Energy Policy 218 (2026) 115492

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Connecting Europe through hydrogen: Cost allocation analysis of cross-border pipeline coalitions under varying subsidy policies

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ARTICLE INFO

Keywords:
Hydrogen pipelines
European hydrogen backbone
Cross-border
Cost allocation games
Cooperative game theory
Subsidy allocation

ABSTRACT

Low-carbon hydrogen can contribute to decarbonization, diversification, and energy security. Today, planning and design for low-carbon hydrogen supply chains are underway with ambitious goals for 2030-2040. The regional availability of renewable sources will require the efficient transportation of green hydrogen from producers to consumers. To increase connectivity, the European Hydrogen Backbone vision proposes developing new and repurposed hydrogen pipelines, which will require massive investment. Continental implementation requires both international coordination and cooperation, and financial subsidies can help reduce the risks associated with demand uncertainty and long-term returns. While implementers see energy policy and regulation as key enablers, policymakers seek the most efficient allocation of resources. This paper explores the impact of subsidies on cross-border pipeline project coalitions. The methodology is applied to *HyCorridorE* (a European south-eastern corridor) and uses cooperative game theory (core solution). Simple rules and subsidy scenarios (30% and 50%, fixed or progressive) are deployed to assess cost allocation, coalition stability, and satisfaction levels. Fixed-rate subsidies threaten coalition stability by favoring smaller alliances, while progressive designs foster cohesive, large-scale cooperation. Since simple rules fail to optimize allocation, integrating game-theoretic approaches is advisable.

1. Introduction

As Europe transitions toward climate neutrality, hydrogen is central to achieving the net-zero emissions target by 2050 (Ferrada et al., 2023; IEA, 2021). Scenarios project that hydrogen energy will account for about 18% of global energy demand by 2050 and contribute up to 20% of the CO_2 emission reductions required to meet climate targets (Hydrogen Council, 2020; Lu et al., 2025). Between 2020 and 2023 alone, numerous initiatives with clear hydrogen targets (such as European and National Roadmaps, the European Clean Hydrogen Alliance, the Clean Hydrogen Partnership, IPCEI Hydrogen Projects, REPowerEU, and the European Hydrogen Bank) were implemented to ensure this ambition would be realized (European Commission, 2020). Originally targeting 10 Mt of green hydrogen by 2030, the EU, under RePowerEU, increased the goal to 20 Mt (10 Mt EU, 10 Mt external) to cut dependence on Russian fossil fuels (European Commission, 2022a). Although this initiative recognizes hydrogen as a clean, versatile energy carrier capable of contributing to decarbonization efforts, a European Court of Auditors Special Report, supported by the European Commission (European Commission, 2024), identified the 20-million-tonne renewable hydrogen target as aspirational and acknowledged uncertainties regarding the scaling up of the hydrogen value chain, project pipeline maturity, and the timely availability of infrastructure connecting producers and consumers, including imports.

Unlocking the full potential of hydrogen depends on the development of distribution infrastructure capable of transporting large amounts of low-carbon hydrogen from production sites, often rich in renewable energy sources (RES), to consumption hubs (Cardinale, 2023; EHB, 2022b; Kotek et al., 2023). Gaseous hydrogen is expected to be transported through gas networks, which are complex systems composed of pipelines, compressors, valves, and other control elements (Mielich et al., 2025). Gaseous hydrogen transportation in pipelines offers several advantages over other modalities (e.g., tube trailers). These include increased connectivity, lower per-unit cost due to economies of scale (transportation cost is expected to be 0.11–0.21 €/kg H_2 per 1000 km along the European onshore backbone, including

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https://doi.org/10.1016/j.enpol.2026.115492
Received 31 August 2025; Received in revised form 1 June 2026; Accepted 6 July 2026
Available online 10 July 2026

compressor stations [EHB, 2022b]), decarbonization, higher throughput and operational efficiency (Khan et al., 2021; Nicolle and Massol, 2023; Wetzel et al., 2023), with gas being transported using repurposed natural gas or new pipelines (Gils et al., 2021).

The European Hydrogen Backbone (EHB) vision has been developed by transmission system operators (TSOs) and calls for deploying a hydrogen pipeline network using repurposed or new infrastructure, with an initial network targeted for 2030, with substantial expansion by 2040 (EHB, 2022b, 2023). This initiative will involve local and international governments, regulatory bodies, and private investors. However, the implementation of hydrogen corridors in Europe faces significant challenges due to hydrogen's unique physical and chemical properties. High compression requirements, limited technological readiness, complex flow dynamics, leakage risks, material embrittlement, and lagging safety standards collectively increase costs, safety concerns, and investment uncertainty, particularly when repurposing existing natural gas infrastructure. Addressing these challenges requires coordinated advances in materials science, compressor and pipeline design, digital monitoring tools, and harmonized technical regulation (Cheng and Cheng, 2023; Fleer et al., 2025; Raj et al., 2024; Zhao et al., 2025). Beyond these technical and operational challenges, hydrogen infrastructure deployment faces major constraints related to market uncertainty and lack of maturity, incomplete regulatory frameworks, financing gaps, unclear permitting processes, resource/technological interdependencies/imbalances (e.g., concerning RES or electrolysis capacity constraints), and insufficient coordination among Member States (De-León Almaraz et al., 2024; European Clean Hydrogen Alliance, 2023, 2024). In addition, the deployment of a hydrogen pipeline network requires substantial capital investment and cooperation among countries with differing economic priorities and energy transition strategies (Jayanti, 2022; Timalsina et al., 2025). In some cases, cost-sharing mechanisms and joint planning strategies can address such cost and infrastructure challenges. The literature on hydrogen infrastructure often focuses on techno-economic assessments (Chaudry et al., 2021; Khan et al., 2021; Kotek et al., 2023), treating infrastructure provision as a top-down planning problem (Kiss et al., 2016). Given the many obstacles, this work focuses solely on investigating economic challenges and cooperation.

Financial instruments (e.g., subsidies) are essential for de-risking investments and fostering collaboration among EU countries and stakeholders (European Commission, 2024; European Hydrogen Backbone, 2023; Pan et al., 2023). Subsidy allocation has been widely examined in the context of RES and other emerging technologies, employing methods such as optimization (Batlle, 2011), and the analytical hierarchy process (Sadeghi and Ameli, 2012). For hydrogen, subsidy allocation can be analyzed using scenario analysis (European Hydrogen Backbone, 2023), optimization approaches (Zhang et al., 2022), econometric models (Pan et al., 2023), system dynamics modeling (Li et al., 2022), and game-theoretic frameworks (Arthur et al., 2026).

Game theory is gaining increasing relevance in the analysis of hydrogen systems dynamics. Unlike optimization approaches, it applies a multi-decision-maker perspective. Moreover, game-theoretic models combine descriptive and predictive analyses of complex multi-agent systems with a prescriptive dimension, offering insights into how preferred outcomes can be influenced or achieved. In game theory, both cooperative (CGT) and non-cooperative (NCGT) models can be applied. While non-cooperative models capture the competitive distribution of costs and benefits, cooperative models explicitly specify allocation mechanisms, making them particularly well-suited to analyzing shared hydrogen infrastructure, such as international pipelines.

CGT enables the modeling of strategic coalitions, joint investment, and cost-sharing mechanisms in environments where multiple agents benefit from shared infrastructure but may face conflicting incentives (Churkin et al., 2021; Young, 1994). Although CGT has been applied to energy networks such as electricity grids and natural gas pipelines (Churkin et al., 2019, 2021), its application to hydrogen pipelines and energy policy remains underdeveloped. This work addresses this gap by investigating the following questions from the CGT perspective:

- RQ1: To what extent do varying financial subsidy rates incentivize full cooperation in pipeline infrastructure development?
- RQ2: How should the related costs (and benefits) be allocated among countries to build stable and satisfactory coalitions?

The main novelty of this work lies in its development and implementation of a methodology that uses CGT to evaluate coalition risks under varying subsidy regimes in the development of hydrogen pipeline infrastructure. The methodology is applied to the "HyCorridorE" case, inspired by Corridor E from the EHB and the South-East European Hydrogen Corridor (SEEHyC, 2024), including six neighboring countries. The proposed mathematical model is positioned downstream of technical feasibility assessments conducted by the TSOs, as reflected in the EHB planning framework for the HyCorridorE, and therefore addresses a policy-design problem. The case is restricted to infrastructure construction, considering the capital cost of pipelines (repurposed or new) and compressors. The core is used as the main game-theoretic solution concept to explore the cohesiveness and stability of the desired situation of full cooperation, while three simple rules are used to allocate the total cost. Different subsidy policy regimes are discussed to provide insights for policymakers, infrastructure planners, and modelers seeking to design or use cost-sharing mechanisms to derisk cross-border investment while fostering long-term cooperation that leads to final investment decisions (FIDs) and the construction of all pipeline segments within specific corridors, thereby ensuring reliable distribution.

The remainder of the paper is structured as follows. Section 2 provides context and offers a brief review of pipeline initiatives and the application of game theory to pipeline infrastructure; it also identifies the research problem. Section 3 outlines the methodology, including the case study, relevant game-theoretical approaches, simple allocation rules, and subsidy scenarios. Section 4 presents and discusses the results. Section 5 highlights the main conclusions and suggests policy implications.

