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SpineOpt

Empowering the Design of Resilient & Integrated Energy Systems

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ACRONYMS

BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture & Storage
CO_2	Carbon dioxide
H_2	Hydrogen
O&G	Oil & Gas
LDES	Long-Duration Energy Storage
RES	Renewable energies
PFS	Power From Shore
SMR	Steam Methane Reforming

Future energy systems must **rely on sustainable but variable energy sources**, making flexibility crucial. This includes storage, sector coupling, demand response, and transferring energy across networks. These approaches help balance supply and demand cost-effectively. Due to uncertainties and limited computational resources, **models should focus on essential system features**.

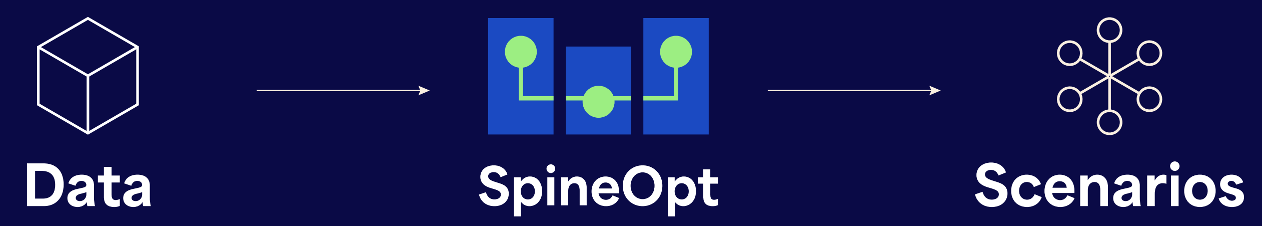
SpineOpt is designed to support flexible, purpose-driven modeling to address specific energy challenges and uncertainties.

INTRODUCTION

SPINEOPT'S TECHNICAL DESCRIPTION

SpineOpt is an **integrated energy systems optimisation tool**, striving towards adaptability for a multitude of modelling purposes. The data-driven tool structure allows for highly customisable energy system descriptions, as well as for flexible temporal and stochastic structures, without the need to alter the tool source code directly.

The **methodology** is based on mixed-integer linear programming (MILP), and SpineOpt relies on JuMP for interfacing with the different solvers. SpineOpt's versatility and user-centric design make it a valuable tool for researchers, policymakers, and energy planners aiming to model and optimise energy systems in a dynamic and uncertain environment.



