2023-2025

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PRODUCED BY **ENERGY REFORM, MULLANGRID,** AND **WIND ENERGY IRELAND**

Spine H2-IRL

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1. INTRODUCTION

Hydrogen-based technologies have significant potential for the broad decarbonisation of the future Irish energy system, but questions remain regarding security of supply, reliability and flexibility. There is potential to make more renewable generation more economical leading to even greater deployments of onshore and offshore wind and PV. This will result in new grid challenges and result in greater variability and uncertainty leading to an increased need for flexibility. Potential solutions include long term storage, flexible hydrogen-based generation technologies and batteries. However, the interactions between technologies and their complex interdependencies mean that the problem is not easily modelled.

In this project, Energy Reform build on previous work using an open approach to focus on unanswered questions. Models have been refined and expanded, and new models have been developed, including a new reliability assessment model.

The aim of Spine H2-IRL is to develop and publish open models for the comprehensive assessment of a future Irish energy system with widescale deployment of hydrogen production and consumption, along with other net zero solutions. This is complimented by analysis using the models to demonstrate their utility and provide useful insights into the future development of the Irish energy system. The detailed models facilitate investment optimisation across different sectors while considering network constraints, long and short-term storage optimisation and a high level of operational detail, with additional models providing more comprehensive flexibility and reliability assessments.

Seven future energy system scenarios are implemented and evaluated using the models, providing insights and highlighting barriers and opportunities for large-scale hydrogen. Our scenarios focus on a net-zero electricity system with high degrees of electrification, representing a significant step towards a net-zero energy system. Although non-electrical

demands in the building and transport sectors are not explicitly modelled in this work, under the high electricity demand assumptions, a sizable portion of the demand is captured along with the associated decarbonisation.

While hydrogen production, via electrolysers, and consumption within the electricity system for power generation is optimised endogenously within the SpineOpt models, collaboration with the HyLIGHT project informs hydrogen demand levels outside of the electricity system (primarily industry and heavy transport) and the location of hydrogen hubs.

High-voltage transmission (220kV and above) is based on Future Grid assumptions from EirGrid's ECP constraint forecasts . Network reduction functionality is used to aggregate the model to 220 kV+. Electricity demand is informed by EirGrid's Tomorrow's Energy Scenarios and ENTSO-E's TYNDP 2024 , with a total energy requirement of 79 and 22 TWh for Ireland and Northern Ireland respectively. The base system (prior to investment decisions) includes 9.2, 5.4 & 6.6 GW of installed onshore wind, offshore wind and solar generation capacity. An operational limit for inertia of 20,000 MWs is assumed, 10,000 of which must come from dispatchable plant. Long duration energy storage is not based on a particular technology. Costs and efficiencies are based on projections by the LDES Council . Further model details and input assumptions can be found in the Spine H2-IRL Final Report. While great care has been taken to develop these models and tools, time and resources were limited and this should not be considered a full and comprehensive analysis of the future Irish energy system. There are manifold uncertainties particularly surrounding sources of flexibility, the evolution of electricity demand and realistic capacities of DC interconnection. Comprehensive sensitivity analysis should be completed, which is beyond the scope of this project. However, the project demonstrates the usefulness of these open models which are available online.

1. https://www.marei.ie/project/hylight/
2. https://www,eirgrid.ie/industry/customer-information/ecp-constraint-forecast-reports
3. https://cms.eirgrid.ie/sites/default/files/publications/TES-2023-Final-Full-Report.pdf
4. https://2024.entsos-tyndp-scenarios.eu/
5. LDES Council. Net-zero power Long duration energy storage for a renewable grid

2. SPINE H2-IRL MODELS

Four distinct models have been developed to carry out the assessments of the future Irish energy system. These models and the associated workflow for the Spine H2-IRL modelling tasks is shown in Figure 1, left.

The flexible structure of Spine allows the various models required for this work to be combined and linked in a workflow using Spine Toolbox . Input data includes fuel costs and investment costs and parameters for various generation and network (electricity and hydrogen) investment options, along with different types of storage. Wind and solar availability and demand (both hydrogen and electricity) times series are also included for 30 weather years.