2. Context and problem definition

2.1. European pipeline initiatives

European countries have depended for several decades mostly on crude oil, natural gas, and coal (Hubert and Ikonnikova, 2011; Jafarzadeh et al., 2021). However, the recent definition of Renewable Fuels of Non-Biological Origin (RFNBO) implies strategic redirection (European Commission, 2020). Transition initiatives for hydrogen distribution often use scenario analysis or optimization to design European H_2 pipeline networks (Kountouris et al., 2024). The EHB initiative, now comprising 33 European TSOs from 28 EU countries, was launched in 2020 to outline a vision for the continent-wide hydrogen pipeline network. The initial approach was developed by TSOs, taking into account existing infrastructure and geographical constraints. Optimization analysis was later developed by the Gas for Climate consortium (Gas for Climate, 2023), projecting that a pan-European hydrogen network would yield cost savings of €330 billion between 2030 and 2050 compared to a more fragmented cluster strategy.

The plan defined in the EHB is to develop an H_2 pipeline network of 31,500 km by 2030 and extend this to 53,000 km by 2040, with the vision to repurpose 60% of existing gas pipelines and create 40% new pipelines that will transport green hydrogen from regions of abundant RES potential to those that require imports to meet their demand (central Europe) (EHB, 2022b, 2023). Some corridors envision diversification to facilitate hydrogen imports from Africa or the Near and Middle East (EHB, 2022a). With EU projections of 20 Mt of green H_2 by 2030 (European Commission, 2022a), the EHB estimates a low-cost hydrogen supply of 14.7 Mt, resulting in CO_2 emission reductions of up to 312 Mt equivalent per year by 2050 if the H_2 pipeline vision is successfully implemented (EHB, 2022a).

The EHB consists of five large-scale corridors (A: North Africa & Central Europe, B: Southwest Europe & North Africa, C: North Sea, D: Nordic and Baltic regions, E: East and South-East Europe) to address regional supply-demand imbalances in a cost-effective manner. Several sections of the EHB corridors are planned to progress from initiation to commissioning within a 7-year timeframe (2023-2030). Currently, the project is at the front-end engineering design stage, with just a year remaining to finalize the technical and financial complexities (FID stage), and four more years for the contracting, construction, and commissioning of the project (European Union, 2022; Skov and Schneider, 2022. Despite this, interdependencies in hydrogen supply chains (HSCs) affect the system's reliability (De-León Almaraz et al., 2024). With green hydrogen projects, a major concern is that many (including hydrogen production and pipeline initiatives) have not reached FID, despite being approved years earlier (Hydrogen Europe, 2025). Three critical challenges for H_2 pipeline deployment can be highlighted regarding EU countries' decision-making (European Commission, 2024; European Clean Hydrogen Alliance, 2024): (1) compliance with decarbonization regulations (e.g., Fit-for-55, RED III); (2) the negotiation of cooperation conditions with relevant stakeholders; and (3) ensuring economic viability and cost-effectiveness. Knowledge gaps exist in all three areas, but this work partially addresses the second and third items.

For hydrogen pipeline construction, key financial instrument options include capital subsidies, grants, and blended finance. Specific examples include the Connecting Europe Facility program (CEF-E) under the revised TEN-E Regulation for Projects of Common or Mutual Interest (PCIs/PMIs), STEP support (Strategic Technologies for Europe Platform), IPCEI state aid exemptions for strategic value chains, and national funding programs (European Clean Hydrogen Alliance, 2024).

The estimated financial support needed for the EHB is about 25 billion euros (post-FID) for construction and operation by 2031 (European Hydrogen Backbone, 2023). For infrastructure co-financing, Regulation (EU) 2021/1153 (policy instrument) provides the legal framework that enables and governs financial instruments such as CEF-E (European Commission, 2021), supporting the provision of grants of up to 50% of eligible CAPEX for cross-border infrastructure projects like pipelines shared by multiple countries designated as PCIs (European Union, 2022; Ysewyn and Maczkovics, 2022).

2.2. Game theory in networks

Game theory can be categorized as NCGT or CGT; this section briefly reviews their applications to representative models.

Regarding the NCGT approach, several papers have used oligopoly models to examine European and Eurasian gas networks (Boots et al., 2004; De Wolf and Smeers, 1997; Gürkan et al., 1999). Others have utilized Nash-Cournot (Abada et al., 2013; Gabriel et al., 2005) or Stackelberg (Breton and Zaccour, 2001) models to describe competitive interactions and negotiations over price-quantity contracts in natural gas markets.

Research that has applied CGT, particularly non-transferable utility (NTU) bargaining models, to gas pipeline networks has primarily examined how infrastructure configuration, investment decisions, and market rules shape bargaining power among producers, transit countries, and consumers. Early studies focused on strategic investment and cooperation in transnational pipeline systems, showing that coordinated investment can improve efficiency relative to non-cooperative outcomes (Hubert and Suleymanova, 2008). Later work analyzed how investments in repurposed and newly constructed pipelines affect geopolitical bargaining positions in European gas trade, particularly between Russia and transit countries supplying Northwestern Europe (Hubert and Ikonnikova, 2011).

Subsequent studies extended NTU bargaining approaches to evaluate how network structures influence the distribution of bargaining power and transfer profits among stakeholders involved in gas pipeline networks (Cobanli, 2014; Hubert and Cobanli, 2015; Jafarzadeh et al., 2021). In particular, Csercsik et al. (2019) introduced an iterative flow mechanism within a partition function form game framework, enabling a more detailed representation of interdependent gas network dynamics in Central and Eastern Europe. Related research has also examined how regulatory changes, such as the liberalization of pipeline access within Europe, alter the balance of power between external suppliers, transit states, domestic incumbents, and consumers (Hubert and Orlova, 2018).

Transferable utility (TU) cooperative games have also been extensively applied to cost allocation problems. The stability of cost allocations over cross-border interconnections is often analyzed using CGT solution concepts such as the core, the Shapley value, and the nucleolus. Regarding coalition formation, the central question is whether the latter generates additional value relative to acting independently, and how that value can be allocated to sustain collaboration. With CGT, the core captures this stability condition by ensuring that no subgroup of players has an incentive to leave a grand coalition. When the core is non-empty, allocation rules such as the Shapley value and the nucleolus can be used to distribute joint gains among players. However, the Shapley value may lie outside the core. In contrast, the nucleolus identifies the most stable allocation within the core or, if the core is empty, the closest approximation to a stable allocation.

Early contributions demonstrated how cooperative game-theoretic solution concepts can be used to evaluate cost-sharing arrangements in regional energy systems, with Gately (1974) applying TU games to electricity cooperation in southern India and analyzing alternative allocation rules. Young (1994) provided a broader conceptual foundation, illustrating how solution concepts such as the core can be used to assess stability in cost-sharing problems, drawing on case studies such as the Tennessee Valley Authority and Swedish water infrastructure development. These studies highlight how stability and fairness considerations can support sustainable cooperation among multiple stakeholders. More recent work has extended these ideas to large-scale cross-border transmission networks, where TU models are used to quantify the benefits of interconnection and assess allocation stability in multi-country systems (Churkin et al., 2019). At the same time, evidence from European transmission contexts shows that insufficient coordination can lead to allocations perceived as unfair, potentially undermining cooperative outcomes (Gerbaulet and Weber, 2018). Table 1 presents recent CGT studies for various integrated energy systems (IES), HSCs, and H_2 technologies in terms of cost or benefit allocation. Current CGT models are primarily applied to Chinese case studies.

Although some works include subsidy analysis, the effects of varying subsidy rates on international pipeline coalitions remain unexplored today. Cooperative cost games can help clarify the impact of different subsidies by assuming that a central financial source grants subsidies. Subsidies and policies have been used in models for carbon capture and storage (Massol et al., 2018; Yuan et al., 2024), hydrogen refueling stations (Tuofu et al., 2022; Zhao et al., 2022), RES and ammonia (Liu et al., 2025), and subsidies for consumers (Yin et al., 2024). Our proposal consists of a CGT-type TU (cost allocation) model and its core-based analysis for a European pipeline corridor.

A review by Churkin et al. (2021) highlights several areas in which cost allocation games have been used to promote cooperation within power systems. In De-León Almaraz et al. (2025), a specific type of cooperative game (the peer-group game) is investigated with application to a three-echelon hydrogen supply chain. It models a hierarchical joint venture in which asymmetric dependency relations limit the generation of added value. Since the core is guaranteed to be non-empty in a peer-group game, the focus is on the various allocation rules. To the best of our knowledge, cooperative cost games have not been applied in the hydrogen pipeline context.

In this context, this paper addresses this gap by applying CGT within a TU framework (cost allocation game) to analyze subsidy allocation in

Table 1
Assessment of cooperative game-theoretical models applied to cost or profit allocation in hydrogen applications.