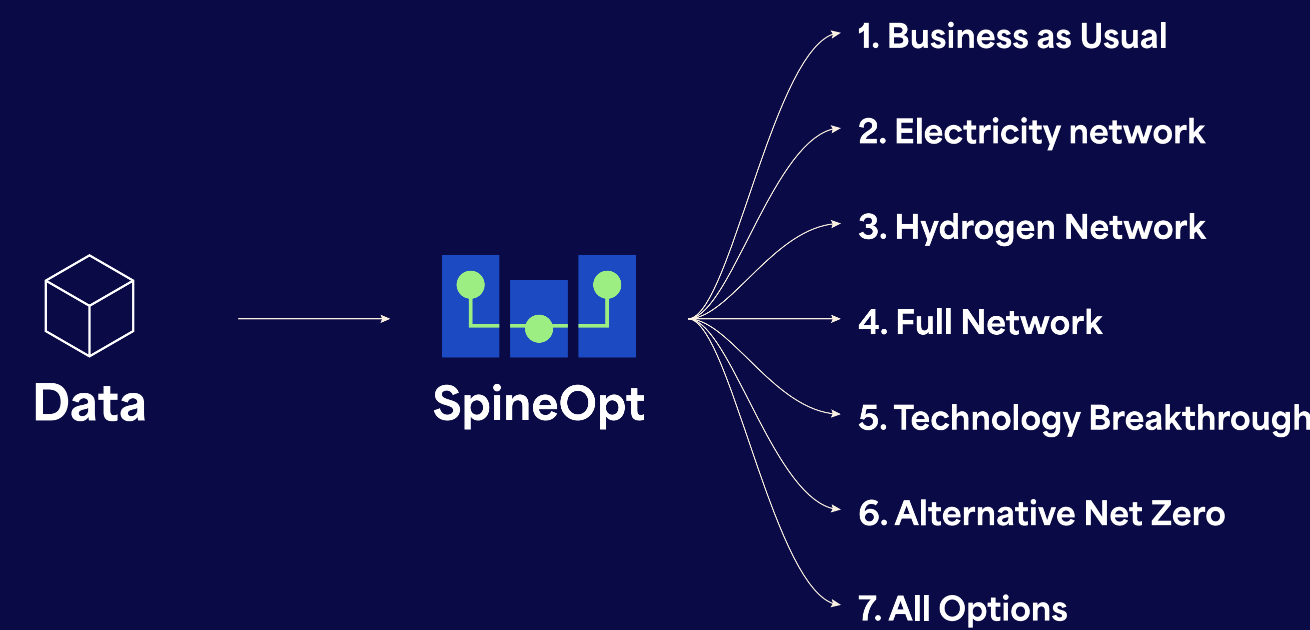
USE CASE 1. REAL-WORLD APPLICATIONS

SPINE H2-IRL

Hydrogen-based technologies hold significant potential for the **decarbonisation** of Ireland's future energy system, but challenges remain regarding supply security, reliability, and flexibility. There is potential to make renewable energy generation more economical, leading to increased deployment of onshore and offshore wind and solar power. This will present new grid challenges, resulting in greater variability and uncertainty, and it will necessitate **enhanced flexibility**. Potential solutions include long-term storage, flexible hydrogen-based generation technologies, and batteries. However, the **complex interdependencies** between these technologies make the system difficult to model accurately.

The Spine H2-IRL builds on previous work using an open approach to address these unresolved questions. Existing models have been refined, expanded, and new models developed, including a reliability assessment model. **The goal of Spine H2-IRL is to develop and publish open models for a comprehensive assessment of a future Irish energy system with widespread hydrogen production and consumption, alongside other net-zero solutions**.
This is complemented by analyses using these models to demonstrate their utility and provide valuable insights into the future development of Ireland's energy system. The detailed models enable investment optimisation across sectors while considering network constraints, long- and short-term storage optimisation, and operational details. Additional models offer more comprehensive flexibility and reliability assessments.

Seven future energy system scenarios are implemented and evaluated with SpineOpt, providing insights into barriers and opportunities for large-scale hydrogen deployment. The scenarios focus on a net-zero electricity system with high levels of electrification, marking a significant step towards a net-zero energy system. While non-electrical demands in the building and transport sectors are not explicitly modelled, a substantial portion of demand is captured under high electricity demand assumptions, along with the associated decarbonisation.



For more information on this use case, please visit the official website: energyreform.ie/spine-h2-irl/

SCENARIO 1

BUSINESS AS USUAL

Not bound by the net-zero target, **this scenario still relies on fossil fuels**, with carbon and fuel prices influencing investments in alternative solutions. Modest hydrogen demand will emerge in hubs around Ireland, requiring some investment in electrolysers and storage. This scenario mainly serves as a cost and emission comparison with core hydrogen scenarios.

FEATURES

CARBON PRICE

A high carbon price justifies investment in low-carbon technologies

HYDROGEN ROLE

Enough hydrogen is produced, but not used for power generation.

RENEWABLE ENERGY

29.5 GW renewables backed by natural gas and Carbon Capture Storage support.

INEFFICIENT

No **decarbonisation** of **other sectors**, as hydrogen is only used to meet low demand, and no net zero target is in place.

2,01 MTonne CO_2 emitted

3,6 B€ investment needed

SCENARIO 2

ELECTRICITY NETWORK

A net-zero compliant scenario with **limited electricity transmission expansion**, relying on 55.4 GW of RES, 26.8 GWh of grid-scale batteries, and hydrogen-fuelled dispatchable generation.
In the absence of large-scale H_2 infrastructure, modest H_2 storage and avoided emissions are achieved, but system costs are over 3× Business as Usual.

FEATURES

NET ZERO CONSTRAINT
Enforced, the system must achieve net-zero CO_2 emissions

HYDROGEN ROLE
H_2 meets low demand, H_2-fuelled electricity generation provides most of (on-demand) capacity.