1. https://www.marei.ie/project/hylight/

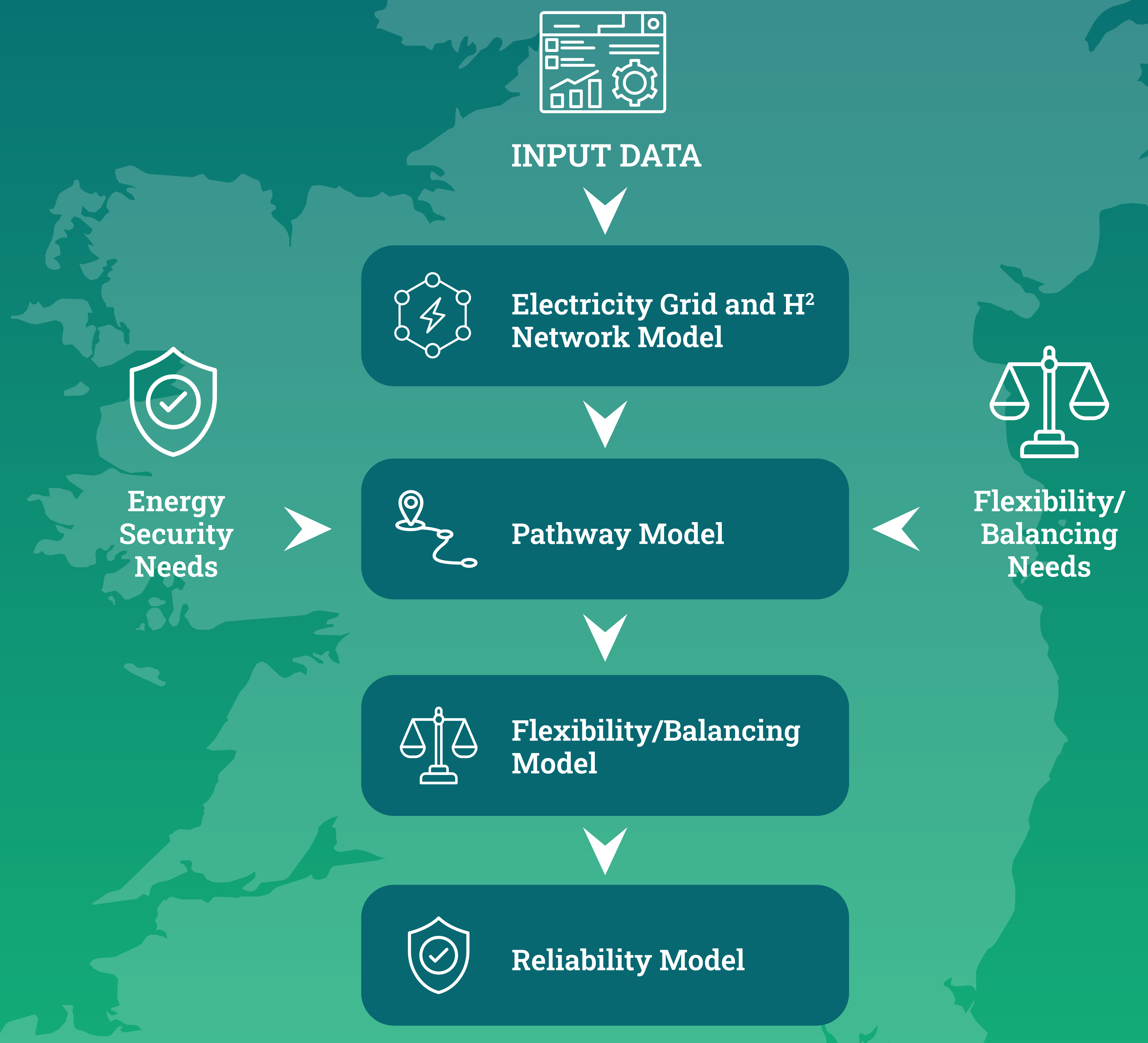

Figure 1. Spine H2-IRL Models and Workflow

NETWORK MODEL

A core **Network Model,** with high voltage electricity transmission and a base generation portfolio (hydro / Pumped Storage Hydro / waste / wind / solar) forms the base network for all scenarios. The core Network Model feeds into the **Pathways Model** which optimises total costs (investments & operating costs) for the 7 Spine H2-IRL scenarios.

PATHWAYS MODEL

The **Pathways Model** incorporates the Network Model and is used to study the future evolution of the energy system, including flexibility requirements (e.g. reserves / inertia floor) and energy security requirements, for each of the 7 scenarios. Thanks to effective collaboration with the Mopo project and TNO, Netherlands, SpineOpt was developed to implement advanced blended representative periods using TulipaClustering , allowing greater detail to be captured whilst also capturing long term seasonality within a manageable model size, co-optimising investments, long term storage and detailed operations.

FLEXIBILITY ASSESSMENT MODEL

The investment decisions from the **Pathways Model** are passed to a Flexibility Model allowing operations to be captured in greater detail. The **Flexibility Model** considers more detailed operations for a full year, facilitating a more comprehensive assessment of the system's capabilities.

RELIABILITY ASSESSMENT MODEL

The **Reliability Model** allows multi-sector resource adequacy to be assessed. SpineOpt was developed within Spine H2-IRL to include monte-carlo capabilities. In combination with SpineOpt's multi-sector flexibility, this allows a mutli-sector reliability assessment accounting for long-term storage over a large number of weather year and outage scenarios.

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2. https://www,eirgrid.ie/industry/customer-information/ecp-constraint-forecast-reports
3. https://cms.eirgrid.ie/sites/default/files/publications/TES-2023-Final-Full-Report.pdf
4. https://2024.entsos-tyndp-scenarios.eu/
5. LDES Council. Net-zero power Long duration energy storage for a renewable grid

“The Business as Usual (BAU) scenario does not impose any emissions target; instead, investments are driven solely by assumed input costs.”

3. H2-IRL SCENARIOS

The Spine H2-IRL scenarios, informed by the Spine H2-IRL Literature Review published at the beginning of the project, focus on achieving a net-zero electricity system. All scenarios involve high degrees of electrification and increased electricity demands, representing a significant step towards a net-zero energy system.

The Business as Usual (BAU) scenario does not impose any emissions target; instead, investments are driven solely by assumed input costs. In contrast, the remaining scenarios aim for a net-zero target for the electricity system, ensuring a more sustainable energy transition.