REF	Scale	GT type	Model	Solution concept	Tech. Involved	Country/Region	Focus of paper
Wang et al. (2022)	HSC	CGT	NTU	Nash bargaining	Wind, H_2 storage	China	Profit balance in a multiple-player system
Zhao et al. (2024)	H_2 tech.	Mixed	Several	Stackelberg, Shapley value, Evolutionarily stable strategy	HRS	Not specified	Business model for this distributed HRS system using a multi-level game model
Zhu et al. (2023)	HSC	CGT	TU	Shapley value	RES, Storage. Power distribution , H_2 storage	China	Optimal trading amount and profit allocation
Liu et al. (2023)	IES	CGT	TU	Shapley value, Core	IES, Electricity, Gas, Heat, Hydrogen	China	Cost allocation, benefit sharing of profits, and risks
Tang et al. (2024)	IES	CGT	NTU	Nash bargaining	IES Electricity, Heat, Hydrogen	China	Cost reduction, carbon emission reduction, and energy trading efficiency
Mi et al. (2022)	HSC	CGT	NTU	Nash-Harsanyi	Wind Farm, HRS	Not specified	Characterize the uncertainties of wind power and the market electricity price to alleviate risk
Barati et al. (2024)	IES	CGT	TU	Shapley value	Several	Not specified	Various energy hubs collaborate to maximize gain, which is fairly allocated among the hubs
Wang et al. (2023)	H_2 tech.	Mixed	Several	Shapley value, Stackelberg	H_2 storage	Not specified	Optimization and benefit allocation mechanism
De-León Almaraz et al. (2025)	HSC	CGT	TU	Core, Gately value, Nucleolus, Shapley value	Solar, Wind, NG, Nuclear, Electrolysis, SMR + Carbon Capture and Storage (CCS), H_2 transport, H_2 storage	Generic 3-echelon Hydrogen Supply Chain case	Compare benefit allocation schemes
Current paper	H_2 tech.	CGT	TU Cost-allocation game	Core	H_2 pipeline	Europe (Hy CorridorE)	Analysis of subsidy variations and cost allocation for cross-border H_2 pipeline deployment

cross-border hydrogen pipeline development (Table 1). A key structural feature of the "pipeline problem" is the interdependence among neighboring countries, whose geographical and infrastructural positions influence both cooperation incentives and the distribution of benefits.

3. Methodology

To assess the cooperative dynamics of hydrogen pipeline development, a 7-step methodology is proposed (Fig. 1). Step 1 involves a case study (Section 3.1.1), in which the research scope and the coalition countries are defined. Step 2 covers pipeline characterization and data collection (Section 3.1.2), and Step 3 identifies a suitable game-theoretical model (Section 3.2). Step 4 defines subsidy and simple-rules scenarios (both Section 3.3). Step 5 discusses the verification of grand coalition stability. Step 6 involves calculations and analyses across various scenarios, culminating in a discussion of the results and a sensitivity analysis (SA) in Step 7.

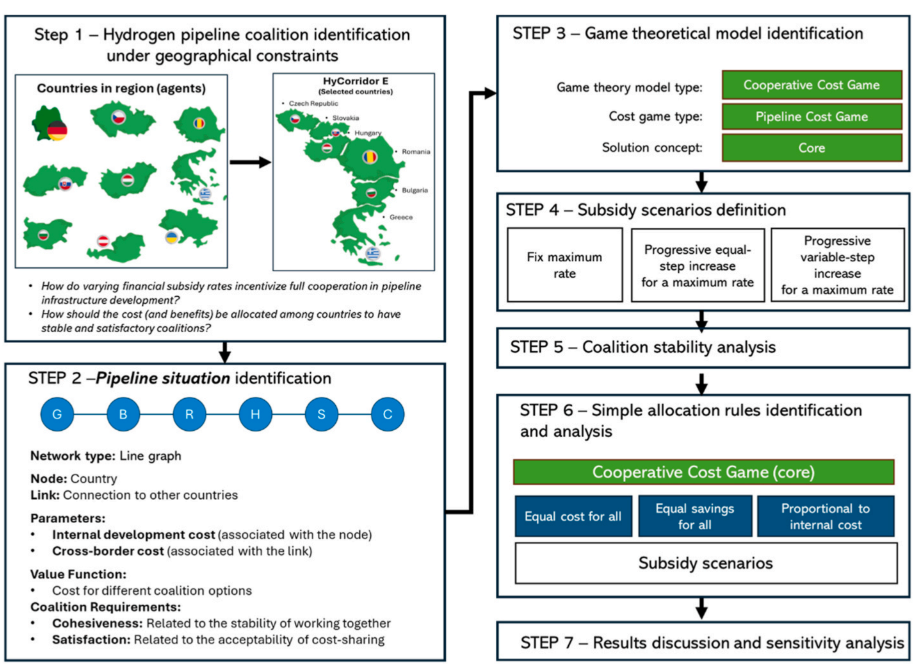

Fig. 1. Methodology.

3.1. Case study: HyCorridorE

3.1.1. Coalition opportunities

The European South-Eastern region could be a net exporter by 2040, transporting H_2 through Corridor E to the central parts of Europe (European Hydrogen Backbone, 2023). The backbone plan has evolved over time, but complete data for all Corridor E countries and pipeline links were unavailable for this study. A similar configuration to Corridor E is presented in the South-East European Hydrogen Corridor (SEEHyC), which offers more complete data (SEEHyC, 2024). Both EHB and SEEHyC plan to repurpose existing gas infrastructure while investing in new hydrogen pipelines and compressor stations. However, Corridor E and SEEHyC differ in how they involve Austria, Germany, and Ukraine.

Accordingly, a new case study, "HyCorridorE," is proposed, inspired by Corridor E and SEEHyC, in which six neighboring countries are selected to evaluate a cross-border hydrogen pipeline linking Greece, Bulgaria, Romania, Hungary, Slovakia, and the Czech Republic (Fig. 2).

3.1.2. Identification of the pipeline situation

HyCorridorE flows northward from Greece (G) through Bulgaria (B), Romania (R), Hungary (H), Slovakia (S), and into the Czech Republic (C), forming a linear corridor in which neighboring countries share one or two borders (Fig. 3).

The data used for HyCorredorE is displayed in Table 2 and Supplementary Material A1. The pipeline infrastructure cost is calculated for both internal and cross-border costs. The $internal\ cost_{country} = internal\ pipeline\ length\ (km)_{country} \times Cost\ per\ km\ (M\ EUR/km)_{country}$ for pipeline type (new or repurposed; onshore or offshore). This cost represents what each country would pay to build the pipeline internally. However, if two countries (e.g., Greece and Bulgaria) or more countries (e.g., Romania, Hungary, and Slovakia) cooperated, they would incur both internal costs and cross-border costs. Although compressors are necessary for internal and/or external pipeline operation, in this analysis, their cost is assumed to equal the cost of building a cross-border connection for countries. Although this is a simplification, it helps illustrate the effects of cooperation. This assumption is tested in the SA (Section 4.3). As a result:

$$Cross\ border\ cost_{country} = Internal\ compressor\ capacity\ needed_{country}\ (MW) \times Compressor\ installation\ cost\ (M\ EUR/MW)_{country} \quad (1)$$

The fixed positions of the players in the line graph restrict their actual cooperative possibilities to connected (interval) coalitions (Section 3.2.2). With structure identification and cost data, evaluations are developed in terms of incentives for stable collaborations and satisfaction with the allocation of the total cost.

Cost uncertainty in hydrogen pipeline infrastructure arises from simplified cross-border cost assumptions, hydrogen-specific technical constraints, limited empirical cost data, and significant geographical and country-specific heterogeneity (Balaji and Rabiei, 2021; European Clean Hydrogen Alliance, 2024; European Hydrogen Backbone, 2023; Fleer et al., 2025; Weiβenburger et al., 2025). Based on this, there is a risk of underestimating internal or cross-border costs, or both. The European Clean Hydrogen Alliance (2024) reports that, for some countries, CAPEX estimates can differ by up to ±50%, depending on project-specific conditions. As a result, an SA is conducted to assess the model's robustness (Supplementary Material B). In addition to the basic scenario that uses the current publicly available cost estimates (Table 2), 24 scenarios are tested by varying the internal and/or cross-border implementation costs by increments of 10%, 20%, 50%, and 75% in the progressive subsidy rates scenarios (see Table 3). Cost decreases are not considered because they are not typical (Nicolle and Massol, 2023).

3.2. Game-theoretical model

3.2.1. Cooperative cost games

Since their introduction by Von Neumann and Morgenstern (1944), cooperative TU games have proven useful for modeling and analyzing complex situations in which several agents influence the possible outcomes, and the influence of various groups can be measured on the same interval scale. The aim is to untangle the intricate interconnections among the agents and quantify the influence of each based on desirable principles. Cooperative game models can be categorized as profit or cost games, where higher (lower) scale values indicate better outcomes for