LARGE-SCALE INFRASTRUCTURE
Electricity transmission investments allowed, excluding grid or H_2 infrastructure.

INEFFICIENT
H_2-based net zero system possible even in absence of large-scale H_2 infrastructure but **inefficient and expensive.**

1,16
MTonne CO_2 emitted

11,6
B€ investment needed

SCENARIO 3

HYDROGEN NETWORK

A net-zero scenario with **large-scale hydrogen infrastructure and salt cavern storage**, enabling efficient H_2 production and dispatch. RES capacity reaches 49.7 GW, with hydrogen displacing grid batteries. High hydrogen demand yields greater avoided emissions and 58% lower costs than the Electricity Network case, though still 35% above Business as Usual.

FEATURES

NET ZERO CONSTRAINT

Enforced for the power system, guiding investment decisions.

HYDROGEN ROLE

H_2 production meets high demand.
Hydrogen-fuelled electricity generation supplies key dispatchable capacity.

LARGE-SCALE INFRASTRUCTURE

Included and expanded gas and hydrogen infrastructure, enabling more efficient system operation.

PARTIALLY EFFICIENT

Good scenario only if large-scale H_2 infrastructures are available.
Otherwise, high cost to produce and stock hydrogen.

0,79
MTonne CO_2 emitted

4,9
B€ investment needed

SCENARIO 4

FULL NETWORK

Combining electricity transmission and hydrogen infrastructure, this net-zero scenario achieves further efficiency gains. With 48.7 GW RES, reduced battery needs, and salt cavern storage, system costs drop slightly below the Hydrogen Network case. High H_2demand yields significant avoided emissions and a 30% cost increase over Business as Usual.

FEATURES

CARBON PRICE

Enforced, driving investment decisions toward zero CO_2 emissions.

HYDROGEN ROLE

H_2 meets high demand, H_2-fuelled electricity generation powers dispatchable load. Net-negative emissions.

RENEWABLE ENERGY

Includes investments in transmission, large-scale H_2 infrastructure, and salt cavern storage.

POTENTIALLY EFFICIENT

More **efficient and cost-effective** if transmission expansion on key lines is facilitated.

0,79 MTonne CO_2 emitted

4,7 B€ investment needed

SCENARIO 5

TECHNOLOGY BREAKTHROUGH

Assuming lower costs and higher efficiency for hydrogen tech, this net-zero scenario **combines full network build-out with increased electrolyser and storage capacity**. RES reaches 48.9 GW, batteries drop to 0.6 GWh. Costs fall 9% below the Full Network case, narrowing the gap with Business as Usual while maintaining high avoided emissions.

FEATURES

NET ZERO CONSTRAINT

Enforced, guiding investments to achieve net-zero CO_2 emissions.

HYDROGEN ROLE

H_2 meets high demand; H_2-fuelled electricity generation supplies dispatchable load.
Result: net-negative emissions (-2.07 Mt CO_2).

LARGE-SCALE INFRASTRUCTURE

Includes investments in both electricity transmission and hydrogen infrastructure.

POTENTIALLY EFFICIENT

H_2 technology costs and **efficiency increased**.

0,79
MTonne CO_2 emitted

4,2
B€ investment needed

SCENARIO 6

ALTERNATIVE NET ZERO

A lower-cost net-zero scenario without hydrogen infrastructure, **relying on CCS, BECCS, and LDES alongside 32.8 GW of RES**. No hydrogen-fuelled power is used; low H_2 demand is met with 1 GW of electrolysers. While costs are the lowest among net-zero cases, decarbonisation beyond the power sector remains limited and dependent on uncertain technologies.

FEATURES

NET ZERO CONSTRAINT

Enforced, transmission investments allowed; no large-scale H_2 infrastructure.

HYDROGEN ROLE

Low H_2 demand met via 1 GW electrolysers, supplemented by minor battery storage (0.12 GWh).

LARGE-SCALE INFRASTRUCTURE

Fossil fuel generation (including CCS), LDES, and BECCS permitted.

PARTIALLY EFFICIENT

If alternative low carbon technologies become viable (ex. carbon capture and storage and alternative LDES 1 technologies), a **net-zero electricity system is less expensive** (but still difficult – e.g. no H_2 infrastructure available).

