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Cost-Efficient Planning of Hydrogen Networks Using a Sequential Brownfield Optimisation Approach

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The large-scale deployment of hydrogen in industry necessitates the strategic planning of a nationwide hydrogen infrastructure. However, most existing planning tools are inadequate for this purpose, as they either lack a sufficiently detailed implementation of repurposing natural gas infrastructure –an essential measure to minimise costs –or are computationally intractable within reasonable timeframes.

In this work, we introduce a novel sequential optimisation model designed to address these challenges. The model minimises investment costs for hydrogen networks and storage facilities while ensuring the security of natural gas supply. Investment decisions regarding the repurposing and construction of infrastructure are made at the level of individual pipelines and storage facilities, and the resulting network is subsequently subjected to flow simulations to verify its fluid-mechanical feasibility. Furthermore, the brownfield approach enables the integration of existing or planned hydrogen infrastructure.

The first step of the sequential optimisation focuses on the optimisation of the pipeline infrastructure. This is achieved using selected network usage cases that represent critical edge cases for the transportation of hydrogen and natural gas. By deciding on the repurposing of natural gas pipelines to hydrogen and the construction of new natural gas pipelines between neighbouring regions, the model identifies the most cost-efficient network capable of supplying all regions with the required amounts of natural gas and hydrogen.

Based on the resulting network, the second step of the sequential optimisation addresses the optimisation of the storage infrastructure. Analogous to the pipeline optimisation, the model can repurpose existing natural gas cavern storages for hydrogen use and construct new hydrogen cavern storages in regions with suitable geological conditions. This optimisation is performed using daily time steps over an entire year to capture storage level trajectories.

After the optimisation of pipeline and storage infrastructure, the resulting network is fluid-mechanically validated to assess its feasibility and to identify potential shortcomings arising from simplifications and linearisations in the optimisation models. By applying the approach to subsequent base years, the model enables the identification of cost-optimal expansion pathways.

The capabilities of the model are demonstrated using a case study for the German federal state of Lower Saxony. The analysis is based on publicly available data on existing pipelines and storage facilities, as well as hydrogen and natural gas supply and demand data from the research project Langfristszenarien 3. Lower Saxony features an extensive natural gas network due to its history of natural gas production and is expected to be among the first federal states connected to the German hydrogen network, owing to its favourable conditions for hydrogen production and imports. In addition, the region hosts numerous existing natural gas storages and offers substantial geological potential for the development of hydrogen cavern storages.

The complete model solves the case study within 12 hours on a standard desktop computer equipped with an Intel Core Ultra 5 processor and 16 GB of RAM. The resulting hydrogen network for Lower Saxony has a total length of 959 km, of which 51% consists of repurposed pipelines. Investment costs and network length can be significantly reduced by supplying only 99% of the hydrogen demand, thereby eliminating the need to connect regions with very low hydrogen demand. Two of the existing 22 natural gas storages are repurposed for hydrogen use, and five new cavern storages with a combined hydrogen capacity of 342 GWh are constructed.

Overall, the model is capable of identifying cost-efficient hydrogen networks for large geographic areas within short computational times. By varying supply and demand assumptions, it can be used to analyse alternative

expansion pathways, assess uncertainties regarding future hydrogen utilisation, and identify no-regret investment options for hydrogen infrastructure. However, as the model relies on supply and demand data derived from energy system models, its results are inherently dependent on the assumptions underlying the chosen scenarios.

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