Within the core hydrogen scenarios, different levels of network expansion, including the electricity transmission network and hydrogen pipelines, are considered. This variation helps to evaluate the relative importance of network expansion in facilitating the optimal deployment of hydrogen technologies and renewable resources.

A further hydrogen scenario presents a more optimistic outlook for large-scale hydrogen deployment within the energy system. This scenario assumes lower costs and increased efficiencies for various hydrogen technologies, potentially accelerating the adoption of hydrogen-based solutions.

The Alternative Net Zero scenario, in contrast, excludes large-scale hydrogen deployment. Instead, it focuses on investments in long-duration energy storage and gas generation combined with carbon capture and storage (CCS) as alternative decarbonization pathways.

The All Options scenario allows investments in both hydrogen solutions and carbon capture and storage, providing flexibility in achieving the net-zero objective through multiple technological avenues

Details of the seven Spine H2-IRL scenarios are expanded below. A carbon price of €147 and a natural gas price of €5.7 are common assumptions across all scenarios.

3. H2-IRL SCENARIOS

Scenario	Fossil Fuel Generation	Electricity Network Expansion	Hydrogen Network Expansion	Hydrogen Demand	Hydrogen Storage	Hydrogen Investment Costs	Net Zero
Business as Usual	✓	✗	✗	●○○	▭▭	€€€	✗
Electricity Network	✗	✓	✗	●○○	▭▭	€€€	✓
Hydrogen Network	✗	✗	✓	●●●	⛰▭▭	€€€	✓
Full Network	✗	✓	✓	●●●	⛰▭▭	€€€	✓
Technology Breakthrough	✗	✓	✓	●●●	⛰▭▭	€€	✓
Alternative Net Zero	✓	✓	✗	●○○	▭▭	€€€	✓
All Options	✓	✗	✓	●●●	⛰▭▭	€€€	✓

3. H2-IRL SCENARIOS

BUSINESS AS USUAL	The only scenario unconstrained by the net-zero target, the Business as Usual scenario still relies on fossil fuel generation, with the assumed carbon price and fossil fuel prices driving investments in alternative supply side solutions. A modest hydrogen demand will exist in hubs around Ireland. To meet this demand, a level of investment will still be required in electrolysers and hydrogen storage tanks. This scenario is primarily for comparison purposes with the core hydrogen scenarios in terms of costs and emissions.
ELECTRICITY NETWORK	The Electricity Network scenario is the first of four core hydrogen scenarios. The net-zero constraint is introduced. However, large-scale infrastructure such as hydrogen pipelines and underground storage are still absent. More expensive and capacity-limited tanks can be selected, along with hydrogen fuelled electricity generation at the designated hydrogen hubs. Electricity network expansion is possible in this scenario.
HYDROGEN NETWORK	The Hydrogen Network scenario has a net-zero constraint enforced. Large-scale hydrogen infrastructure is now included as an investment option. With the possibility of large-scale storage and transport, the higher hydrogen demand is assumed. Hydrogen fuelled electricity generation can be selected both at the designated hydrogen hubs and along the assumed pipeline routes. However, in this scenario electricity transmission expansion is not permitted, which may limit the optimal expansion of both renewable generation and hydrogen production.
FULL NETWORK	The Full Network scenario has a net-zero target, and expansion of both the electricity transmission system and the hydrogen network is facilitated. In this scenario, the model will be free to co-optimise investments in and locations of renewable generation, hydrogen infrastructure, and electricity network capacity expansions. The high level of hydrogen demand is assumed for this scenario.
TECHNOLOGY BREAKTHROUGH	The Technology Breakthrough scenario has a net-zero target and has similar assumptions to the Full Network scenario. More optimistic assumptions are used for costs and efficiencies of the key hydrogen investment options. Expansion of both the electricity transmission system and the hydrogen network is facilitated. As with the Full Network scenario, the model will be free to co-optimise investments in and locations of renewable generation, hydrogen infrastructure, and electricity network capacity expansion.
ALTERNATIVE NET-ZERO	As with the core hydrogen scenarios, the Alternative Net-Zero scenario has a net-zero target. However, hydrogen expansion is not considered. The low level of hydrogen demand is assumed for sectors outside the power system, which will require modest investments in electrolysers and hydrogen storage tanks. As hydrogen fuelled electricity generation is not considered, dispatchable generation can be provided by fossil fuel generation in combination with carbon capture and storage (CCS). To balance out the low level of emissions from the CCS plant, negative emission technologies (NETs) will also be considered, namely bioenergy with carbon capture and storage (BECCS), although maximum capacities will be limited. Long duration energy storage (LDES) investment options will also be considered.
ALL OPTIONS	With the net zero target applied in the All Options scenario, large-scale hydrogen infrastructure is included as investment options and dispatchable generation can be provided by hydrogen fuelled generation or fossil fuel generation (with or without carbon capture and storage) combined with BECCS. The high level of hydrogen demand is assumed.

INVESTMENT OPTIONS SUMMARY

As a level of hydrogen demand exists in all 7 scenarios, electrolysers and hydrogen storage tanks are common investment options. Other common investment options include onshore and offshore wind and solar generation, and grid-scale batteries. Underground hydrogen storage is included as an option for those scenarios with hydrogen network expansion options, and LDES is considered in the Alternative Net-Zero scenario only.

Gas generation can be invested in in the Business as Usual scenario, the **Alternative Net-Zero** scenario, and the **All Options** scenario, although investments in CCS may also be required to reduce emissions, and Negative Emission Technologies (i.e. BECCS) investments will be required to counterbalance any emissions from the gas plants for scenarios with a net zero target.