1,16
MTonne CO_2 emitted

4,1
B€ investment needed

SCENARIO 7

ALL OPTIONS

This net-zero scenario **combines hydrogen infrastructure with CCS, using hydrogen-fuelled gas** (mainly with CCS) and 37.9 GW of RES. Electrolyser and battery capacities rise to meet high H_2 demand and flexibility needs. Costs match the Technology Breakthrough case, while enabling deep emissions cuts across the energy system.

FEATURES

NET ZERO CONSTRAINT

Enforced, allowing both large-scale hydrogen infrastructure and CCS investments.

HYDROGEN ROLE

H_2 meets high demand; H_2-fuelled gas (mainly with CCS) and electrolyser capacity reaches 5 GW.

LARGE-SCALE INFRASTRUCTURE

Investments in H_2 production, renewables (37.9 GW), electricity transmission, and 0.95 GWh battery storage support high demand (CCS deployed for decarbonisation).

EFFICIENT

The combination of technologies delivers efficient solutions and helps achieve reduced emissions.

0,79
MTonne CO_2 emitted

4,3
B€ investment needed

	Scenario	MTonne CO_2 emitted	B€ investment needed	Conclusion
1	BUSINESS AS USUAL	2,01	3,6	INEFFICIENT
2	ELECTRICITY NETWORK	1,16	11,6	INEFFICIENT
3	HYDROGEN NETWORK	0,79	4,9	PARTIALLY EFFICIENT
4	FULL NETWORK	0,79	4,7	POTENTIALLY EFFICIENT
5	TECHNOLOGY BREAKTHROUGH	0,79	4,2	POTENTIALLY EFFICIENT
6	ALTERNATIVE NET ZERO	1,16	4,1	PARTIALLY EFFICIENT
7	ALL OPTIONS	0,79	4,3	EFFICIENT

USE CASE 2. THEORETICAL APPLICATIONS

OFFSHORE INFRASTRUCTURE

SpineOpt can be used to **model asset-specific investment optimisation,** accounting for lumpy investments and the detailed operations of multivector energy systems. These investments can span multiple years, incorporate uncertainty, and consider refurbishing options alongside regular investments and decommissioning activities.

An offshore infrastructure transition study implements such an analysis. This case study aims to **identify the least-cost option among various offshore oil and gas (O&G) platform development scenarios**.

The study includes a **high level of detail**, representing the evolution of reservoir recovery, electrical and heat-related demands, electric boilers, contingency reserves (on-platform electrical power), the transport of produced fuels to shore, power from shore, offshore wind turbine-based electricity supply with or for green hydrogen (H_2) storage and generation (electrolyser, fuel cell, and H_2 tank), and blue H_2 by steam methane reforming (SMR) and carbon capture and storage (CCS).

Five scenarios with specific transition configuration options were simulated over a 4-decade horizon, with the scheduled decommissioning of the modeled platform at the end of the third decade:

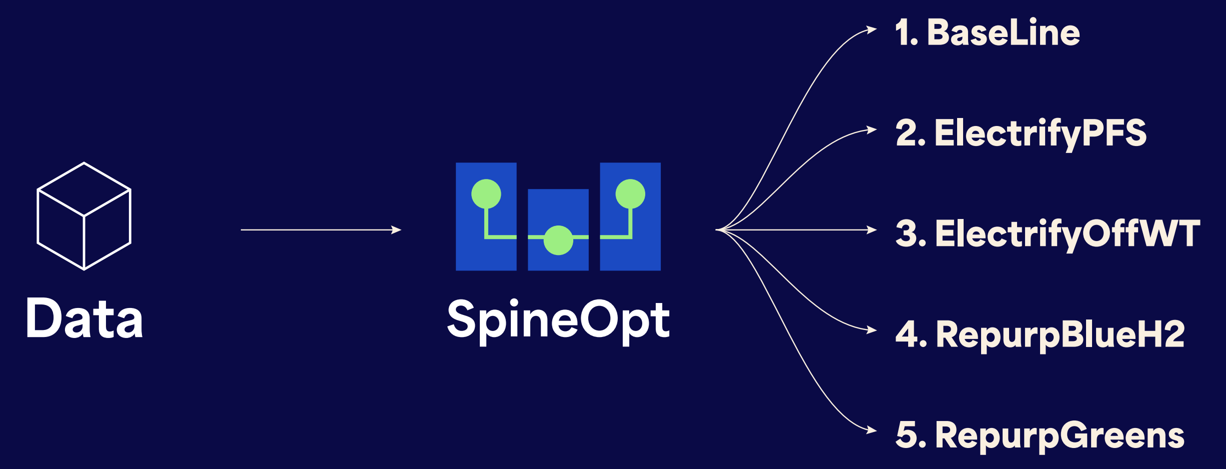
1. BaseLine for conventional O&G production operations on the modelled platform,

