

TransHyDE-Sys: An Integrated Systemic Approach for Analyzing and Supporting the Transformation of Energy Systems and Hydrogen Infrastructure Development

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In addition to the long-term goal of mitigating climate change, the current geopolitical upheavals heighten the urgency to transform Europe's energy system. This involves expanding renewable energies while managing intermittent electricity generation. Hydrogen is a promising solution to balance generation and demand, simultaneously decarbonizing complex applications. To model the energy system's transformation, the project TransHyDE-Sys, funded by the German Federal Ministry of Education and Research, takes an integrated approach beyond traditional energy system analysis, incorporating a diverse range of more detailed methods and tools. Herein, TransHyDE-Sys is situated within the recent policy discussion. It addresses the requirements for energy system modeling to gain insights into transforming the European hydrogen and energy infrastructure. It identifies knowledge gaps in the existing literature on hydrogen infrastructure-oriented energy system modeling and presents the research approach of TransHyDE-Sys. TransHyDE-Sys analyzes the development of hydrogen and energy infrastructures from "the system" and "the stakeholder" perspectives. The integrated modeling landscape captures temporal and spatial interactions among hydrogen, electricity, and natural gas infrastructure, providing comprehensive insights for systemic infrastructure planning. This allows a more accurate representation of the energy system's dynamics and aids in decision-making for achieving sustainable and efficient hydrogen network development integration.

1. Introduction

In addition to the long-term goal of limiting the impact of climate change through decarbonization measures,^[1,2] current geopolitical upheavals—most prominently the war in Ukraine—are intensifying the urge to transform Europe's energy system.^[3] How we generate, supply, transport, and use energy will be subject to profound change, both in the short and the long term. The essential prerequisite is an expansion of renewable energies, especially wind and photovoltaics.^[4,5] This will be accompanied by the challenge of dealing with intermittent and seasonally fluctuating power generation. This intermittency and the increasing electrification in transport, households, services, and industry sectors pose significant challenges to the energy system and its infrastructure, especially the electricity transmission networks.^[6,7]

To date, fossil fuels play a crucial role in balancing energy demand and supply

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because of their high energy density, ease of storage and distribution, and suitability for conversion to electricity in the current power plant landscape. They are also used as feedstock in chemical processes. However, to reduce absolute greenhouse gas emissions, the carbon intensity of the future energy system must be reduced. While progress is made in reducing the carbon footprint of fossil fuels, for example, through carbon capture and storage, direct electrification measures and hydrogen and its derivatives will play an essential role in growing energy supply and decarbonizing applications that cannot be easily electrified.^[8–10]

Grey hydrogen is already being produced from fossil fuels at an industrial scale today. The currently deployed production routes emit greenhouse gases as they are based on natural gas. Carbon capture and storage can reduce emissions, and grey hydrogen is rebranded as blue. As an established technology, this could form the bridge to green hydrogen, produced from renewable electricity sources via electrolysis. To date, green hydrogen is produced almost exclusively on a small scale.^[8] To ensure the security of supply on a scale like that of current fossil fuels, a new hydrogen infrastructure consisting of hydrogen production plants, trade routes, large-scale storage facilities, and distribution networks is necessary. Its design is a topic of current scientific and public discussion.^[9–11] These discussions recently increased because the war in Ukraine required short-term decisions to cope with energy-economic fallouts that may influence Europe's long-term ability to ensure a seamless transition from fossil to climate-neutral energy sources.^[12]

Of course, hydrogen infrastructure cannot be planned as an end in itself. The transition toward a hydrogen economy is interdependent with the development of the use of natural gas, the shift to new production processes in energy-intensive industries, and the establishment of new hydrogen production centers and trade routes.^[13] The increased use of hydrogen also influences the expansion of renewable electricity production capacities and the electricity grid. When, where, and how specific changes will take place are not immediately apparent and subject to many decisions: economic and political stakeholders make decisions based on their perceived environment, shaping the transformation and thereby influencing the decisions of others. This interplay between the system and stakeholder perspectives, which can be described as a chicken-and-egg problem, highlights the necessity for a comprehensive analysis of the hydrogen transition.

The project TransHyDE-Sys, funded by the German Federal Ministry of Education and Research, addresses open questions based on energy system analysis and other hydrogen network development tools. It also follows a dual approach by comparing a stakeholder perspective with the system's. It is part of the hydrogen flagship project TransHyDE, which aims to assess the viability of a future hydrogen infrastructure and focuses research and development on solving the related key issues.^[14] This article places TransHyDE-Sys's efforts in the context of current policy discussions and explains how energy system analysis can provide insight into unanswered questions. We aim to contribute to the recent debate on infrastructural planning and transformation at the European level and draw attention to the related systemic issues. This article gives a first insight into our approach, which incorporates the integration of hydrogen infrastructure into energy system modeling (ESM) frameworks, using

a complete toolchain for a more detailed view encompassing diverse methodologies and models. By considering the different perspectives of stakeholders, this article shall serve as a starting point to establish contact among European countries, encouraging an exchange of country-specific views to find common European solutions.

The article is structured as follows. First, an overview of the current political discussion is given (Section 2). Then, the systemic perspective on infrastructure planning is introduced: Interactions between different energy system components are highlighted, and the consequences of neglecting interrelations are pointed out (Section 3). The current method of ESM for systemic hydrogen infrastructure development is presented in the next chapter. Key capabilities necessary to answer the main questions raised in Section 2 are determined, and an overview of the current state of research is given, from which gaps and necessary further research emerge (Section 4). We point out why TransHyDE-Sys is not yet another study on hydrogen demand and supply but instead will provide additional knowledge by building up toolchains, including ESM, to help guide the transition toward a European hydrogen economy due to the project's architecture and model landscape (Section 5) and finally end with a conclusion and describe the following steps and perspective for the TransHyDE-Sys project (Section 6).

2. The Current Discussion on Hydrogen Infrastructure Planning in Europe

This section is intended to serve as an overview of the present situation regarding European hydrogen infrastructure planning. It provides a systematic overview of the infrastructure, explores financing mechanisms, examines the issue of standardization, and highlights the importance of considering the specific interests of individual nations within and beyond Europe. By enhancing our understanding of the current situation, this section aids in helping us understand the next steps that need to be taken.