SCENARIO	GAS CCGT/OCGT	H2 CCGT/OCGT	BECCS	WIND/SOLAR GEN	BATT (2-6H)	LDES (25-100H)	ELEC NETWORK	H2 NET-WORK	ELECTRO INVERTERS	H2 TANK	H2 UNDER-GROUND
BUSINESS AS USUAL	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗
ELECTRICITY NETWORK	✗	✓	✗	✓	✓	✗	✓	✗	✓	✓	✗
HYDROGEN NETWORK	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓
FULL NETWORK	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
TECHNOLOGY BREAKTHROUGH	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
ALTERNATIVE NET ZERO	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓	✗
ALL OPTIONS	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓

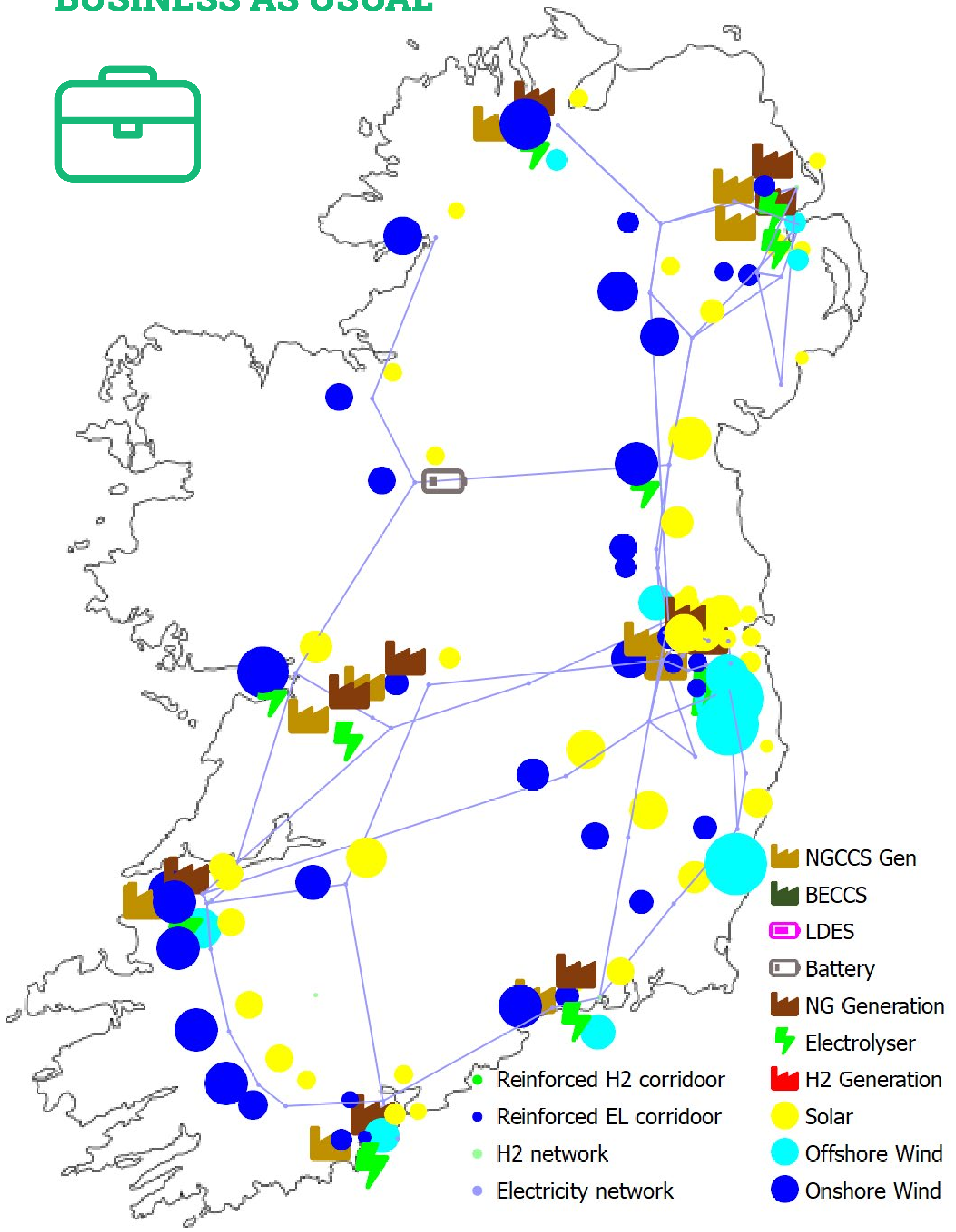
4. RESULTS

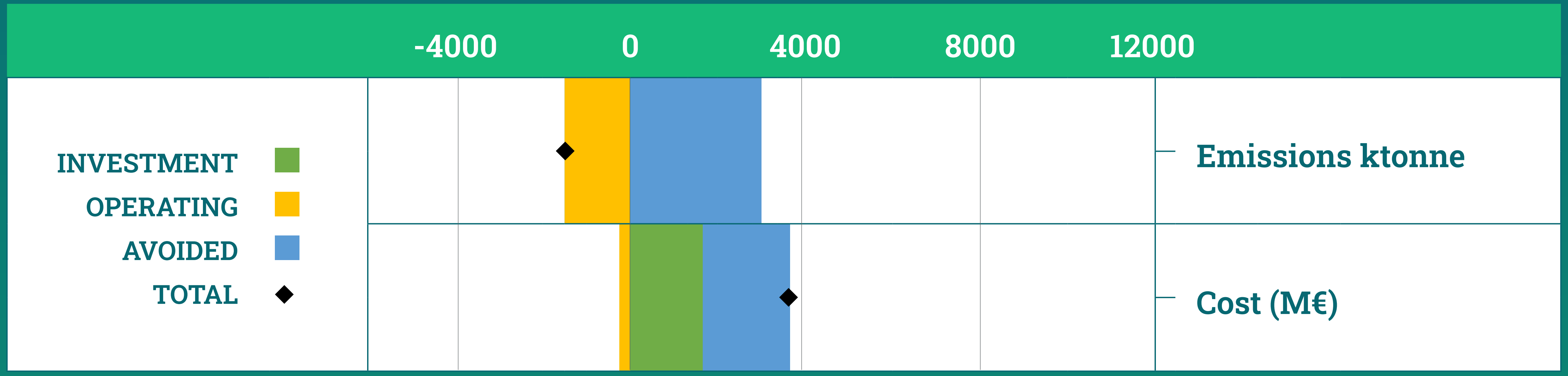
The following section contains the results for each of the 7 scenarios. A map is provided showing the locations of the different investments. The electricity transmission network and hydrogen pipelines are also shown, with investments (where considered in the scenario) shown in a heavier line and darker colour.

A graph shows the total costs and emissions for each scenario. The emissions and costs are calculated for the power system for the island of Ireland. As the scenarios contain one of 2 different possible levels of hydrogen demand (comprised of demand from industry and transport), avoided emissions and fuel costs in these sectors are included as negative costs / emissions. For the purpose of these calculations, the hydrogen is assumed to primarily displace diesel in the heavy transport sector and natural gas in the industrial sector.

A table displays the investment decision for each of the 7 scenarios. For renewable generation, the total capacities (base plus investment) are displayed. A summary and brief discussion of the results for each of the 7 scenarios is also provided.