2. ElectrifyPFS for electrification by power from shore,

3. ElectrifyOffWT for electrification by dedicated offshore wind turbines,

4. RepurpBlueH2 for platform repurposing with SMR and CCS to utilize indigenous natural gas, and

5. RepurpGreens for platform repurposing with a utility-scale offshore wind farm for green power or H_2 supply to the shore. In *ElectrifyOffWT*, H_2 serves solely for energy storage to smooth offshore wind power intermittency, whereas in *RepurpGreens*, H_2 may be exported to onshore markets for revenue.



SCENARIO 1

BASELINE

The Baseline scenario represents **conventional O&G production operations** (i.e. standard offshore oil and gas extraction and processing activities) on the modeled platform. There are no significant transition or decarbonization efforts, as the focus is on traditional energy resource management.
This scenario serves as the baseline for comparison against other low-emission scenarios.

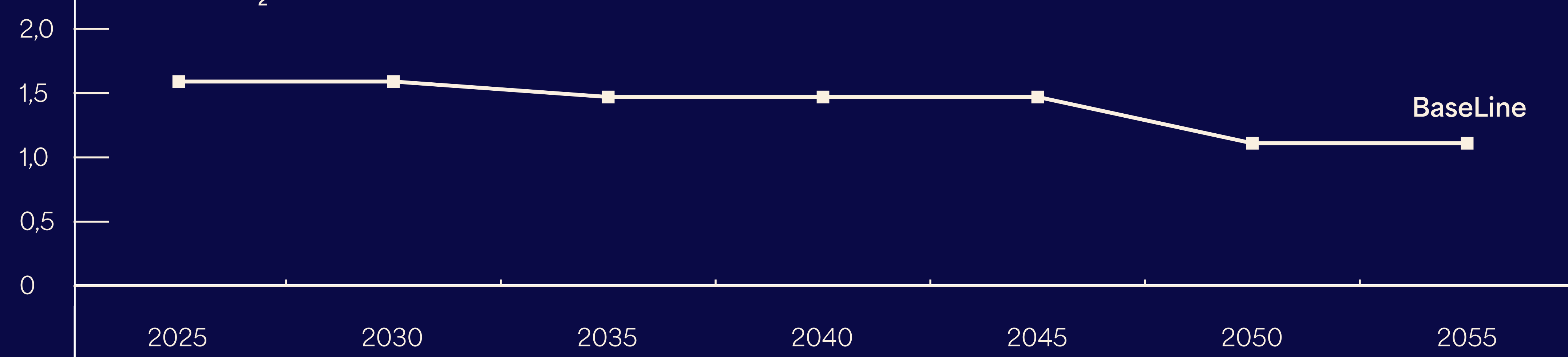
FEATURES

ENERGY SOURCES
Serves as the baseline for comparison

HEAT SUPPLY
Full use of gas turbine

COSTS/REVENUES
Highest operational emissions and fuel usage

MTON CO_2 EMISSIONS EVERY 5 YEARS



9,8
MTonne CO_2 emitted

24,9
B€ investment needed

SCENARIO 2

ELECTRIFYPFS

In this scenario, the **O&G platform undergoes electrification by importing electricity from the onshore grid**, transitioning away from self-generated power from natural gas. This shift to power-from-shore (PFS) reduces emissions but makes the platform sensitive to the price ratio between electricity and natural gas. This approach reflects a more sustainable energy model while increasing dependency on external power sources.

FEATURES

ENERGY SOURCES

Use of power from shore. Economically unfavourable if electricity prices rise.