2.1. Hydrogen Transport Infrastructure

Besides hydrogen procurement and production, a core element of a European hydrogen economy is an appropriate infrastructure for transporting hydrogen from production sites or import terminals to consumption centers. This infrastructure may include pipeline networks, storage facilities, and other means of transport such as road and rail. It could be designed solely for hydrogen transportation or include hydrogen derivatives, for example, ammonia (NH₃).^[15]

The European hydrogen backbone (EHB),^[9] based on a pan-European initiative of gas transmission system operators (G-TSO), represents a conceptualization of a hydrogen pipeline network in 28 European countries. The EHB is expected to cover about 53 000 km by 2040, much of which will be built by repurposing existing natural gas infrastructure. The cost is estimated at 80–143 billion euros. The EHB describes the G-TSO's vision and displays its commitment, but its proposals are neither planning specifications nor based on energy system analyses. It does not take a systemic perspective, ignoring the implications of a

prospective hydrogen pipeline network on expanding renewable energy production capacities or the electricity grid.

At the national level, the network development plans (NDP) of each country's G-TSOs specify the new pipeline sections to be implemented. In Germany, for example, the NDP gas presents concrete plans for a possible hydrogen network for different time horizons.^[16] For 2050, the G-TSOs envisage a German hydrogen network with a length of around 13 300 km, which, similar to the EHB, is to be built mainly by repurposing existing gas networks.

Thus, the EHB and the German NDP gas assume that the future hydrogen transport network will be built primarily by rededicating natural gas pipelines. The keyword to consider when repurposing gas pipelines is H₂ readiness, which is the ability of a natural gas pipeline to transport blended or pure hydrogen. While the maximum admixture of hydrogen to natural gas of 20 vol% is assumed for today's infrastructure and 100% by 2050,^[17,18] the transport network is expected to carry 100% hydrogen from the implementation date.^[19] The pipeline steels used are assumed to be not considered critical under current operating conditions. Despite this positive assessment, adjustments will be necessary to replace valves and equipment. However, this is still the subject of recent research.^[20,21] In this context, the G-TSOs in Germany are calling for integrated network development planning for hydrogen and methane. This is to function analogously to the already proven planning instruments of the gas and electricity NDPs.

Beyond a prospective hydrogen pipeline network's scale and scope, discussions about its operation and implementation are ongoing. In the case of a hydrogen network primarily created by repurposing natural gas pipelines, current gas network operators can make a good case to also be responsible for operating a future hydrogen network due to their monitoring, quality assurance, and maintenance expertise. However, in the course of "horizontal unbundling," the EU stipulates that gas network operators should not be hydrogen network operators.^[11] This decision was met with resistance from the gas network operators.^[22]

Stakeholders also see the complicated planning and approval procedures as a significant obstacle to the rapid development of a hydrogen network. The EU currently discusses an overarching gas regulation for all member states. The EU Commission presented a legislative package for hydrogen and decarbonized gas markets at the end of 2021.^[11] EU parliament and council adopted positions in early 2023, respectively, and the matter has now been put forward in a formal trialogue between the three legislative bodies as of April 2023.^[23]

2.2. Financing Hydrogen Infrastructure

While a hydrogen transport infrastructure's technical feasibility and operation comprise one part of the discussion on hydrogen infrastructure planning, another revolves around financial and regulatory questions and standardization and certification. Significant investments are required to establish a hydrogen economy. These are accompanied by a corresponding amortization risk, especially in the initial phase. Here, it is essential to create confidence through reliable framework conditions and to offer possibilities to minimize the risk. One such possibility, proposed by the German Energy Agency (dena) in August 2022,

is the idea of an amortization account to spread the risk among various players: For a new hydrogen pipeline project (newly built or repurposed), operators would enter into a contract with the federal government. They would keep track of their discounted investments and income in an independent account, and a state fund would compensate for notable differences at the end of the depreciation period.^[24]

Carbon contracts for difference (CCfDs), transformation funds that compensate for cost differences between new, more expensive technologies and established less costly technologies, are much discussed in German politics. CCfDs could be applied to hydrogen production, transport, and utilization technologies. Funding via CCfDs will only remain in place if there is a difference in the production costs between low-emission and conventional products. Another example to finance the transition toward a hydrogen economy is the two-sided auction model of the H2Global foundation. Tenders are to be held for production and demand contracts. The foundation would then buy green hydrogen (and its derivatives) for the lowest possible price and sell it for the highest possible price in a separate demand tender, effectively making a loss, supplying the difference between the hydrogen purchase and selling expenses from state-supplied funds.

2.3. Standardization and Certification for Renewable Hydrogen

The key to any claims of sustainability for a hydrogen economy is the setting of standards for what can be called green hydrogen. For actors with detailed decarbonization roadmaps, knowledge of available hydrogen by production route is essential for ensuring that these roadmaps are credible and that hydrogen will offer real-world emissions reductions. Available amounts and emissions reductions will depend on standards set by governments and international agencies. International companies aim for standards that allow their activities to be considered sustainable in all countries rather than a patchwork of regulations.

With the release of the Delegated Act on criteria for electricity for the production of renewable fuels of nonbiological origin and the Delegated Act for assessing greenhouse gas emissions savings from renewable fuels,^[25,26] the European Commission has set standards for the production of renewable hydrogen via electrolysis.^[27] Although the Delegated Act only applies to the transport sector, an extension to other sectors seems likely.^[28] Branches that already produce hydrogen as a byproduct of different processes, such as the chemical industry, question whether standards may be technology based, limiting sustainable hydrogen to electrolysis and pre-empting such byproduct sources from being considered renewable regardless of their carbon footprint.^[29]

2.4. The National and Global Perspective

In addition to the ongoing European discussions on implementing a hydrogen infrastructure, it is crucial to consider the diverse global perspectives. Each country in Europe and regions outside Europe may have its own goals and views regarding its role in the future global hydrogen economy, which must be considered. While ESM, as discussed in the following sections, typically aims to finding an optimal solution for the area under investigation, in

this case, Europe, its results may need to align with the national plans or strategies of countries outside the modeled scope.

For instance, Japan took an early initiative by establishing a hydrogen strategy in 2017, demonstrating its commitment to a hydrogen economy.^[30] Similarly, the United States has recently passed the Inflation Reduction Act, which includes incentives for producing green hydrogen.^[31] These examples illustrate the proactive measures being taken by different countries to support their hydrogen strategies.