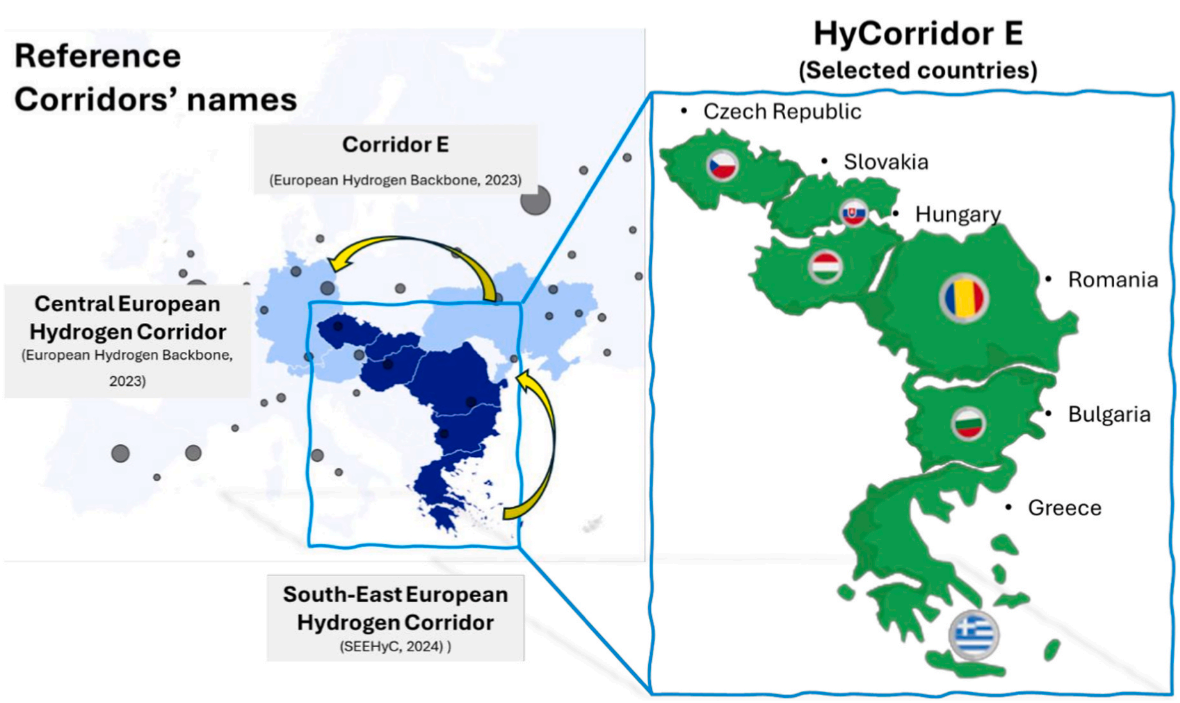

Fig. 2. HyCorridorE.

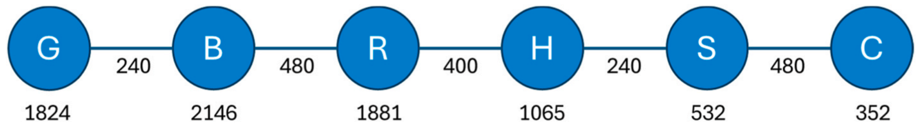

Fig. 3. HyCorridorE pipeline situation with cost (M EUR) per node (internal cost) and link (cross-border cost).

Table 2
HyCorridorE: Internal and cross-border connection cost.

Country	Internal cost (M EUR)*	Cross-border cost (M EUR)*
Greece	1824	240
Bulgaria	2146	480
Romania	1881	400
Hungary	1065	240
Slovakia	532	480
Czech Republic	352	0
Total	7800	1840

Note: (*) refers to calculations based on European Hydrogen Backbone (2023) and SEEHyC (2024). Details are presented in Supplementary Material A1.

Table 3
Subsidy scenario names and descriptions.

Name	Description
Max 30% = fix30%	30% subsidy rate applicable to all coalitions containing 2-6 countries
A30 : Max 30% = 5 × 6%	6% subsidy rate for coalitions of 2 countries, and an equal step increase of 6% to coalitions with every additional country until reaching the maximum of 30% for the grand coalition.
B30 : Max 30% = 14% + 4 × 4%	14% subsidy rate for coalitions of 2 countries, and an equal step increase of 4% to coalitions with every additional country until reaching the maximum of 30% for the grand coalition.
C30: Max 30% = (12 + 6 + 5 + 4 + 3)%	30% for the grand coalition, with a variably degressive subsidy, with a minimum subsidy rate of 12% for coalitions of 2 countries.
Max 50% = fix50%	50% subsidy rate to all coalitions containing 2-6 countries
A50 : Max 50% = 5 × 10%	10% subsidy rate for coalitions of 2 countries, with an equal 10% step increase for each additional country, up to a maximum of 50% for the grand coalition.
B50 : Max 50% = 18% + 4 × 8%	18% subsidy rate for coalitions of 2 countries, and an equal step increase of 8% to coalitions with every additional country until reaching the maximum of 50% for the grand coalition.
C50: Max 50% = (20 + 9 + 8 + 7 + 6)%	50% for the grand coalition, with a variably degressive subsidy rate, with a minimum subsidy rate of 20% for coalitions of 2 countries.

all agents. Since the research described in this paper analyzes a multi-agent cost-sharing situation, the necessary concepts and terminology for cost games are introduced.

A cooperative *cost game* is a pair (N, c), where $N = \{1, 2, \dots, n\}$ is the finite set of *players* and $c : 2^N \to R$, satisfying $c(\emptyset) = 0$, is the real-valued *cost function* that assigns to each *coalition* $S \subseteq N$ its value $c(S)$. Thus, an n-player cost game consists of a collection of 2^n real numbers which are obtained (in an adequate way) from the parameters of the multi-agent situation to be modeled by the game. Due to their abstract nature, cost games can capture group effects for a very wide range of multi-agent situations (Young, 1994). The focus of this paper is on a special type of situation in which the agents are positioned on a line graph, restricting cooperation to connected coalitions. Although similar settings where an exogenously given linear structure determines the cooperative possibilities of the agents and only consecutive coalitions can generate added value have been analyzed using cooperative game theoretic tools in several papers (e.g., Potters and Reijnierse, 1995; van den Brink et al., 2007; van Velzen et al., 2008), to the best of our knowledge, the proposed model is new in at least two respects. First, in the underlying line graph, costs are associated with both the nodes and the links. Second, the actual costs also depend on external subsidies; hence, the collaboration of neighboring connected coalitions may not always be beneficial.

A cost game (N, c) is called *cohesive*, if $c(N_1) + \dots + c(N_k) \geq c(N)$ for all partitions $N_1 \cup \dots \cup N_k = N$ $(k \geq 2)$ of the *grand coalition* N. This property means that if disjoint groups of agents merge into the grand coalition, the total cost can only decrease; therefore, collaboration to form the grand coalition can only be beneficial. In this paper, the main question is whether the grand coalition is the most cost-effective means of cooperation; thus, the cohesiveness of the cost game will be the primary concern.

In the cost game (N, c), an *allocation* is a vector of cost shares $(x_1, x_2, \dots, x_n)$ satisfying $\sum_{i \in N} x_i = c(N)$. This specifies the *payments* to be made by the players to jointly cover the cost of the grand coalition. The *core* of the cost game (N, c) is the set of allocations that satisfy the *acceptability* inequalities $\sum_{i \in S} x_i \leq c(S)$ for all coalitions $S \subseteq N$, $S \neq \emptyset, N$. The difference $f(S, x) = c(S) - \sum_{i \in S} x_i$ is called the *satisfaction* of coalition S with allocation x. The core can thus be seen as the set of allocations no coalition is dissatisfied with. Formally,

$$Core(N,c) = \{x \in \mathbf{R}^N : f(N,x) = 0 \text{ and } f(S,x) \geq 0 \text{ for all coalitions } S \neq \emptyset, N\}. \tag{2}$$

Note that some of the inequalities in (2) might be redundant. Coalition S is called *inessential* in a cost game c if it has a partition $S = S_1 \cup \dots \cup S_k$ with $k \geq 2$ such that $c(S_1) \cup \dots \cup c(S_k) \leq c(S)$, since then $f(S, x) \geq f(S_1, x) + \dots + f(S_k, x)$ for any payment vector x, thus $f(S_j, x) \geq 0$ for all $1 \leq j \leq k$ together imply $f(S, x) \geq 0$ and make this constraint *redundant* in the core system (i.e., it can be left out without enlarging the set of solutions). Coalitions that are not inessential are called *essential*. Notice that single-player coalitions are always essential.

In general, the core may be empty even if the cost game is cohesive (Young, 1994), but cohesiveness is necessary for the non-emptiness of the core. Indeed, if a cost game (N, c) is not cohesive because of, for example, $c(S_1) + \dots + c(S_k) < c(N)$ for some partition $S_1 \cup \dots \cup S_k$ of N, then for any allocation x, the inequality $f(S_1, x) + \dots + f(S_k, x) < f(N, x) = 0$ holds, implying that at least one of the satisfaction values $f(S_1, x), \dots, f(S_k, x)$ must be negative. Thus, no allocation x can belong to the core. Intuitively, if operating separately in the coalitions $S_1, \dots, S_k$ is less expensive than forming the grand coalition N, why form the latter if the difference in the total costs, i.e., the *gains from merging*

$$g(S_1, \dots, S_k) := c(S_1) + \dots + c(S_k) - c(N) \tag{3}$$

is negative? In the specific type of cost games introduced next, cohesiveness is also a sufficient property for the non-emptiness of the core.

3.2.2. Pipeline cost game for HyCorridorE

The development of the HyCorridorE hydrogen network motivates the graph model shown in Fig. 3, called the *pipeline situation*, in which the agents are the nodes of a line graph, and a nonnegative cost is associated with each node and each link.

The fixed positions of the players in the line graph restrict their actual cooperative possibilities to connected coalitions, in which any player positioned between two members of a coalition is also a member of that coalition. The actual development cost $d(S)$ of connected coalition S is the total cost of all included nodes and connection links. The cost of a disconnected coalition is simply the sum of the costs of its connected components. For example, in the HyCorridorE pipeline situation $d(\{B,R,H\}) = 2146 + 480 + 1881 + 400 + 1065 = 5972$ for the connected coalition $\{B,R,H\}$. On the other hand, $d(\{G,B\} \cup \{H,S\}) = (1824 + 240 + 2146) + (1065 + 240 + 532) = d(\{G,B\}) + d(\{H,S\})$ for the disconnected coalition $\{G,B,H,S\}$. This component additivity of the development cost function $d(.)$ implies that it is fully determined by the development costs $d(S)$ of the connected coalitions S.