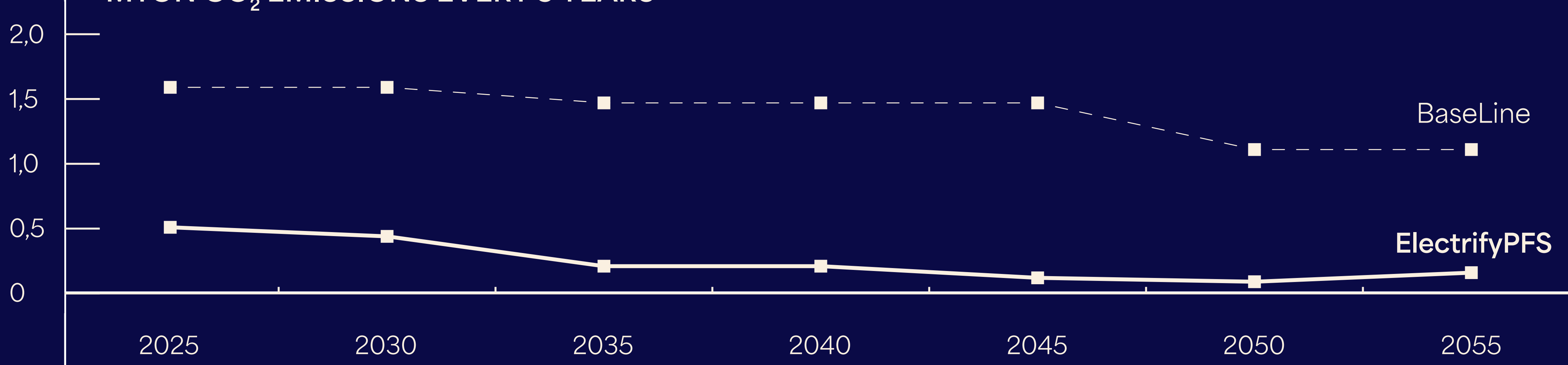
HEAT SUPPLY

One gas turbine remains and electric boilers supply heat.

COSTS/REVENUES

Saves on-site natural gas, leading to 0.5 B€ net revenue.

MTON CO_2 EMISSIONS EVERY 5 YEARS



1,7
MTonne CO_2 emitted

25,8
B€ investment needed

SCENARIO 3

ELECTRIFYOFFWT

In this scenario, electrification using dedicated **offshore wind turbines** also reduces operational costs by 0,2 B€, while still requiring one gas turbine during the 2055-60 period due to fluctuations in offshore wind power output.

FEATURES

ENERGY SOURCES

H_2 is used only for energy storage, not export. Offshore wind turbines used for electrification.

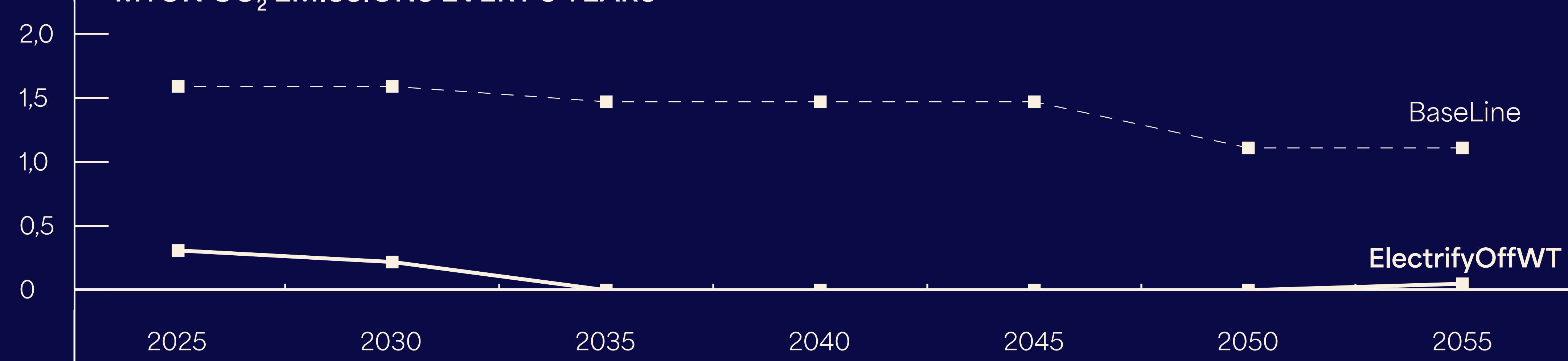
HEAT SUPPLY

An electric boiler provides heat, while one gas turbine is still required during 2055-60.