Considering the increasing global demand for environmentally friendly products and the ongoing decarbonization efforts, the timely realization of a European hydrogen infrastructure is crucial for maintaining the competitiveness and long-term resilience of the European industry. It is imperative to navigate these global perspectives and dynamics while ensuring the successful development and integration of the European hydrogen infrastructure. In conclusion, our analysis underscores the current situation's complex nature, revealing many factors at play. A systemic perspective becomes indispensable to navigate this complexity and progress toward the next steps in research.

The upcoming section expands on this thought by presenting the necessity of adopting such an approach, providing a robust foundation for further scientific inquiry and enabling a comprehensive understanding of the intricate dynamics involved.

3. The Need for an Integrated Systemic Approach in Infrastructure Planning

As shown, the discussion on hydrogen infrastructure planning comprises many different aspects. In this complex landscape, individual actors make decisions from their perspectives without full regard for the interactions with other parts of the energy system. Creating path dependencies and transport infrastructure requirements, this risks a suboptimal outcome when total system costs are considered.^[32]

Therefore, an integrated systemic perspective is crucial to ensure a holistic understanding and informed decision-making process in hydrogen infrastructure planning. Here, we understand the systemic perspective as considering all elements of the energy system when assessing the value of a particular technology option. This includes the entire value chain of the relevant energy vector and interactions with other energy vectors in the current state and future development.

For example, the decision for a new natural gas power plant to provide stability of electricity supply should consider the current natural gas and electricity transport infrastructure, the potential connection to a hydrogen transport grid that would allow for a fuel switch, as well as prospective expansions of the electricity grid or of renewable electricity generation sources that could make the natural gas power plant obsolete.

This example demonstrates the relevance of transport infrastructures when assessing technology options from a systemic perspective. **Figure 1** provides a stylized illustration of the energy system, showing the elements of the energy system that are considered most relevant for the systemic perspective. For the three energy vectors, electricity, hydrogen, and natural gas, generation, storage, and consumption infrastructures are connected by their respective transport infrastructures.

Another essential property of the energy system shown in Figure 1 is that it is not static. Transition processes are taking place, leading to a dynamic environment. Individual stakeholders' decisions or system needs can drive these transition processes. Many of the transition processes involve the uptake of hydrogen and the associated interactions with other energy vectors.

The industrial sector is expected to be the most prominent hydrogen-consuming sector in many hydrogen roadmaps.^[33,34] Therefore, the perspective of these individual stakeholders offers relevant information about how they picture the transformation process toward a hydrogen economy. While decarbonization options differ between branches of industry, some branches have begun to settle on hydrogen as a viable technological solution. In some cases, hydrogen is a necessary component of vital chemical reactions within industrial processes, such as the synthesis of ammonia via the Haber-Bosch process,^[32] or it is seen as the primary pathway to decarbonize an otherwise emission-heavy process, such as in primary steel production. For other branches, such as the glass industry, the relative simplicity of switching from natural gas to hydrogen to provide process heat is seen as a significant benefit when compared to the direct electrification of industrial-scale glass melting furnaces.^[35]

Two fundamental questions dominate the discussion of industrial actors: How much hydrogen will be available, and how much will it cost? The combined effects of multiple individual decisions by different stakeholders in and outside the hydrogen value chain influence the answers to these questions. To make an investment decision for new processes that use hydrogen to decarbonize production, industrial actors require information about the amounts of decarbonized hydrogen that can be expected to be available at different points in time in the future. The operators of any industrial process that runs continuously throughout the year must ensure sufficient production amounts and constant temporal availability before a transition to hydrogen can be considered. Just as network operators hesitate to construct transport infrastructure in an area without indications of profitability, industrial consumers hesitate to invest in hydrogen-based production processes without signs of secure supply at competitive prices. Regional partnerships and pilot projects are the first step toward finding general solutions.

Differentiating installed production capacity and expected production by geographic origin also offers essential information for industrial actors. The price of green hydrogen will likely vary based on production location, as the different sources of renewable electricity available at various locations influence the total load hours available for electrolysis and production costs.^[36] For industrial actors in Germany, a country expected to be a significant importer of green hydrogen, the location of origin will further impact the price they must pay based on how far it must be transported.^[37] To assess the availability of green hydrogen, stakeholders must consider the development of the global hydrogen market and its feedback on regional production and import capacities.

Once adequate import capacities are established, the distribution of imported hydrogen is the next primary concern for individual actors. The extent and expected completion date of hydrogen pipeline networks may decide the future of individual