The other element of a pipeline situation is the subsidy function $r(s)$, which specifies the portion of the development cost $d(S)$ of connected coalition S of size s (the number of players in the coalition) that is financed by an external source. Since the aim of the subsidies is to incentivize the formation of the grand coalition of the six countries, the subsidy function $r(s)$ is assumed to satisfy $0 = r(1) < r(s) < 1$ for all $s \geq 2$, and be monotone non-decreasing. Note that the subsidy rate only depends on the number (but not on the identity) of the countries forming a connected coalition. Condition $r(1) = 0$ implies that no country can receive external financing for internal network development; only collaboration is to be subsidized. Two cases for the maximum rate are considered: $r(6) = 0.5$ or $r(6) = 0.3$. The monotone non-decreasing pattern is chosen because a sequential build-up of the pipeline network is envisioned, and only a non-decreasing subsidy policy maintains steady incentives at each step of the network build-up process. These assumptions are in line with two policy instrument/regulations: 1) Financing cross-border cooperation where the guidelines for applicants in CEF-E calls for renewable cross border projects emphasize "projects focusing on cross-border cooperation that helps EU countries achieve the 2030 renewable energy targets in a more cost-efficient manner'' (European Commission, n.d.) and 2) EU Regulation (EU) 2021/1153, which allows higher subsidy rates (co-financing) for energy infrastructure projects involving cross-border interconnection (two or more member countries), especially if designated as PCIs with a maximum of 50% under some circumstances, as detailed in its Article 15 (European Commission, 2021).

A pipeline situation, i.e., a node- and link-weighted line graph with node set N and subsidy function $r(s)$, induces a special cooperative cost game called the *pipeline cost game*, with player set N and coalitional cost function $c(S)$. For a connected coalition S of size $s = |S|$, this is defined as

$$c(S) = (1 - r(s)) \cdot d(S) \tag{4}$$

For a disconnected coalition T with component partition $T = T_1 \cup \ldots \cup T_h$, the coalitional cost is simply the sum of the coalitional costs of its connected components; that is, $c(T) = c(T_1) + \ldots + c(T_h)$. This component additivity of the coalitional cost function $c(.)$ implies that it is fully determined by the coalitional costs $c(S)$ of the connected coalitions S. It also immediately follows that any disconnected coalition is inessential in the pipeline cost game (N,c), implying that the core is fully determined by the connected (also called interval) coalitions. Formally,

$$Core(N,c) = \{x \in \mathbf{R}^N : f(N,x) = 0 \text{ and } f(S,x) \geq 0 \text{ for all interval coalitions } S \neq \varnothing, N\}. \tag{5}$$

Notice that while the core system (2) of an n-player general cooperative cost game contains $2^n - 1$ constraints, the core system (5) of an n-player pipeline cost game only contains $n(n+1)/2$ constraints. Analogously to arguments in van Velzen et al. (2008), it follows that in pipeline cost games the core is nonempty if and only if the coalitional cost function is cohesive.

In the 6-player HyCorridorE pipeline cost game, the cost of the $21 = 6(6+1)/2$ connected coalitions fully determine the core, the $42 = 2^6 - 1 - 21$ disconnected coalitions are redundant and can be neglected. The same simplification applies when checking the cohesiveness of the pipeline coalitional cost function, implying that the non-negativity of the gains by merging values, given in (3), only needs to be checked for the $31 = 2^5 - 1$ interval partitions of N composed of connected coalitions. In contrast, the number of all partitions, the so-called Bell number of a 6-element set, is 203 (Aigner, 1999), thus the 172 partitions containing disconnected coalition(s) can be ignored.

3.3. Simple rules and subsidy scenarios

Distributive justice (Sovacool and Dworkin, 2015) and fairness are important concepts when discussing allocation schemes. However, determining a fair distribution of the costs or benefits of joint endeavors is not straightforward; different rules lead to different allocations, and mutual acceptance is crucial to the contractual cooperation of the parties. Stakeholders' willingness to participate depends on the perceived fairness of the system (Soares et al., 2024). Regarding distributive justice, Deutsch (1975) identified four basic distributive principles (simple allocation rules) related to group dynamics: 1) winner-takes-all (under this rule, whoever performs the task best in the group wins all the money the group is paid); 2) proportionality (each person is rewarded in proportion to their contribution to the group); 3) egalitarian or equality (each person in the group gets an equal share of the money to be distributed within the group), and 4) need (each group member is rewarded according to the need expressed). These rules can be applied to cross-border projects such as PCIs, where the involvement of multiple countries may reflect inherent asymmetries and the "territorial principle" is often used as an allocation rule (i.e., each Member State bears the cost of the portion of the infrastructure within its territory (ACER, 2026)). However, Regulation (EU) No 347/2013 (TEN-E Regulation), with its Article 12 (4) (ACER, n.d.; European Commission, 2013), introduced the concept of Cross-Border Cost Allocation (CBCA) for PCIs.[1] This is designed to address situations in which cross-border benefits are unevenly distributed among Member States, potentially discouraging those that face costs that exceed their benefits from proceeding. CBCA opens the opportunity to propose alternative cost allocation rules. In CGT, the proportionality and egalitarian rules are often used (De-León Almaraz et al., 2025). As an example, Lowing and Nicolle (2025) propose using egalitarian, proportional (Common Projects) and hybrid allocation rules as benchmarks for cross-border PCI projects related to CCS, ensuring that project participants contribute to the costs borne by their partners in a manner consistent with the beneficiary-pays principle.

Correspondingly, three simple, easy-to-calculate allocation rules ("simple rules") were applied to the HyCorridorE. First, the "equal cost" rule stipulates that all countries should bear an equal share of the subsidized total cost. Similarly, the "equal savings" rule allocates the subsidized total cost so that, relative to unsubsidized internal costs, all countries enjoy the same cost savings. Third, the "proportional to internal costs" rule allocates the subsidized total cost in proportion to the countries' individual costs. In contrast to the first two egalitarian-type rules, this one combines proportionality and need-based principles, as individual investments in developing the internal subnetworks serve as the reference weights for the proportional allocation.

The subsidy scenarios are presented in Table 3. All of them satisfy the conditions of the subsidy rate function discussed in subsection 3.2.2. Two subvention regimes, allowing a maximum of 50% or 30% support, taking as a reference the CEF-E co-financing rates (European Commission, 2022b; European Union, 2022). The selection of scenarios varies along two dimensions: subsidy ceilings (fixed-subsidy policy scenarios) and allocation structure (progressive-subsidy scenarios).

The allocation structure captures the different policy design philosophies regarding cross-border cooperation. It answers the question: how

[1] See also: Article 16 of TEN-E (Regulation (EU) 2022/869) or Article 17 Enabling investments with a cross-border impact of EC proposal for TEN-E revision (2025/0399/COD) (ENNOH – ENTSOG, 2026).

should the regulatory maximums (30% or 50%) from external financiers be allocated among the coalitions to enable cooperation? The scenarios in Table 3 aim to introduce variation in the progressive subsidy rate functions. For instance, *Max* 30% = 5 × 6% allocates 6% of the 30% maximum external finance to 2-player coalitions, 12% to 3-player coalitions, 18% to 4-player coalitions, 24% to 5-player coalitions, and up to 30% for the 6-player coalition. The progressive subsidy policy scenarios are designed to overcome cooperation hurdles while respecting the regulatory maximums (30% or 50%) for the grand coalition.

4. Results and discussion

The total internal cost for countries in HyCorridorE is €7.8 billion, while the cross-border cost is €1.84 billion (Table 2). Using the data presented in Supplementary Material A1, the total actual (unsubsidized) project development cost $d(N)$ is estimated at € 9.64 billion. With 30% subsidies, the grand coalition cost $c(N)$ is estimated at € 6.75 billion, and with 50% aid, $c(N)$ decreases to €4.82 billion. While the subsidies create incentives for cooperation, the way they are distributed affects the stability of the grand coalition.

As explained in Section 3.2.1, the cohesiveness of the pipeline cost game (N, c) is required for the full cooperation to be beneficial, thus, for any division of the grand coalition N into connected (interval) coalitions $S_1,\ldots,S_k$, their gain by merging, $c(S_1) + \ldots + c(S_k) - c(N)$ should be non-negative. If the pipeline cost game is cohesive, then the core is nonempty, implying that the grand coalition cost can be allocated so that all coalitions are satisfied. Fig. 4 presents all 31 interval partitions and their gains, with values ranging from no cooperation (at the bottom) to full cooperation (at the top), for the two fixed subsidy-rate designs. Since the gain by merging value is negative for at least one interval

Max30% = fix30%

GBRHSC

G-BRHSC	GB-RHSC	GBR-HSC	GBRH-SC	GBRHS-C
379.20	-336.00	-280.00	-168.00	-230.40

size (s)	subsidy rate
1	0
2	0.3
3	0.3
4	0.3
5	0.3
6	0.3

G-B-RHSC	G-BR-HSC	G-BRH-SC	G-BRHS-C	GB-R-HSC	GB-RH-SC	GB-RHS-C	GBR-H-SC	GBR-HS-C	GBRH-S-C
687.00	99.20	211.20	148.80	-51.70	-504.00	-566.40	-128.50	-510.40	-238.80

G-B-R-HSC	G-B-RH-SC	G-B-RHS-C	G-BR-H-SC	G-BR-HS-C	G-BRH-S-C	GB-R-H-SC	GB-R-HS-C	GB-RH-S-C	GBR-H-S-C
971.30	519.00	456.60	250.70	-131.20	140.40	99.80	-282.10	-574.80	-199.30