COSTS/REVENUES

Reduces operational costs by 0.2 B€.

MTON CO_2 EMISSIONS EVERY 5 YEARS



0,6

MTonne CO_2 emitted

24,7

B€ investment needed

SCENARIO 4

REPURPBLUEH2

This scenario extends the profitability of offshore O&G platforms by focusing on **large-scale offshore wind power generation**. The platform is repurposed to produce blue hydrogen using SMR and CCS installed from the start for CO_2 injection. This scenario generates 7,4 B€ in net revenue while enabling early decarbonization through CO_2 injection.

FEATURES

ENERGY SOURCES

CCS installed from the start for CO_2 injection.
Offshore wind power generation.

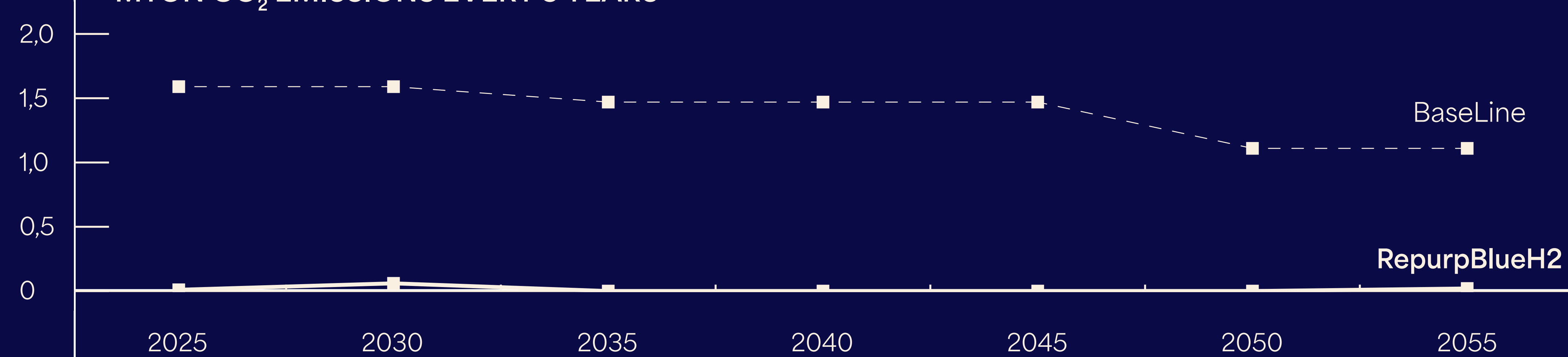
HEAT SUPPLY

Heat is supplied by gas turbine, electric boiler and SMR, run by electricity from offshore wind turbines.

COSTS/REVENUES

Generates 7,4 B€ in net revenue.

MTON CO_2 EMISSIONS EVERY 5 YEARS



0,1
MTonne CO_2 emitted

30,7
B€ investment needed

SCENARIO 5

REPURPGREENS

This scenario repurposes an offshore platform for **utility-scale wind power generation and optional green H_2 production**. Profitability (9.2 B€ revenue) comes mainly from offshore wind electricity, not from H_2 sales. H_2 plays a secondary role, as it is not cost-effective under current market conditions. The overall system is profitable even if hydrogen production alone is not.

FEATURES

ENERGY SOURCES

H_2 may be produced and exported to onshore markets.