BUSINESS AS USUAL



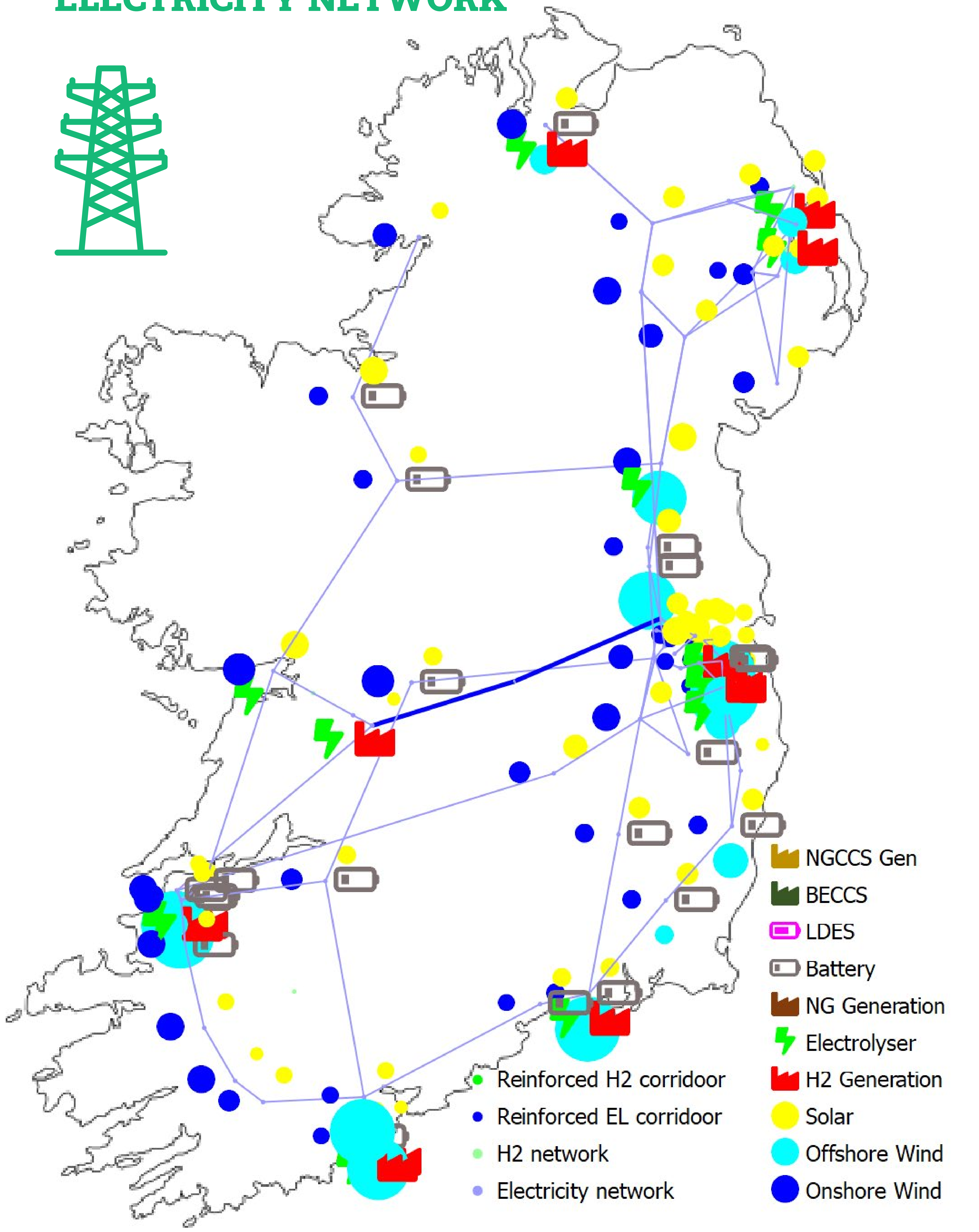


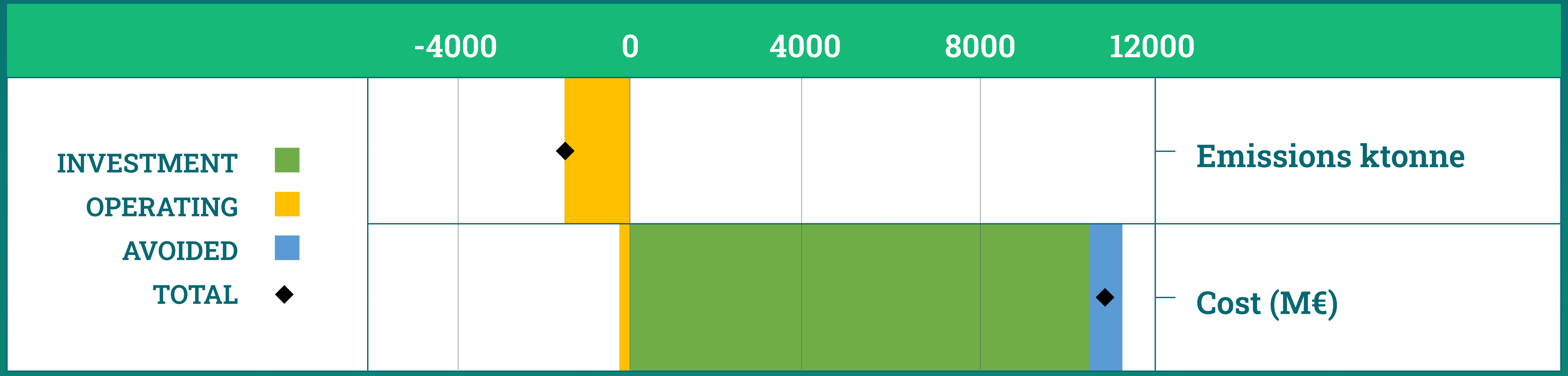
TECHNOLOGY		CAPACITY
SOLAR		10.8 GW
ONSHORE WIND		13.3 GW
OFFSHORE WIND		5.4 GW
H2 GEN		-
ELECTROLYSERS		1.0 GW
H2 TANKS		3 GWH
SALT CAVERN		
BATTERIES		0.13 GWH
TRANSMISSION		
PIPELINES		
NG GEN		5.2 GW
NGCCS GEN		5.4 GW
LDES		
BECCS		

BUSINESS AS USUAL

- The carbon price drives investments in low carbon technologies.
- Hydrogen production is sufficient to meet the low hydrogen demand, but hydrogen fuelled electricity generation is not selected.
- Modest additional investments in renewable generation result in 29.5 GW of installed RES, backed up by almost equal capacities of natural gas fuelled generation and natural gas fuelled generation combined with carbon capture and storage.
- The base portfolio provides most of the flexibility requirements (flexible demand, interconnectors, PHS & hydro) along with the 1 GW of electrolysers required to meet the low hydrogen demand.
- A small additional capacity of batteries is selected (0.13 GWh) along with 3 GWh of above ground hydrogen storage tanks.
- As low hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are modest at 0.85 million tonnes of CO2.
- Emissions from the electricity generation portfolio amount to 2.86 million tonnes, with a total emissions for the scenario of 2.01 million tonnes of CO2.
- In the absence of a net zero target, overall costs are low compared to the other scenarios, with annualised investment costs accounting for 43% of the overall costs.
- The hydrogen produced to meet the low demand result in M€100.2 of avoided fuel and carbon costs, giving total annualised costs of M€3,636.
- This scenario demonstrates that a high carbon price justifies significant investments in low carbon technologies, but emissions remain in the absence of a net zero target and there is limited potential for decarbonisation of other sectors.