G-B-R-H-SC	G-B-R-HS-C	G-B-RH-S-C	G-BR-H-S-C	GB-R-H-S-C
1122.80	740.90	448.20	179.90	29.00

G-B-R-H-S-C
1052.00

Max50% = fix50%

GBRHSC

G-BRHSC	GB-RHSC	GBR-HSC	GBRH-SC	GBRHS-C
792.00	-240.00	-200.00	-120.00	-64.00

size (s)	subsidy rate
1	0
2	0.5
3	0.5
4	0.5
5	0.5
6	0.5

G-B-RHSC	G-BR-HSC	G-BRH-SC	G-BRHS-C	GB-R-HSC	GB-RH-SC	GB-RHS-C	GBR-H-SC	GBR-HS-C	GBRH-S-C
1625.00	592.00	672.00	728.00	500.50	-360.00	-304.00	212.50	-264.00	82.00

G-B-R-HSC	G-B-RH-SC	G-B-RHS-C	G-BR-H-SC	G-BR-HS-C	G-BRH-S-C	GB-R-H-SC	GB-R-HS-C	GB-RH-S-C	GBR-H-S-C
2365.50	1505.00	1561.00	1004.50	528.00	874.00	913.00	436.50	-158.00	414.50

G-B-R-H-SC	G-B-R-HS-C	G-B-RH-S-C	G-BR-H-S-C	GB-R-H-S-C
2778.00	2301.50	1707.00	1206.50	1115.00

G-B-R-H-S-C
2980.00

Fig. 4. Gains from merging for interval partitions under the fixed subsidy-rate policies.

partition, the cost game is not cohesive; thus, the core is empty in both cases. On the other hand, if a subsidy function would make all gains by merging values non-negative, the core of the induced pipeline cost game would be non-empty; thus, the cost of the grand coalition could be allocated in a way that is satisfactory to all coalitions.

4.1. Fixed subsidy rates

Under this subsidy design, flat subsidy rates of 30% and 50% are applied such that the pipeline development cost is reduced by the subsidy rate, as explained in Section 3.2.2. Under the 30% flat rate (Fig. 4), the cost of full cooperation is reduced from € 9.6 billion to € 6.7 billion, yielding cost gains of over € 2.8 billion. Nevertheless, the core is empty, and cohesiveness is violated by 14 interval partitions. For instance, the total cost of the interval coalitions Greece-Bulgaria and Romania-Hungary-Slovakia-Czechia separately is less than the cost of the grand coalition $c(GB) + c(RHSC) - c(GBRHSC) = 2{,}947 + 3{,}465 - 6{,}748 = -336$. The same applies to several other interval partitions, indicating that certain configurations of partial cooperations are more attractive than full cooperation; thus, this subsidy policy does not support the formation of the grand coalition. The same occurs with the flat 50% subsidy rate (Fig. 4). The cost game is not cohesive, even though full cooperation reduces the cost by 50%. Although the number of non-advantageous mergers is reduced due to the more generous subsidy rate, there are still eight interval partitions that exhibit negative gains from merging.

Under both uniform rates, countries have a stronger incentive to cooperate in smaller groups than in the grand coalition, indicating instability in the desired fully unified pipeline project. This phenomenon is inherent to any uniform subsidy-rate policy because once countries receive the maximum subsidy within their smaller groups, they have no additional financial incentive to merge. In fact, linking coalitions accrue additional costs due to the positive costs of cross-border connections. Notice that the gain by merging value is negative for all four interval partitions composed of multi-player coalitions (GB-RHSC, GBR-HSC, GBRH-SC, GB-RH-SC) in both fixed subsidy scenarios.

Formally, let S and $N\backslash S$ be two multi-player interval coalitions. If $0 < r_s = r_n < 1$ for all $2 \leq s \leq n = |N|$, then $c(S) = (1 - r_n)\cdot\ d(S)$ and $c(N\backslash S) = (1 - r_n)\cdot d(N\backslash S)$. Let $d_{ij} > 0$ denote the unsubsidized cost of the link between S and $N\backslash S$ that must also be built to merge the two groups. The subsidized cost of the grand coalition is thus $c(N) = (1 - r_n)\cdot \left(d(S) + d(N\backslash S) + d_{ij}\right) = c(S) + c(N\backslash S) + (1 - r_n)\cdot d_{ij} > c(S) + c(N\backslash S)$. Therefore, it is strictly disadvantageous for S and $N\backslash S$ to merge and form the grand coalition, thus, the core of the cost game $c(.)$ is empty.

In summary, although the uniform maximum subsidy rate policies support small-scale cooperation, they fail to incentivize the formation of the grand coalition, calling for a more flexible subsidy design that is sensitive to the number of collaborating countries. Without this, some countries may have justifiable economic reasons to exit or delay cooperation, weakening the overall hydrogen infrastructure plan.

4.2. Progressive subsidy rates

Since the formation of the grand coalition is threatened by the fixed-rate policy design, progressive subsidy-rate functions are implemented to assess whether grand coalition stability is achievable. For each of the six progressive policy scenarios, all gains by merging values are positive (see Table A3 – Supplementary Material A), indicating that it is not advantageous to split the grand coalition into any interval partition. Under these policy designs, the core (the set of stable allocations) is non-empty. This will be demonstrated by exhibiting (at least) one cost allocation that satisfies all core conditions in equation (5) for each scenario. This implies that full cooperation is beneficial under all six progressive subsidy designs.

Partial cooperation, however, may not be beneficial if the subsidy rate is not high enough. For example, under the linearly increasing "$A30 : \max 30\% = 5 \times 6\%$" design, Bulgaria and Romania are not inclined to build their interconnection: the 6% subsidy their coalition receives on their internal costs, $0.06 \times (2146 + 1881) = 241.62$ is less than the subsidized cross-border cost between the two countries $451.2 = 0.94 \times 480$ (see Table 2). The same applies to the interconnection between Romania and Hungary. Even when Bulgaria, Romania, and Hungary form a coalition, the 12% gained on their internal costs $0.12 \times (2146 + 1881 + 1065) = 611.04$ is not enough to offset the cost of the two cross-border connections, at 88%: $0.88 \times (480 + 400) = 774.4$. Under the "$A30 : \max 30\% = 5 \times 6\%$" scenario, collaboration without Greece only becomes beneficial when the subsidy rate reaches 18% for coalition BRHS (see the yellow bars in Fig. 5, and for the precise values, the "Gain of coalition" column in Table A4(A30), which reports the reduction $v(S) := \sum_{i \in S} c(i) - c(S)$ in total costs relative to the situation in which none of the member countries cooperate).

The same phenomenon is seen under all other subsidy policies. In the "$B30 : \max 30 = 14 + 4 \times 4\%$" design, the higher subsidy rates make cooperation beneficial for almost all groups of countries. Slovakia and Czechia remain reluctant to form a coalition, even if Hungary and Romania join (see the green bars in Fig. 5, and the *v(S)* values in Table A4(B30)), but to a lesser extent than under the "$A30 : \max 30\% = 5 \times 6\%$" design. The 23% subsidy rate for coalitions of four countries in the concavely increasing "$C30 : \max 30\% = (12 + 6 + 5 + 4 + 3)\%$" design is high enough to support the formation of the CSHR coalition (see the blue bars in Fig. 5, and the *v(S)* values in Table A4(C30). The fixed-rate "max 30% = fix30%" design is associated with the highest subsidy rates across all coalition sizes and provides the largest number of positive v(S) values (see the red bars in Fig. 5 and the corresponding *v(S)* values in Table A2). Recall, however, that it does not guarantee the stability of the grand coalition against all partitions of interval coalitions (Fig. 4); thus, it is not suitable for supporting the primary goal of the hydrogen pipeline project.

Similar observations can be made about the 50% progressive subsidy designs (see Fig. 6 and Table A4 (A50, B50, C50)). The higher rates reduce the number of coalitions with negative gains compared with the corresponding max 30% subsidy functions. The fixed rate "max 50% = fix50%" design makes even the Slovakia–Czechia collaboration beneficial (see Fig. 6 and Table A2), but is incapable of providing stability to the grand coalition (Fig. 4). Therefore, the analysis of cost gains (savings) from full cooperation, compared only to no cooperation, may lead to incorrect decisions if the possibilities for partial cooperation (as captured by the model's cohesiveness) are not considered.

Figs. 5 and 6 also reveal that, in all progressive subsidy regimes, Greece's involvement is necessary for cooperation to be beneficial, indicating that Greece is a key H_2 supplier in the HyCorridorE pipeline development. The reason lies in the cost structure of Greece within the network. Among the participating countries, Greece exhibits a relatively high internal project cost (1824 M EUR) and a comparatively low connection cost (240 M EUR), while also being located at the end of the corridor. Consequently, when Greece joins an already connected multi-country coalition, the merger generates substantial additional subsidy benefits while requiring only limited additional interconnection expenditures.

4.3. Sensitivity analysis

To test the robustness of the various progressive subsidy policies, 24 scenarios were examined by varying the internal and/or cross-border implementation costs by increments of 0%, 10%, 20%, 50%, and 75% in the progressive subsidy rates scenarios (Supplementary Materials B: "scenarios - cost increase"). This is necessary to test whether future cost increments ensure cohesiveness. The next step is to check if the cost increment sends an unsatisfactory signal to some coalitions (connected subnetworks with negative savings).