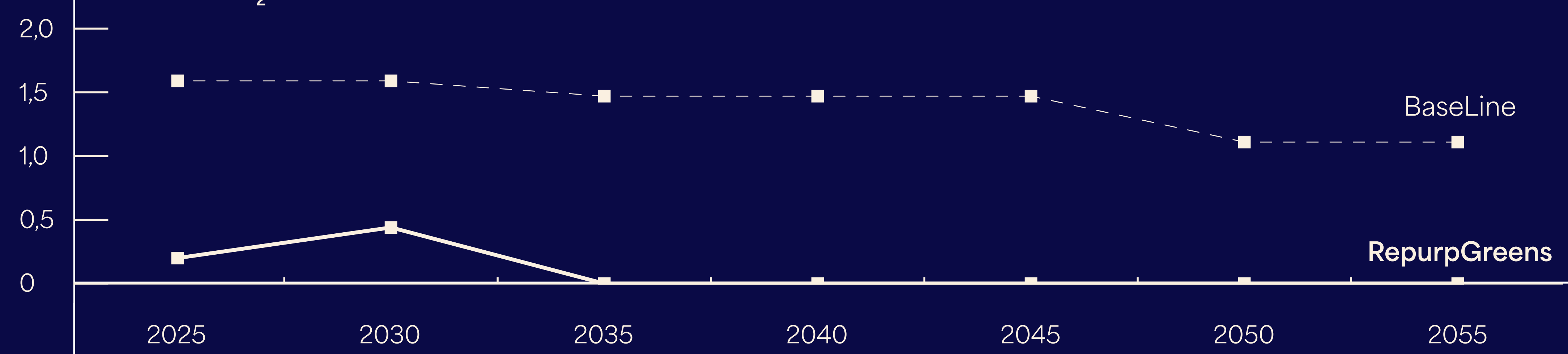
HEAT SUPPLY

Gas turbine (early stage) and electric boiler.

COSTS/REVENUES

9.2 B€ net revenue, wind-driven.

MTON CO_2 EMISSIONS EVERY 5 YEARS



0,6
MTonne CO_2 emitted

50,2
B€ investment needed

	Scenario	MTonne CO_2 emitted	B€ investment needed
1	BASELINE	9,8	24,9
2	ELECTRIFYPFS	1,7	25,8
3	ELECTRIFYOFFWT	0,6	24,7
4	REPURPBLUEH2	0,1	30,7
5	REPURPGREENS	0,6	50,2

FLEXIBLE MODELLING FEATURES

SPINEOPT'S FEATURES

FLEXIBLE MODELLING FEATURES

FLEXIBLE TEMPORAL STRUCTURE

The temporal structure uses different time resolutions for each energy carrier, giving higher accuracy with the same time steps as typical representative day methods. It also supports representative days with seasonal storage.

FLEXIBLE STOCHASTIC STRUCTURE

The stochastic framework allows for the integration of uncertainty through scenarios within the model, resulting in more robust outcomes. This stochastic structure can be applied to many parameters in the model.

FLEXIBLE MODELLING OPTIONS, INCLUDING:

Incorporation of multiple physics: power flows, pressure-driven gas flows, and heat diffusion.

Adding constraints that represent flexibility requirements (e.g., unit commitment, ramping, reserves, inertia, etc.).

User-defined constraints allowed to extend the model's capabilities.

BUILT-IN ALGORITHMS

ROLLING WINDOW OPTIMIZATION

This feature enables the solution of a series of sub-problems defined within successive - and potentially overlapping - rolling windows.

BENDERS DECOMPOSITION FOR INVESTMENT PROBLEMS

This method automatically defines and solves a two-stage decomposition algorithm for large-scale investment problems, where investment decisions are addressed in the master problem and operational decisions in the sub-problems.

MODELLING TO GENERATE ALTERNATIVES (MGA)

This approach explores near-optimal solutions that maximize or minimize investment in specific technologies (or multiple technologies simultaneously) while ensuring that the objective function remains within a certain threshold.

MULTI-STAGE OPTIMIZATION

This feature lets you create multiple linked optimization stages. For example, one stage may solve the whole year at daily resolution, while another refines seasonal storage at hourly resolution.

MONTE CARLO FUNCTIONALITY

Useful for resource adequacy studies, it defines multi-level scenarios and evaluates their impact on reliability. For example, it combines weather years and outages, solving them in parallel to get reliability metrics.

PATHWAY INVESTMENTS

SpineOpt provides the option for multi-year investments with milestone years, incorporating the economic representation of operations and investments over time, as well as the evolution of the technology mix with cost discounting.

SpineOpt

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