ELECTRICITY NETWORK



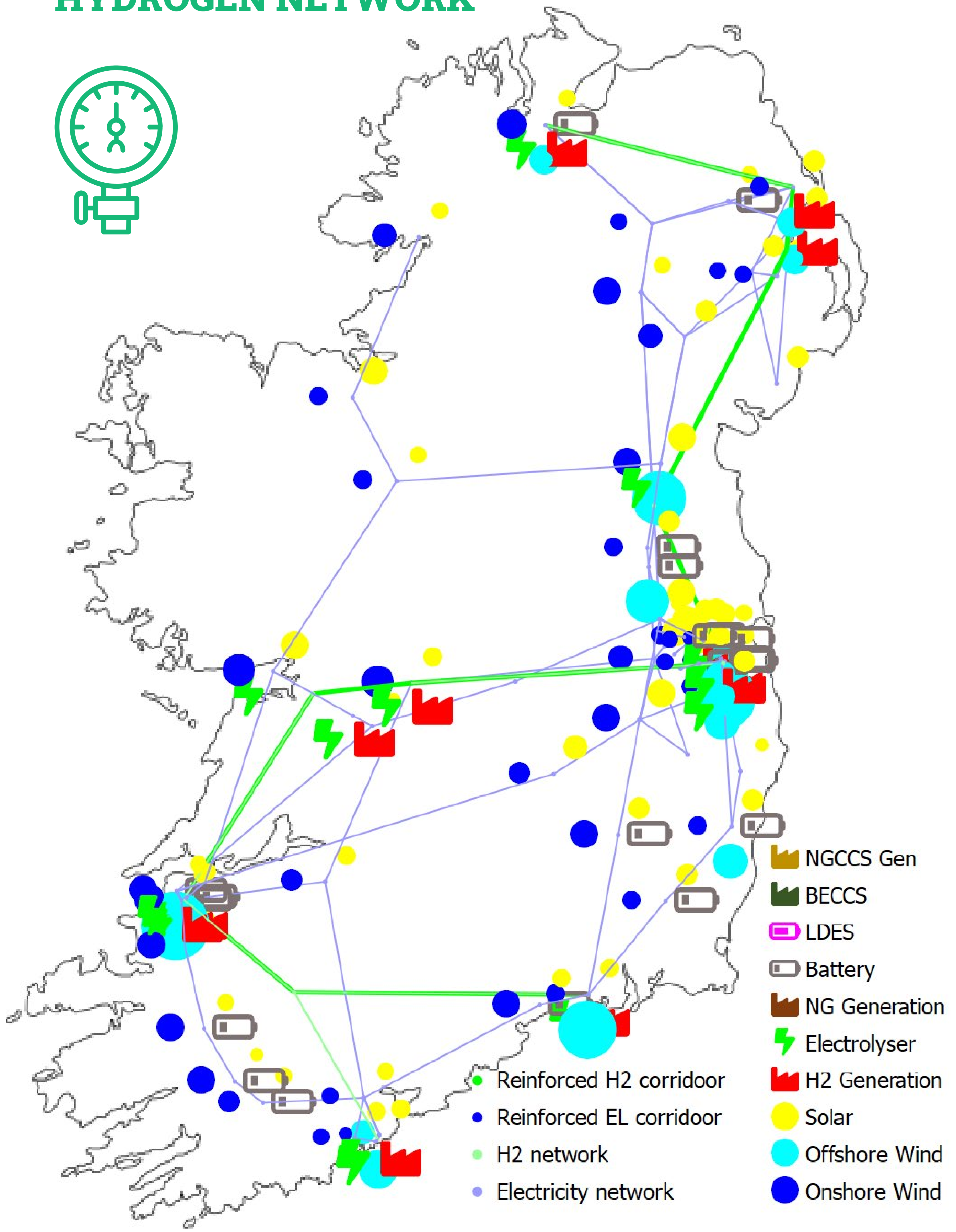


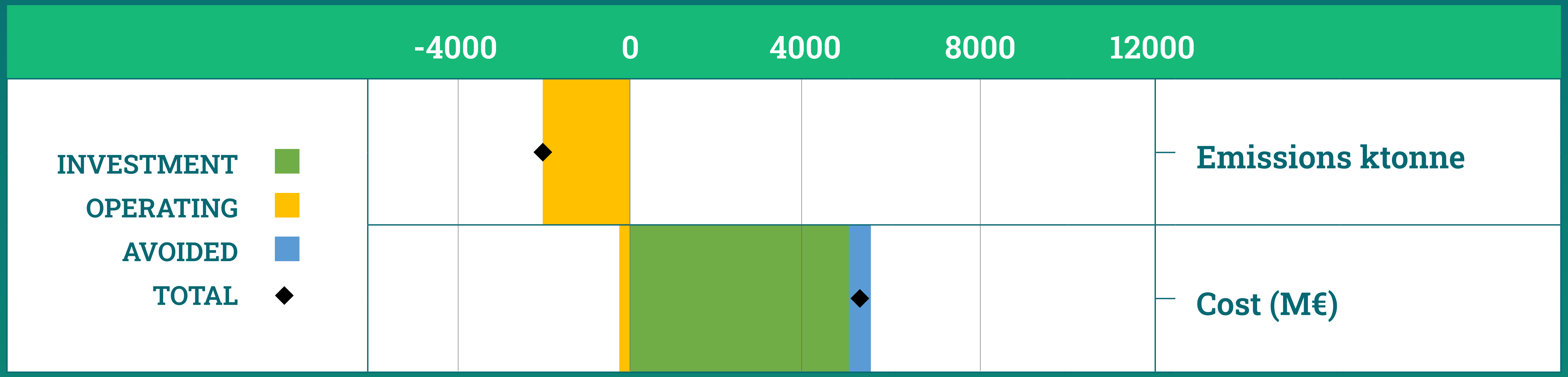
TECHNOLOGY	CAPACITY
SOLAR	15.6 GW
ONSHORE WIND	15.7 GW
OFFSHORE WIND	24.1 GW
H2 GEN	9.1 GW
ELECTROLYSERS	14.0 GW
H2 TANKS	557.8 GWH
SALT CAVERN	
BATTERIES	26.8 GWH
TRANSMISSION	160.0 KM
PIPELINES	
NG GEN	
NGCCS GEN	
LDES	
BECCS	