Among the max 30% subsidy regimes, the linear $A30 : 30 = 5 \times 6$

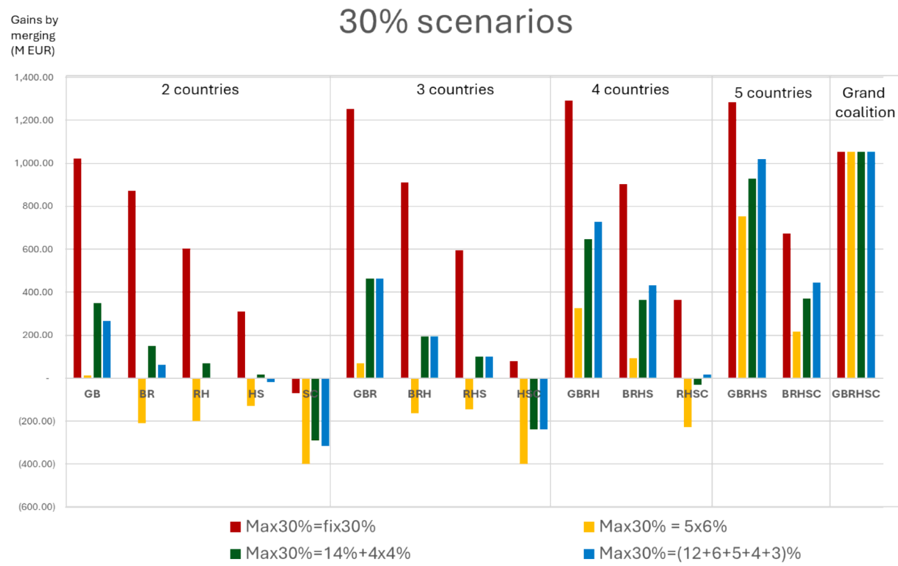

Fig. 5. Gains (savings) of coalitions under the max 30% subsidy scenarios.

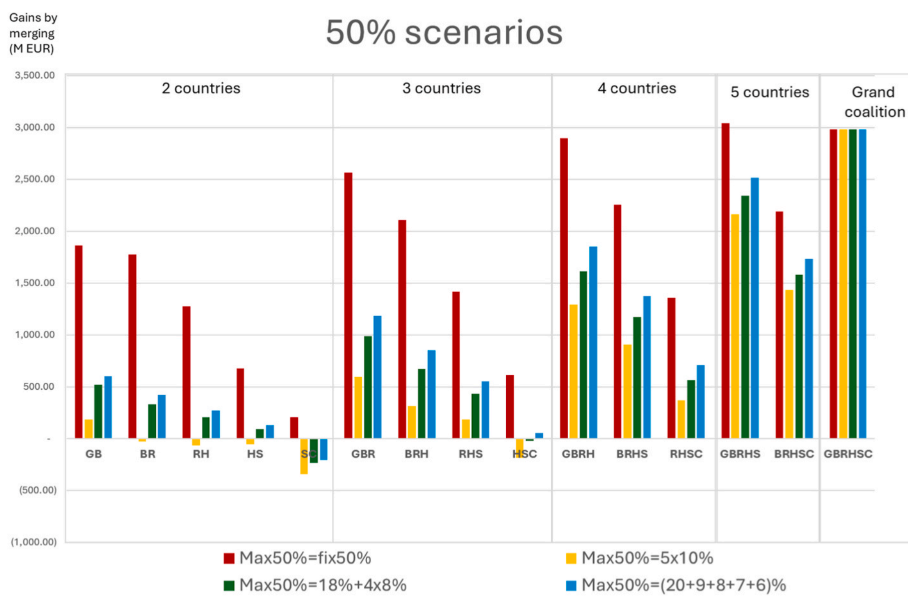

Fig. 6. Gains (savings) of coalitions under the max 50% subsidy scenarios.

policy appears to be the most robust, thus, supports its cohesiveness; however, it performs poorly in terms of the nonnegativity of savings. In the 30% regime, an increase in the cross-border cost sharply reduces cooperation savings/benefits. It is found to affect the stability of the coalition when the internal costs remain unchanged. For instance, under $B:30 = 14 + 4 \times 4$, coalition formation is threatened when cross-border costs increase from 50% upward with no corresponding increase in internal costs. A similar result is seen in $C:30 = 12 + 6 + 5 + 4 + 3$. Coalition formation is threatened when the cross-border costs increase from 20% upward, with no corresponding increase in internal costs. When cross-border costs increase faster than internal costs, coalition formation and stability may also be threatened. In situations where internal costs increase by 10% or 20%, coalition formation is threatened when cross-border costs increase by 75%. This highlights the importance of working on the most realistic approximations of cross-border and internal costs for stakeholders with full data. An increase in internal cost appears to yield positive savings (see Supplementary Materials B: “Combined 30%“).

All maximum 50% subsidy regimes are sufficient to support the formation of the grand coalition under any of the subsidy policies discussed. However, the number of coalitions affected by negative savings may send an unsatisfactory signal to some coalitions/countries about joining the unified H_2 project (Supplementary Materials B: “Combined 50%“). Between 1 and 8 coalitions may be affected by negative savings. However, any increase in internal costs reduces the number of dissatisfied coalitions, whereas an increase in cross-border costs has the opposite effect. It is worth noting that when future internal and cross-border costs increase uniformly (at the same rate), the base case scenario's results still hold for both the 30% and 50% subsidy regimes.

Policies A (A:30% and A:50%) are the most robust, but are associated with the highest number of critical situations (connected subnetworks with a negative savings value). In the case study, the Czech Republic is the country that threatens coalition formation (by linking with Slovakia) due to the high cross-border cost compared to its internal cost. These types of situations also exist with cross-border initiatives for other technologies, where countries with losses could apply for additional support (ACER, n.d.). However, the purpose of the model presented here is to prevent such situations. It is important to highlight that the trends we observe cannot be generalized to other pipeline corridors due to the specificities of the case study's configuration and data. The analysis considers ad hoc subsidy policies and tests their robustness. In the future, the policy regime scenarios could be optimized for both the maximum subsidy rate and the size of the step increases.

4.4. Simple allocation rules analysis

As seen in Subsection 4.2, the core of the HyCorridorE pipeline cost game is non-empty (the game is cohesive) under all six progressive rate subsidy designs. Thus, the cost of the grand coalition can be allocated among the six countries so that no smaller coalition is asked to pay more than its stand-alone cost. Alternatively, no subgroup of countries can do better by rejecting the allocation and forming its own smaller coalition instead. The satisfaction $f(S,x) = c(S) - \sum_{i\in S} x_i$ is a measure of this kind of stability of allocation x of the cost shares. Although not part of the core concept, the non-negativity of the cost shares, i.e., $x_i \geq 0$ for all $i \in N$, is also a natural stability requirement when costs are allocated. Three simple, but frequently applied, allocation rules are tested for each of the six progressive rate designs. The numerical results are given in Table A4 (A30, …, C50).

4.4.1. Equal cost shares (EC)

The Equal Cost allocation rule divides the grand coalition cost evenly among the players. Formally, in cost game (N,c), the cost share of player i is $EC_i := \frac{c(N)}{n}$ for all $i \in N$, where n is the number of players in N. Note that this rule is based on an egalitarian principle that completely ignores any differences among the players. The EC rule is computed only from the cost of the grand coalition. Thus, it comes as no surprise that the Equal Cost allocation falls outside of the core in all six games. In fact, the EC allocations are not even individually acceptable for Slovakia and Czechia; both countries would be asked to pay more than their internal costs in all cases. Therefore, for the HyCorridorE pipeline project, the Equal Cost allocation rule is not recommended due to its instability.

4.4.2. Equal savings (ES)

Under the Equal Savings rule, the total gain achieved by merging the players into the grand coalition is shared equally among the players, and the cost shares are determined to yield this uniform savings. Formally, in cost game (N,c), the cost share of the player i is $ES_i := c(i) - \frac{v(N)}{n}$ for all $i \in N$, where $v(N) = \sum_{i\in N} c(i) - c(N)$ is the cost gain (savings) achieved by forming N. This rule equalizes the individual satisfactions but still ignores the differences among the coalitions. The ES rule is computed solely from the grand coalition cost and the players' stand-alone costs; thus, stability cannot be expected in all cases. Indeed, the ES allocation falls outside the core in the "B30 : max 30% $= 14\% + 4\times\ 4\%$", "C30 : max 30% $= (12+6+5+4+3)\%$", and "C50 : max 50% $= (20+9+8+7+6)\%$" cases, because coalition GBRHS is dissatisfied.

In the other three cases, the Equal Savings rule yields a stable (core) allocation. However, in the "A50 : max 50% $= 5\times 10\%$" and "B50 : max 50% $= 18\% + 4\times 8\%$" cases, Czechia's cost share is negative, violating the standard requirement that every participant should bear a share of the costs, thus also making these two core allocations questionable. The ES allocation passes both the stability and the non-negativity test only in the "A30 : max 30% $= 5\times 6\%$" case (Table A4 (A)).