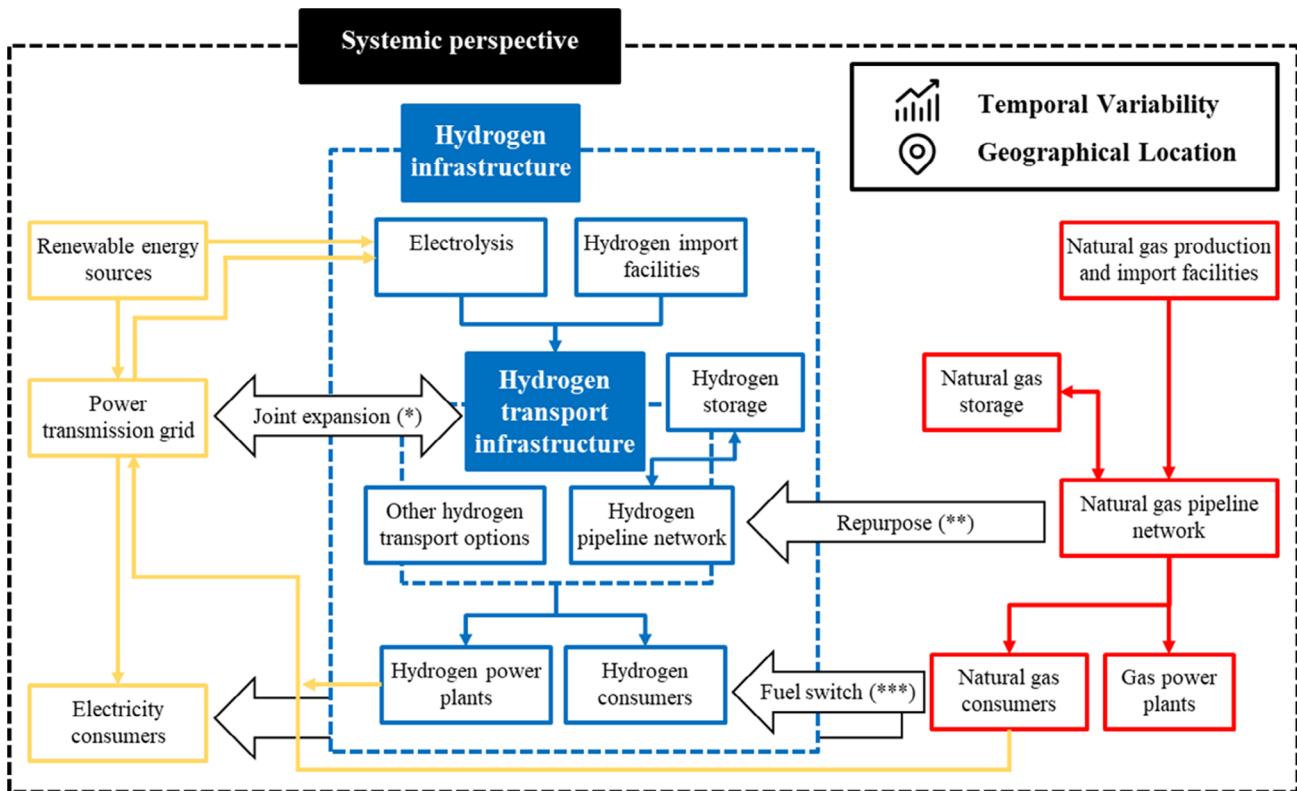


Figure 1. Illustration of the hydrogen infrastructure and hydrogen transport infrastructure as parts of an evolving energy system. The energy vectors electricity (yellow), hydrogen (blue), and natural gas (red) establish interactions between the different stakeholders. The transformative processes are subject to conditions: (*) In a cost-optimal solution of the electricity grid and hydrogen transport infrastructure expansion, mutual redundancies are considered. (**) Natural gas pipelines and storage sites can only be repurposed when they are technically suited for use with hydrogen and are no longer required from a consumption point of view. (****) Natural gas consumers must change their production processes or heating systems in parallel to making a fuel switch.

industrial sites. Closely tied to a hydrogen network's geographic expansion is the question of which existing natural gas pipelines are repurposed to transport hydrogen. For those sites that will be forced to wait for the connection to (inter-)national networks, questions regarding government support for on-site hydrogen generation infrastructure, electricity prices for own hydrogen production, and potential guarantee of origin certification schemes are emerging.

As pictured by individual stakeholders, the transition strongly depends on the systemic perspective but might not coincide with an optimal system design. The stakeholder perspective cannot consider feedback effects on the entire energy system. This is especially important as the hydrogen infrastructure is predicted to be strongly interconnected with other energy system parts.^[38] On the other hand, an exclusively systemic view can only sometimes meet the needs of individual stakeholders. For this reason, the planning of hydrogen infrastructure needs to be executed in an integrated manner, reflecting both perspectives, to achieve future viability, avoid stranded investments, and ensure a close-to-minimal total systemic cost. This kind of planning is not trivial. As the illustration of the systemic perspective in Figure 1 shows, several interrelated factors impact hydrogen infrastructure development.

The location and generation of renewable energy sources strongly influence infrastructure planning. Integrating large amounts of renewable energy into the electricity system is challenging due to time variability in renewable electricity generation and regional differences in renewable energy generation potential and electricity demand.^[39,40]

Besides large-scale deployment of battery storages, electrolysis can be one technology, among others, to additionally balance the time variability of electricity generation and demand. By consuming electricity when high amount of renewable electricity is available, these technologies increase the utilization of renewable energy sources. Since hydrogen production from renewable sources is volatile, hydrogen storage facilities must always be available to meet demand. While the prospective hydrogen transmission grid can act as a storage,^[41] additional hydrogen storage would be needed to balance seasonal differences.^[42] The location and size of such hydrogen storage would have to be subject to optimization and contingency analysis to ensure the safety of hydrogen supply in marginal situations.^[43]

Electrolysis can also ease the regional imbalance between renewable electricity generation and electricity demand. Suppose an enormous surplus of renewable electricity is generated in a particular area but cannot be consumed on-site, in that

case, it must be transported off-site via the power transmission grid. However, transmission capacity is limited, and capacity expansion projects are time-consuming and expensive. Alternatively, surplus electricity can be used on-site for hydrogen generation. Hydrogen pipeline networks offer potentially lower transportation costs for energy than electricity transmission lines,^[44] which incentivizes the production of hydrogen close to centers of renewable electricity generation on the systemic level.

At the level of transport networks, the simultaneous consideration of natural gas and hydrogen is imperative. In particular, the repurposing of natural gas pipelines requires intensive planning. Repurposing a pipeline from natural gas to hydrogen means that connected facilities—both for consumption and for further distribution—can no longer access the transportation capacity at a specified time. The currently ongoing conversion from L-gas (low calorific gas from the Netherlands, etc.) to H-gas (high calorific gas) in the Netherlands and Northwestern Germany makes challenges related to repurposing pipeline infrastructure apparent: Each device connected to the grid needs to be checked for compatibility and possibly has to be exchanged.^[45] Newly constructed pipelines face significant challenges: long planning and permitting procedures and high investment costs. Only a small number of hydrogen consumers will connect to the newly established pipelines initially, making this a risky investment without supporting policy measures.

Prospective hydrogen consumers, on the other hand, face the complementary problem: Before a first hydrogen pipeline is established, they cannot transform to renewable hydrogen unless local hydrogen production or transitory road transport of hydrogen is established—at possibly higher total systemic cost. Acceptable hydrogen purities also have to be coordinated.

Therefore, the underlying challenge can be seen as a three-sided chicken and egg problem: Hydrogen producers, infrastructure operators, and consumers can only operate a fully scaled business model if the other two are already in place, so a coordinated approach is required for joint hydrogen uptake. As the hydrogen uptake also impacts the remainder of the energy system and repercussions might occur, a systemic perspective on hydrogen infrastructure planning can help find feasible transformation paths with minimal systemic cost. Finally, a combination of the stakeholder's perspective and the systemic view can allocate the necessary resources so that the highest added value is achieved.

In conclusion, neither the stakeholder nor the systemic perspectives can provide satisfactory assessments of future technology pathways. Recognizing the inherent significance of a systemic perspective in infrastructure planning establishes a foundation for the forthcoming State-of-the-Art section. Therein, an in-depth exploration of ESM is performed, analyzing the current energy system models' capabilities and weaknesses and identifying research gaps.

