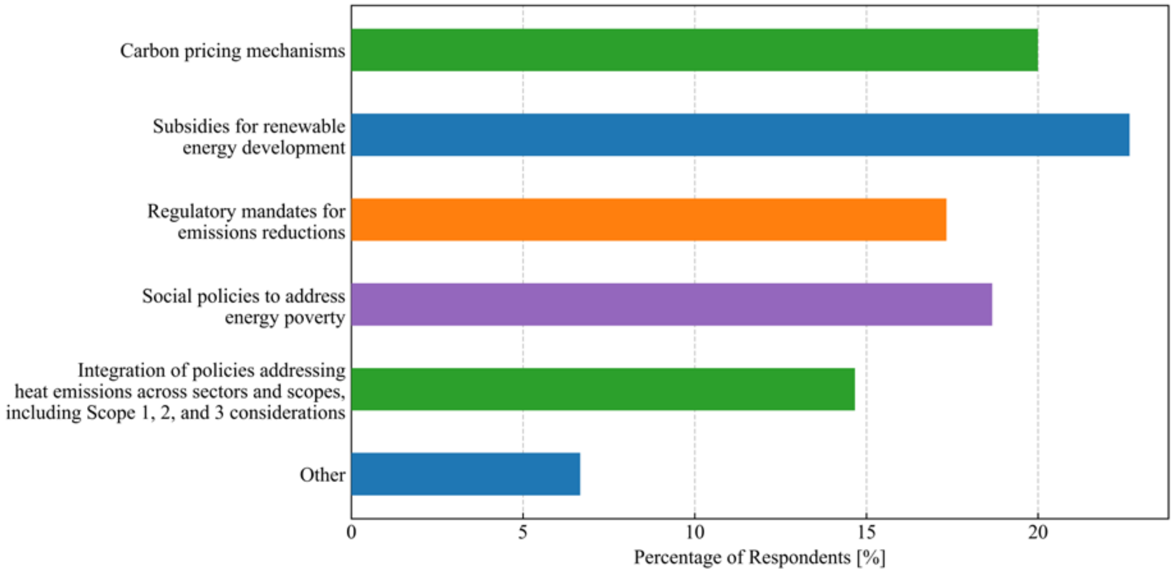
Q19: How do you rate the co-optimization of gas and electricity systems can contribute to the affordability of energy for consumers in NI by 2050?

Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective



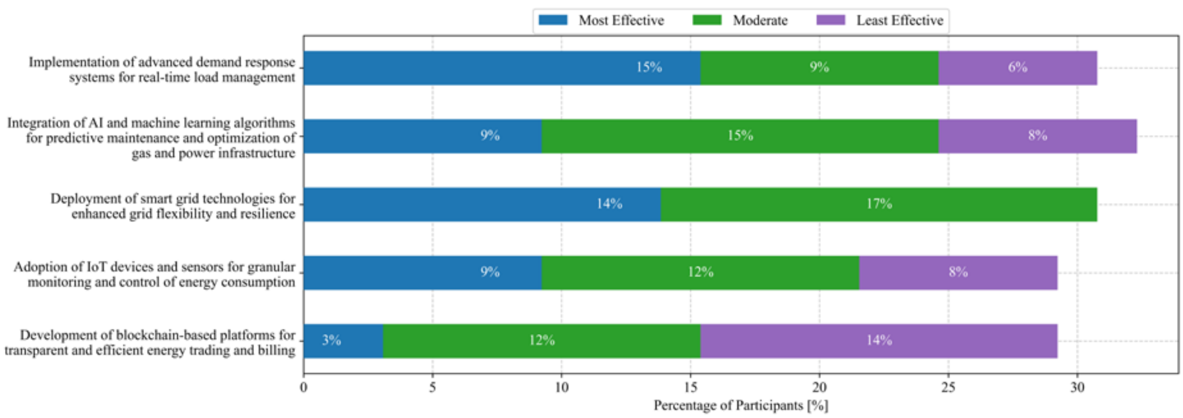
Q21: What policy measures do you believe will be essential for supporting the successful transition to a net-zero emissions energy system in NI by 2050?

Please select all applicable options



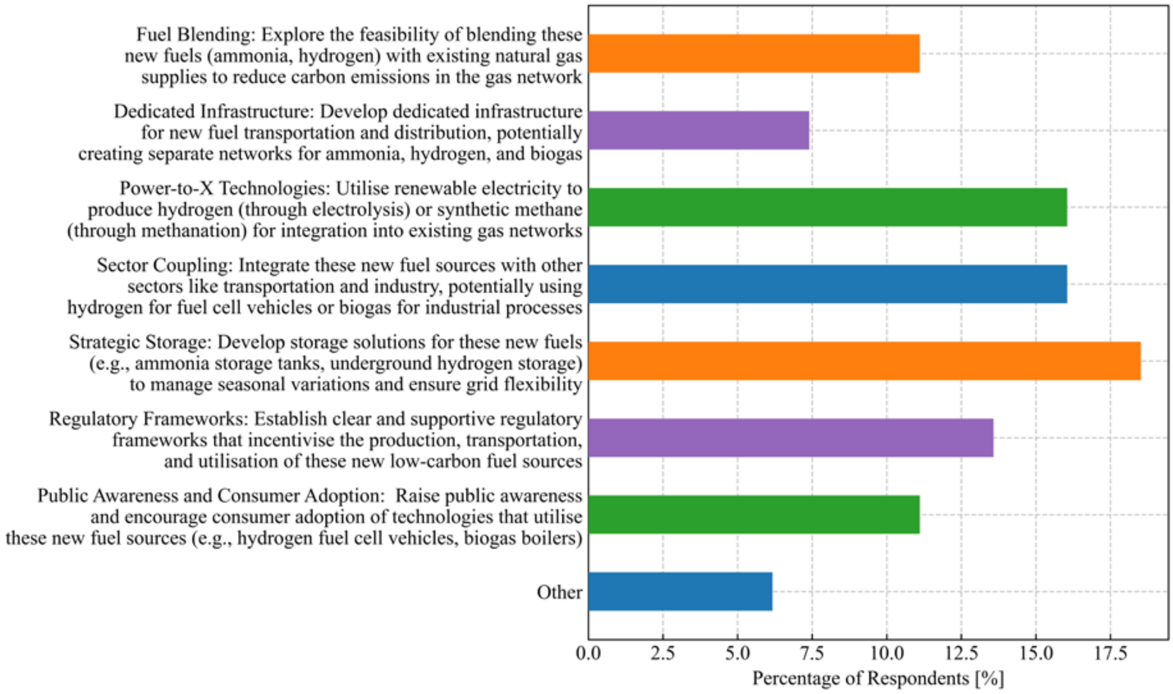
Q22: What potential advancements in smart technology do you foresee significantly impacting the co-optimization of gas and electricity systems in the next decade?

Please rate the effectiveness of each listed factor on a scale of 1 to 3, with 1 most effective, 2 moderate, and 3 least effective



Q23: Looking towards 2030 and beyond, how can the potential integration of new fuel sources like ammonia, hydrogen, and biogas contribute to the co-optimization of gas and electricity networks in NI?

Please select all applicable options - Selected Choice



Q24: Looking towards 2030 and beyond, how can the potential integration of new fuel sources like ammonia, hydrogen, and biogas be facilitated while considering future taxation policies aimed at reducing carbon emissions in NI?

Please select all applicable options