4.4.3. Cost shares proportional to internal costs

This rule allocates the cost of the grand coalition in proportion to each player's internal (stand-alone) cost. Formally, in cost game (N,c), the cost share of player i is $ICP_i := \frac{c(i)}{\sum_{i\in N} c(i)} \cdot c(N)$ for all $i \in N$. The ICP emphasizes individual differences but disregards those at the group level. The ES rule is also computed solely from the grand coalition cost and the players' stand-alone costs. Although non-negativity is guaranteed, stability cannot be. Indeed, in the "C30 : max 30% $= (12+6+5+4+3)\%$" case, coalition GBRHS is asked to pay 13.63 M more than its stand-alone cost (Table A4(C30)), so the ICP allocation is not satisfactory for all coalitions. In this case, all three simple allocations fall outside the core; thus, neither one supports the formation of the grand coalition. The nucleolus allocation is recommended, as it is always in the core when the core is non-empty (see e.g. Young, 1994; Potters and Reijnierse, 1995). The nucleolus is the outcome of a sequential optimization process that maximizes the lowest, then the second-lowest, etc., satisfaction values for all coalitions, thus providing the lexicographically most stable allocation. For the HyCorridorE pipeline project, the nucleolus cost allocation for the "C30 : max 30% $= (12+6+5+4+3)\%$" case is given in Table A5.

Table 4 summarizes the material discussed above. Given that core allocations guarantee cost distributions that are robust against deviations by both single- and multi-player coalitions, whereas the considered simple rules may not provide stable cost distributions, more sophisticated allocation rules should be considered. Since for monotone cost functions, all core allocations provide non-negative cost shares (see, e.g. (Young, 1994)), the nucleolus, as the lexicographic center of the core, could be recommended. It provides a non-negative cost allocation which is as stable as possible.

4.5. Limitations

This study is subject to several limitations. While cross-border hydrogen infrastructure development involves multifactorial challenges, the analysis focuses primarily on economic mechanisms, in line with the objective of assessing subsidy policy strategies for cross-border cooperation. Technical and operational constraints (such as technological reliability, safety, and implementation feasibility) are not explicitly modeled. They are assumed to be adequately reflected in the secondary (open-source) reference data that were used. In particular, the current technological constraints and cost efficiencies of long-distance hydrogen transmission are taken as given, and cross-border costs are approximated by compressor costs; robustness is assessed through sensitivity analyses of internal and cross-border transmission costs. Infrastructure planning is outside the model's scope; only pipeline CAPEX is considered, given anticipated investment needs (ENNOH – ENTSOG, 2026). Operating costs, lifetime maintenance costs, revenues, and demand uncertainty are all highly relevant variables that warrant further investigation. In practice, scaling up European hydrogen pipelines does not depend solely on economic factors, policy, and regulation. The complexity of hydrogen pipelines is also related to resource availability (e.g., water and RES), system design (including the physical properties

Table 4
Stability (and non-negativity) of simple allocations under progressive subsidy designs.

Subsidy rates	Equal Costs	Equal Savings	Proportional to Internal Costs
Max 30% $= 5\times 6\%$	X	√	√
Max 30% $= 14\% + 4\times 4\%$	X	X	√
Max 30% $= (12+6+5+4+3)\%$	X	X	X
Max 50% $= 5\times 10\%$	X	(√)	√
Max 50% $= 18\% + 4\times 8\%$	X	(√)	√
Max 50% $= (20+9+8+7+6)\%$	X	X	√

(√) indicates that the allocation is in the core, but violates the non-negativity of cost shares.

of hydrogen), interdependencies (e.g., scale and efficiency of electrolyzer installations), and socio-political factors, to name just a few.

Moreover, the analysis relies on three simple allocation rules as benchmarks and adopts ad-hoc progressive subsidy rate functions as a first approximation. CBCA was originally developed for mature electricity and gas markets. While it enables alternative cost allocation rules, it does not reduce aggregate market risk and is not designed to support anticipatory investment in a nascent market such as hydrogen (ENNOH – ENTSOG, 2026). In this paper, an anonymity assumption is used as a standard principle of distributive justice, which appears to be appealing to a neutral subsidizer whose purpose is to provide incentives for countries to form a grand coalition. This is a limitation, as in practice, differences in individual characteristics may or may not be taken into account in allocation rules (e.g., an equal split versus an internal-cost-proportional split of total costs). Lowing and Nicolle (2025) propose egalitarian, proportional (Common Projects) and hybrid rules as benchmarks for cross-border PCI CCS projects, aligning cost contributions with the beneficiary-pays principle. Although incorporating country-specific features into the subsidy function is certainly feasible and easily implementable within this framework, in the absence of any indication of such an intention in the central planner's public documents, it would imply a more restrictive assumption than anonymity and remains an avenue for future work. The study considers direct EU-level grants (i.e., CEF-E grants) as the primary cross-border support mechanism. In terms of de-risking, the ENNOH–ENTSOG report (2026) concludes that no single mechanism is sufficient in practice to address the scale and complexity of cross-border hydrogen infrastructure challenges. Alternative mechanisms, such as intertemporal cost allocation and long-term capacity bookings, may also be considered.

While this work acknowledges the shortcomings of specific applications, the proposed model is clearly defined as exploratory and provides useful insights for subsidy policy design. At this stage, the main model's purpose is to analyze the effects of subsidy regimes and to highlight concerns that may further affect the deployment of hydrogen pipelines. The model can be integrated or sequentially applied to pipeline infrastructure planning models or hydrogen supply chain models.

5. Conclusions and policy implications

European policies and regulations play a key role in the deployment of H_2 pipelines. Given the constraints associated with budget allocations, any financial support must be well justified. Each nation has its own energy transition plans and requires incentives to engage in large-scale initiatives. However, the substantial capital costs associated with developing these pipelines highlight the need for international collaboration to strengthen connectivity across regions, making it necessary for energy policymakers and pipeline developers to evaluate whether a grand coalition constitutes the most cost-effective form of cooperation.

This work was inspired by two research questions. The first was understanding the extent to which varying financial subsidy rates incentivize full cooperation in pipeline infrastructure development. To do this, a methodology was proposed and applied to the European HyCorridorE case study (Greece, Bulgaria, Romania, Hungary, Slovakia, and Czechia). The case structure is represented as a line graph, with neighboring countries connected to each other. Costs are associated with both nodes and links, and actual costs depend on external subsidies; hence, collaboration among neighboring connected coalitions may not always be beneficial. Cooperative cost games applicable to the pipeline situation were applied. The core was the main solution concept employed to examine the possibility of stable allocations. Non-emptiness of the core was examined by assessing the cohesiveness of the game, which only requires elementary calculations. Fixed and progressive subsidy-rate scenarios were examined to show that even small changes in the subsidy strategy can have major implications for the existence of stable allocations.

The second research question guided the examination of how three simple but frequently used cost allocation rules perform in the pipeline setting. The findings call for applying more sophisticated rules. To the best of our knowledge, the abovementioned contributions are all novel in the field of hydrogen pipeline development.

The results of different policy strategies (50% and 30%, fixed or progressive) suggest several policy implications for H_2 pipeline development in Europe. Under the fixed-rate subsidy strategies, the formation of a grand coalition is seriously threatened. This type of strategy promotes only small-scale, not full-scale, cooperation. This is because, once countries receive the fixed maximum subsidy within their smaller groups, they are not inclined to incur additional connection costs. This suggests that a uniform rate subsidy structure may inadvertently disincentivize cooperation by favoring bilateral agreements or smaller groupings. Fixed subsidies may be easier to communicate but difficult to implement when the interests of participating countries diverge. For the case study, a higher fixed subvention rate does not guarantee stable or satisfactory coalitions.

However, the analyzed progressive subsidy designs provide the desired cohesiveness (grand coalition formation) except in certain scenarios where the cross-border cost is high relative to internal costs (as shown in the sensitivity analysis). These designs may reduce political resistance from smaller or less central countries, facilitate multilateral negotiations, and support robust, stable infrastructure planning aligned with long-term decarbonization goals. They will also encourage larger, more integrated coalitions, which are essential for transnational hydrogen corridors. This scheme promotes broader cooperation, with the potential to reduce fragmented investments.

For simple rules, the "Proportional to internal cost" allocation is satisfactory for all coalitions in most, but not all, cases.

In this paper, the focus is on designing a subsidy rate system that yields a game model with a nonempty core. Since the core typically does not prescribe a single allocation, the nucleolus is recommended as the most stable payoff allocation.

The proposed framework contributes to ongoing European hydrogen infrastructure de-risking efforts (e.g., ENNOH – ENTSOG, 2026) by providing an analytical and decision-support tool for evaluating the potential of cross-border hydrogen pipeline projects.

Future research may include the further development of the case study, the application of game-theoretic rules (e.g., nucleolus and Shapley), and further development of the sensitivity analysis (e.g., Monte Carlo). Another avenue would be coupling the model with optimization tools to integrate it into pipeline planning and HSC design frameworks. Refining the subsidy scenarios is also important, particularly through identifying optimal allocation rules and subsidy levels that ensure stable full-scale cooperation, using optimization techniques. Finally, the model could be extended to incorporate hydrogen pipeline OPEX and long-term infrastructure maintenance costs.

Funding

The project is supported by the National Research, Development, and Innovation Fund of Hungary [grant numbers: OTKA FK 146575 and OTKA K 146649].

CRediT authorship contribution statement

Emmanuel Kwesi Arthur: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Sofía De-León Almaraz:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tamás Solymosi:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review &

editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sofia De-Leon Almaraz, Emmanuel Kwesi Arthur, and Tamas Solymosi report financial support was provided by National Research, Development, and Innovation Fund of Hungary.

Acknowledgement

We would like to thank Borbála Takácsné Tóth, Péter Kotek and Viktor Rácz for the helpful comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2026.115492.

Data availability

Data will be made available on request.

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