4. ESM as a Method for Hydrogen Infrastructure Planning

Based on the conclusion that a systemic perspective is needed, we perform a literature review of existing energy system models

and their functionalities in this section. After collecting recent publications that analyze hydrogen infrastructure development using ESM, we identify the gaps that need to be addressed and establish a comprehensive understanding of the role of hydrogen in the energy system. Closing these gaps with a comprehensive energy system model will be important in the process of the TransHyDE-Sys project.

Energy system analysis is the method of choice in TransHyDE-Sys to analyze the transition toward a hydrogen economy. Energy system models provide a mathematical formulation to describe the balance and flow of energy vectors, accounting for production, conversion, and consumption.^[46,47] This allows formalizing the interactions between the energy vectors electricity, natural gas, and hydrogen over a geographical region such as Europe. By adding data about technology costs and primary resources, a market for producing and using energy carriers can be simulated. Assumptions on future developments of technology costs and the economic environment enable scenario-based simulations of possible evolutions of the energy system, including capacity expansions and dispatch of production and conversion facilities.

Key to an accurate description of the transition toward a hydrogen economy is the representation of electrical, natural gas, and hydrogen transport infrastructure. These are either directly incorporated into the energy system model or separate models linked to the energy system model—that is, data about demand and production is transferred from the energy system model to the infrastructure model. In contrast, data about transportation capacity is fed back.^[10,48] Just like the energy system, the modeled infrastructure undergoes cost-optimized capacity expansion or, in the case of the natural gas grid, pipeline repurposing for use with hydrogen.

As diverse as the research questions surrounding the development of a hydrogen economy are, so are their intersections with the modeling process. For some questions, the output of the energy system model takes the form of a possible answer. For example, the cost of hydrogen at a specific industrial site and year could be extracted from the results, giving a possible solution to the question, "How much hydrogen is available in a given year, and how much does it cost?". Their respective answer is required for other questions as input to the model. For example, comparing model outcomes for different policy assumptions allows assessing the impact of political decisions. Subsidy schemes, possible delays in regulation and permitting procedures, and market design changes will all affect the model outcome. This allows the evaluation of political decisions concerning their impact on the prospective hydrogen economy ahead of time.

An energy system model should fulfill specific criteria to accurately capture technological and market dynamics. In particular, high temporal and geographical resolutions are vital.^[40,48] They act as a basis for many other desired capabilities. Temporal resolution is required to describe the intermittency of renewable energy sources, the dispatch of flexibility options in the electricity grid—including power-to-gas plants—and the impact of peak demand on the viability of hydrogen-fired power plants. On the other hand, high geographic resolution makes it possible to study the interactions between potential and expansion of renewable energy sources, hydrogen demand and production centers, power-to-gas plants and hydrogen infrastructure, and

electricity infrastructure. In addition, the model should provide an accurate representation of the world outside the system boundaries—including potential and costs for hydrogen and natural gas imports.

Despite the sizable number of criteria, many energy systems, gas grids, and power system models exist that model energy systems with great detail. In the past two decades, the challenges of fully decarbonized energy systems have received considerable attention.^[39,40] This has prompted the development of numerous energy system models capable of capturing the fluctuating behavior of renewable energy sources, including flexibility options such as flexible hydrogen production.^[46] Among them are REMix,^[47] the MARKAL/TIMES family,^[49] REMod,^[50] OSeMOSYS,^[51] ENERTILE,^[52] and ISAaR.^[53]

Similarly, new challenges to the electricity grids due to higher peak loads and intermittency of renewable sources have been met with recent developments on the electricity grid modeling side.^[54,55] Models for the infrastructure of gaseous energy carriers have also experienced improvements, focusing on integrating gas grids and flexible electricity production^[56] or on the interactions between the existing natural gas grid and nascent hydrogen infrastructure.^[57]

A literature review was performed to understand the recent developments in ESM to analyze future hydrogen infrastructure. Publications of interest were included from various sources. First, recent reviews on ESM were screened for models that include the hydrogen sector.^[46,58,59] Second, energy system models from older reviews^[60] that describe flexibility options in the electricity sector with sufficient detail were checked individually for recent extensions to include the hydrogen sector. This strategy was chosen because only a few models covered in reviews dating before 2020 consider hydrogen as an energy carrier for uses beyond seasonal storage. However, capturing flexibility in the electricity market is essential for adequately representing the interaction between hydrogen and electricity

production.^[58,61] Third, a Scopus search with the combined search terms “hydrogen,” “infrastructure,” and “energy system model” was carried out. In all three cases, only publications that describe an expansion of the hydrogen infrastructure and a model of the electricity sector were considered. A list of the included publications is shown in Table 1.

Most of these publications investigate the role of hydrogen as an additional energy carrier beyond electricity and natural gas until 2045 or 2050 in an energy system increasingly dominated by renewable energy sources. Among these publications, there are differences in how the energy system model is constructed and how the particularities of hydrogen are treated. To capture the spread of approaches, papers were classified according to seven binary criteria focusing on the depiction of the transformation process and on factors that affect the demand for hydrogen infrastructure, see Table 2.

First, to gain an understanding of the process of the transformation, it is desirable that the model takes into account the current state of the energy system in a brownfield approach and models multiple base years in the course toward the target year, in each consecutive year building on the capacity that was added in the preceding years. In this case, the model is marked with a check mark (✓). If a model neglects the current state of the energy system and starts from a greenfield or models only a target year or both, it is marked with a cross (✗).

Second, while all models describe the expansion of hydrogen infrastructure, it is also relevant to consider the transportation of electrical power. Hydrogen pipeline systems could strongly affect the required electrical grid capacity. Therefore, model-endogenous expansion of electricity grid transport capacities between model regions is desirable and is marked with a ✓.

The third significant competing infrastructure is that of natural gas. The increasing use of hydrogen and shrinking demand for natural gas open up the possibility of repurposing natural gas pipelines for hydrogen transport. This primarily contributes to a

Table 1. List of energy system model publications considered for analysis.

Author and [year]	Model name/family [if given]	Case study	Number of nodes in case study
Han et al. 2019 ^[68]	—	South Korea	15
He et al. 2021 ^[69]	—	US Northeast	7
Frischmuth et al. 2022 ^[10]	SCOPE SD/IMAGINE ^{a)}	Europe	32
Arduin et al. 2022 ^[79]	Artelys crystal super grid	Europe	34
Martínez-Gordón et al. 2020 ^[66]	IESA-NS	North Sea region	7 + 5 ^{b)}
Evangelopoulou et al. 2019 ^[64]	PRIMES ESM	Europe	32
Gils et al. 2020 ^[38]	REMix	Germany and neighboring countries	10 + 12 ^{c)}
Bødal et al. 2020 ^[70]	—	Texas	13
Husarek et al. 2021 ^[67]	Energy System Development Plan	Germany and neighboring countries	47
Lux et al. 2022 ^[52]	Enertile	Europe	29
Victoria et al. 2022 ^[65]	PyPSA-Eur-Sec	Europe	37
Schaffert et al. 2022 ^[63]	REMix + MuGriFlex ^{d)}	Germany	10
Kigle et al. 2022 ^[53]	ISAaR	Europe	30

^{a)}Scope SD provides upstream energy system analysis, including hydrogen demand and electrolysis capacities, while IMAGINE computes hydrogen transport infrastructure;

^{b)}Including seven onshore regions and five offshore regions; ^{c)}Ten regions within Germany, where hydrogen transport is modeled, as well as 13 surrounding countries between which hydrogen transport is not considered; ^{d)}REMix is used for energy system analysis, MuGriFlex for analysis of plant operator perspective.

Table 2. Results of the model analysis. The described model was tested for five criteria for each publication (see main text). If the model fulfills a criterion, it is marked with a ✓; otherwise, with a ✗.

Author and [year]	Model of transformation	Electricity transport capacity expansion	Repurposing of natural gas pipelines	Geographical potential of salt caverns	Consideration of hydrogen imports	Joint consideration of transport infrastructure cost	Regional resolution is better than country level
Han et al. 2019 ^[68]	✗	✓	✗	✗	✗	✗	✓
He et al. 2021 ^[69]	✗	✓	✗	✗	✗	✗	✓
Frischmuth et al. 2022 ^[10]	✓	✗	✓	✓	✓	✗	✗
Arduin et al. 2022 ^[79]	✗	✓	✓	✗	✗	✗	✗
Martínez-Gordón et al. 2020 ^[66]	✗	✓	✗	✗	✓ ^{a)}	✗	✗
Evangelopoulou et al. 2019 ^[64]	✓	✓	✗	✗	✗	✗	✗
Gils et al. 2020 ^[38]	✓	✓	✗	✓	✓	✓	✓
Bødal et al. 2020 ^[70]	✗	✓	✗	✗	✗	✗	✓
Husarek et al. 2021 ^[67]	✗	✗	✗	✗	✓	✗	✓
Lux et al. 2022 ^[52]	✓	✓	✗ ^{b)}	✗	✓	✗	✓
Victoria et al. 2022 ^[65]	✓	✓	✗	✓	✗	✗	✓
Schaffert et al. 2022 ^[63]	✓	✓	✗	✓	✓	✓	✗
Kigle et al. 2022 ^[53]	✓	✓	✗	✓	✗	✗	✗

^{a)}In the sensitivity analysis. ^{b)}Analyzed afterward.

prospective hydrogen grid; see Section 2.1. However, not all models consider this option. Here, a ✓ is awarded to models that include this option.

Fourth, hydrogen has the characteristic that it can be used as seasonal energy storage. However, large-scale hydrogen storage is currently state of the art only in certain geological formations, namely, underground salt caverns, whose distribution depends strongly on the region.^[62] In Germany, for example, salt caverns are predominantly situated in the north, while none are in the south. This regional distribution of hydrogen storage potential influences the demand for hydrogen infrastructure and should, therefore, be included in the model (✓).

Fifth, hydrogen imports are relevant for arranging hydrogen infrastructure as the import location acts as another large-scale production site. When hydrogen imports outside the modeled region are considered, the model is marked with a ✓.

The sixth criterion considers the interactions between the different energy vectors: Beyond the representation of crucial elements in the individual energy vector's value chains, as tested in criteria two through five, it's essential for the systemic perspective that the costs of energy transport infrastructures are considered in the planning of all other elements of the energy system. Therefore, models are marked with a ✓ if, for each of the three

energy vectors, electricity, natural gas, and hydrogen, the model considers the cost of its respective transport infrastructure in expanding other transport infrastructures and optimizing the generation and conversion capacities. Despite being a fossil fuel with a perspective for phase out, natural gas is included here explicitly as well, as some publications even see further expansion of natural gas transport infrastructure in the coming years, most notably the most recent NDP of the German gas transmission operators.^[16]

Finally, the last criterion considers the spatial resolution of the model. A low spatial resolution introduces two crucial inaccuracies in the cost assessment of technology options from the systemic perspective. For one, costs for transport infrastructure necessities within model regions are underestimated: By assuming full connectivity within a model region or node, no transport infrastructure must be built to distribute energy vectors within a model region. This can lead to significant distortions, for example, when a production center on one end of the model region and a demand center on the other are connected with no cost. In contrast, sufficient transport infrastructure would have to be built in reality. The other inaccuracy coming with coarse spatial resolution is the representation of transport links between model regions. Typically, costs for transport infrastructures between

nodes are calculated from the distance of the centroids of the model regions. However, the geographical center often deviates from the centers of demand and production. For this criterion, models with spatial resolution better than country level are marked with a checkmark (✓). While this level of spatial resolution does not completely alleviate the problems discussed earlier, it represents a step in the correct direction.

The results of the model comparison are shown in Table 2. Each model satisfies at least one of the criteria. Around half of the boxes are ticked (✓), though some requirements differ.

Most of the publications follow the more involved but informative approach of modeling the whole transformation under consideration of the current state-of-the-energy system. Few models favor a greenfield over a brownfield approach or model only the target year. For those approaches that model the transformation with multiple base years, a distinction exists between short-sighted (myopic) and joint optimization. In the first case, each base year is optimized individually based on the capacity additions in the year before.^[38,63] In the second case, the optimization occurs for all base years simultaneously.^[10,52,64] This second approach can lead to lower-cost pathways, as future effects of investments are immediately factored in. However, it is also more computationally intensive and possibly less realistic. While individual stakeholders plan amortization over a long time, they cannot know the state of the economy 10 or 20 years from the investment decision.

All but one of the studied models allow for expanding electricity transport capacities between model regions. An explanation for this conclusive result could be that hydrogen infrastructure models are based on older energy system models, traditionally focused on the electricity sector, to which hydrogen was added as a new energy vector in a later step. Therefore, the interaction between hydrogen and electricity infrastructure on an interregional level can be considered as implemented in the ESM. However, detailed electricity grid simulations are outside the models' scope. In particular, the analysis of intraregional interactions between the electricity grid and the nascent hydrogen pipeline network is yet to be combined with an overarching energy-system analysis.

A contrasting result arises from the natural gas infrastructure repurposing criterion, included in only 3 out of 12 models. This may be caused by the difficulty of modeling the interaction between demand sectors and infrastructure: Typically, regional demand projections for natural gas are given as exogenous inputs, which must be satisfied by the model. In most demand projections, a residual amount of natural gas demand continues to stay present, no matter the speed of transformation. This means that a connection to the natural gas grid remains necessary. When pipelines are modeled realistically, that is, on a single pipeline level, this small residual demand will block the repurposing from natural gas to hydrogen. From the systemic point of view, this represents a suboptimal solution: The total systemic cost might be lower if the last consumers were forced to switch from natural gas to hydrogen. A possible method to include the option for repurposing is to relax the objective of the energy system model from strict demand satisfaction to optional demand satisfaction with penalties: Instead of the boundary condition that demand must always be satisfied, solutions are allowed in

which demand is not fulfilled, but a high penalty is added to the system cost for each unit of unsatisfied demand.

Similarly to repurposing natural gas infrastructure, only a few models consider the geographical dependence of hydrogen storage potential. Between the models, varying assumptions are made for the large-scale underground storage potential, in one case based on a previous potential analysis and^[65] in other cases based on currently available natural gas storage potential.^[10,38,63] As a result, the importance and geographical distribution of hydrogen storage vary between the model results. While this might be a data problem, it could also be caused by a need for higher geographical resolution. This calls for an improvement in the treatment of storage in hydrogen infrastructure modeling.

Hydrogen imports from outside the modeled region are considered in roughly half the models. It is observed to be a very sensitive parameter: When import prices are modeled based on a flat potential curve (i.e., the cost of hydrogen imports is fixed and independent of the import quantity), there is a price level above which hydrogen imports are almost not realized, whereas below this level imports overtake local production as the favorable purchase option and account for the majority of hydrogen supply.^[52,66] This can skew model results. More justifiable data, such as potential price curves for imports, are needed for more detailed approaches. One option is to consider different import regions with individual export potentials.^[67] More studies are required on international hydrogen markets to obtain a clearer picture of the impact of hydrogen imports on regional hydrogen infrastructure.

About the joint consideration of transport infrastructure costs, it is noteworthy that only two of the included studies fully fulfill this criterion. While most include hydrogen and electricity transport infrastructure, many lack the explicit description of natural gas pipelines but instead assume unlimited transport capacity, thereby neglecting maintenance and decommissioning costs and possibly intermediate expansions of the natural gas grid. Similarly, some publications think of unlimited hydrogen transport infrastructure capacities. The two publications in which feedback between transport infrastructure development and other energy system elements is considered feature a high technological resolution of flexibility options. However, the geographical scope is limited to Germany. We conclude that considering energy transport infrastructure costs in planning the energy system is yet to be a research focus. Additions to model capabilities help elucidate the effects of interacting energy transport infrastructures and lead to a more accurate assessment of the different technology options.

Finally, while some models work with a spatial resolution better than the country level, those that do only consider a limited geographical scope: Four concentrate on Germany,^[38,52,65,67] while the others study Korea, the US Northeast, and Texas, respectively.^[68–70] In addition, the spatial resolution of these models is often not much better than the country level: The highest observed resolution in the included models is NUTS-2,^[67] while the others are on the level NUTS-1 or comparable. Higher spatial resolutions are needed to accurately represent the transport infrastructure requirements on the regional level, and limiting the geographical scope to a single country or

subcountry model region neglects interactions with other countries' energy systems.

In conclusion, several models investigate the development of a hydrogen infrastructure using energy system analysis in a systemic approach—considering other energy vectors such as electricity and natural gas and interactions between the different energy infrastructures. For each of the five criteria chosen to assess the suitability of the models, at least one model fulfills it. However, only 2 of the 13 included studies analyze the interaction between the expanding hydrogen infrastructure and the existing natural gas infrastructure, indicating a less explored question in current research. Further, while four studies consider the geographical potential of large-scale hydrogen storage and six studies consider the possibility of hydrogen imports, assumptions for storage potential and hydrogen imports vary widely between the studies. Accordingly, there is a wide range of results for storage use and location and for the importance of hydrogen imports. This shows that while models can capture these hydrogen-specific processes, more care must be taken to determine and coordinate input data and respective assumptions.

Two significant gaps in current research have been identified in criteria six and seven: Only a few models consider the costs of all relevant transport infrastructures in the capacity expansion planning process, and those that do are limited in geographical scope. Meanwhile, the spatial resolution of most models is relatively coarse, neglecting essential effects in the computation of transport infrastructure costs, which could distort the results. In addition, some models' geographical scope is limited, looking at only a region or a single country.

Both research gaps are also addressed as potential future research in the considered studies. In particular, in one of the two publications that consider the feedback between all energy transport infrastructures and the rest of the energy system (marked with a checkmark in criterion six), a further investigation of the interactions between hydrogen and natural gas infrastructure and additional flexibility options in the European context is called for.^[38] Meanwhile, the study with the highest spatial resolution found in the literature (NUTS-2) considers an even higher spatial resolution beneficial for identifying natural gas pipeline repurposing and hydrogen pipeline corridors.^[67]

For an accurate systemic assessment of hydrogen technologies in the European context, a spatially highly resolved modeling approach capable of representing all relevant interactions in the energy system is needed, covering Europe as a whole in geographical scope. This is yet to be accomplished. This would further improve the accuracy of the results with respect to different input parameters and enable a better understanding of the interactions among different parts of the energy system and its infrastructure.

Notably, the forthcoming TransHyDE-Sys project seeks to address these gaps and inconsistencies. It aims to integrate and refine existing models, encompassing comprehensive representations of the hydrogen infrastructure's interaction with other energy sectors and infrastructures. TransHyDE-Sys strives to provide a holistic and accurate understanding of the energy system's transformation and its implications for hydrogen infrastructure planning by adopting a meticulous approach to input data coordination and assumption alignment.

5. How Will TransHyDE-Sys Provide Answers?

Embedded within the larger TransHyDE project, one of the three German Hydrogen Flagship Projects, TransHyDE-Sys aims to address the challenges pointed out in the previous sections. It aims to provide an integrated model landscape to accompany the development of a European hydrogen infrastructure, describing the temporal and spatial evolution of production, transport, storage, and demand of hydrogen, electricity, and natural gas in great detail.

The ramp-up of a hydrogen economy is a dynamic process subject to many uncertainties that must be monitored continuously. Therefore, a flexible model landscape that can be adapted to a highly dynamic environment is essential to provide guidance. Existing energy system models from different partners will be interleaved and coupled with other types of models and tools, like hydraulic pipe simulation tools, to reflect the interactions between the different energy infrastructures. Some of the already introduced models in the last section, ENERTILE, PypsaSec, and ISAAr, will be part of the TransHyDE-Sys analysis.^[52,53,65]

In TransHyDE-Sys, two methodological approaches are employed to illuminate the systemic and stakeholder perspectives.

The System Perspective: One research consortium focuses on the system perspective, which has been described in the previous chapters. The gaps in the existing ESM are compensated for by connecting additional tools in so-called toolchains. Similar to the idea by Cao et al.^[71] ESMs are combined with grid simulation tools and linked via a shared database. Among others, additional tools involved are FORECAST,^[72] IEEOpt,^[73] pandapipes,^[74,75] and H2ProSim.^[76] An overview of a gas network toolchain is described in more detail.

The Stakeholder Perspective: Another research consortium captures the options of industrial transformation in close exchange with the affected energy-intensive industries. Embedded in a European energy system, it identifies infrastructural prerequisites for industrial change from a stakeholder perspective and identifies relevant needs for action. This perspective will be based on a comprehensive consultation with industry partners. This includes surveying expected production volumes and transformation paths for relevant industrial processes. These will then be incorporated into the modeling framework as input parameters. Finally, the multi-ESM ISAAr is combined with grid simulations and the infrastructure development model InfraInt.^[53,77,78]

Both perspectives will be combined and compared via an intensive exchange between the research consortia to generate reliable data. This is done, for example, by validating input data and assumptions through an extensive industry survey, consultation of various stakeholders, and a rigorous scenario comparison between the system and stakeholder perspective. The broad network of partners in the larger TransHyDE project is used in a normal feedback process to address issues typically outside the scope of traditional energy system analysis. Thus, all assumptions and model results are subject to a scientific review within the research consortia and a practical check by industrial stakeholders. Second, an integrated model landscape allows for the joint description of hydrogen, natural gas, and hydrogen infrastructure. In particular, the transport networks of all three energy

carriers are modeled in great spatial detail (NUTS-3), and their interactions in the transformation are fully represented. Repurposing and decommissioning of natural gas pipelines and extensions of hydrogen and electricity networks are covered. Due to the flexible model landscape, new information in an emerging field can easily be incorporated.

Finally, the dual approach contrasts the system and the stakeholder perspective. Both methods feature fully integrated model chains and build on clearly defined scenarios to compare results. Therefore, differences between local and systemic benefits regarding infrastructural decisions can be identified, and robust findings can be extracted. This process will identify obstacles and provide a deeper understanding of possible solutions for a viable transformation of the European energy infrastructure.

6. Key Observations

As shown, the infrastructural transition from fossil energy carriers to hydrogen that enables the decarbonization of the European energy system is a complex undertaking and requires a systemic analysis that covers all aspects of the energy system. This is all the more true as the transition can only be successful if it is harmonized between all European countries. This highlights the importance of a European perspective.

The conclusions drawn from the analysis of the current situation and the literature review further reinforce the significance of the TransHyDE-Sys project. The identified critical deficits in recent research, such as the limited analysis of interactions between expanding hydrogen infrastructure and existing natural gas infrastructure, the divergent assumptions and results regarding geographical potential and hydrogen import, and the necessity for careful coordination of input data and assumptions, are effectively addressed within the project.

The main points addressed in the TransHyDE-Sys Project are the following.

Integrated Model Landscape: TransHyDE-Sys aims to provide an integrated model landscape that comprehensively describes the temporal and spatial development of hydrogen, electricity, and natural gas production, transport, storage, and demand within the European hydrogen infrastructure. This approach allows for a detailed analysis of the interactions between different energy infrastructures.

System Perspective: One research consortium focuses on the system perspective, addressing gaps in existing energy system models by connecting them with other tools in toolchains. This interconnection enhances the accuracy and granularity of the models, enabling a more comprehensive understanding of large-scale energy systems.

Stakeholder Perspective: Another research consortium explores the options for industrial transformation, closely engaging with energy-intensive industries to identify infrastructural prerequisites and actionable needs from a stakeholder perspective. This perspective contributes valuable insights into the challenges and opportunities related to industrial transition.

Collaboration and Validation: The TransHyDE-Sys project emphasizes intensive cooperation between the system and stakeholder perspectives. Through a validation process involving industry surveys, stakeholder consultations, and scenario

comparisons, the project ensures robust findings and a more holistic understanding of the transformation of the European energy infrastructure.

Comprehensive Representation: The integrated model landscape adopted by TransHyDE-Sys facilitates the joint description of hydrogen, natural gas, and electricity infrastructure. It includes high spatial detail for the transport networks of all three energy carriers and considers their interactions throughout the energy system transformation. This comprehensive representation encompasses the repurposing, decommissioning, and extension of infrastructure components.

Contrasting Perspectives: The dual approach of TransHyDE-Sys enables a contrasting analysis between the system and stakeholder perspectives. The project facilitates a rigorous comparison of results by utilizing fully integrated model chains and employing clearly defined scenarios. This comparative analysis aids in identifying obstacles and generating a deeper understanding of potential solutions for a sustainable and viable transformation of the European energy infrastructure.

In summary, the TransHyDE-Sys project addresses existing gaps in ESM by adopting a systemic perspective and engaging stakeholders. Through collaboration, validation, and an integrated model landscape, TransHyDE-Sys aims to provide insights, identify obstacles, and offer solutions for a successful and sustainable transformation of the European energy infrastructure.

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Conflict of Interest

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