ELECTRICITY NETWORK

- While electricity transmission investments can occur, no large scale infrastructure is included in this scenario. A net zero constraint is enforced for the power system, driving investment decisions.
- Hydrogen production is sufficient to meet the low Hydrogen demand, and hydrogen fuelled electricity generation provides most of the dispatchable capacity.
- Large capacities of additional renewable generation result in 55.4 GW of installed RES.
- The large capacity of renewable generation is balanced by investments in grid scale batteries (26.8 GWh).
- Some transmission investments occur, but the model preferentially selects sites for renewable generation and invests in batteries as a lower cost option to wide-scale transmission investments.
- In the absence of large scale hydrogen infrastructure, 558 GWh of above ground hydrogen storage tanks are required.
- As low hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are modest at 0.85 million tonnes of CO2, which results in a small negative total for emissions in this scenario.
- Overall costs are extremely high for this scenario, with annualised investment costs accounting for 96% of the overall costs.
- The hydrogen produced to meet the low demand result in M€100.2 of avoided fuel and carbon costs, giving total annualised costs of M€11,679 (over 3 x Business as Usual).
- This scenario demonstrates that it may be technically possible to achieve a hydrogen based net zero system in the absence of large scale hydrogen infrastructure and low cost storage, but it is a very expensive and inefficient solution.

HYDROGEN NETWORK



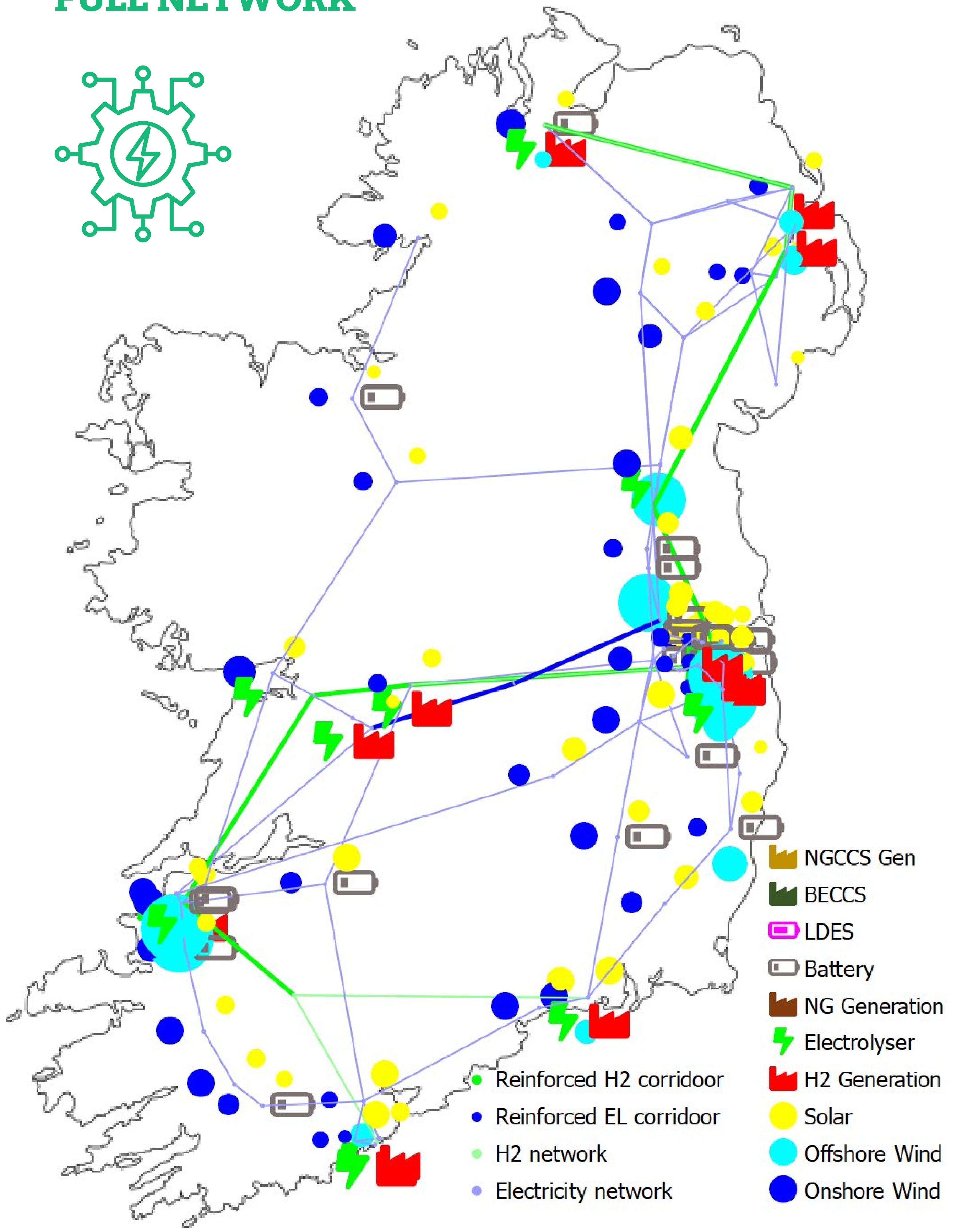


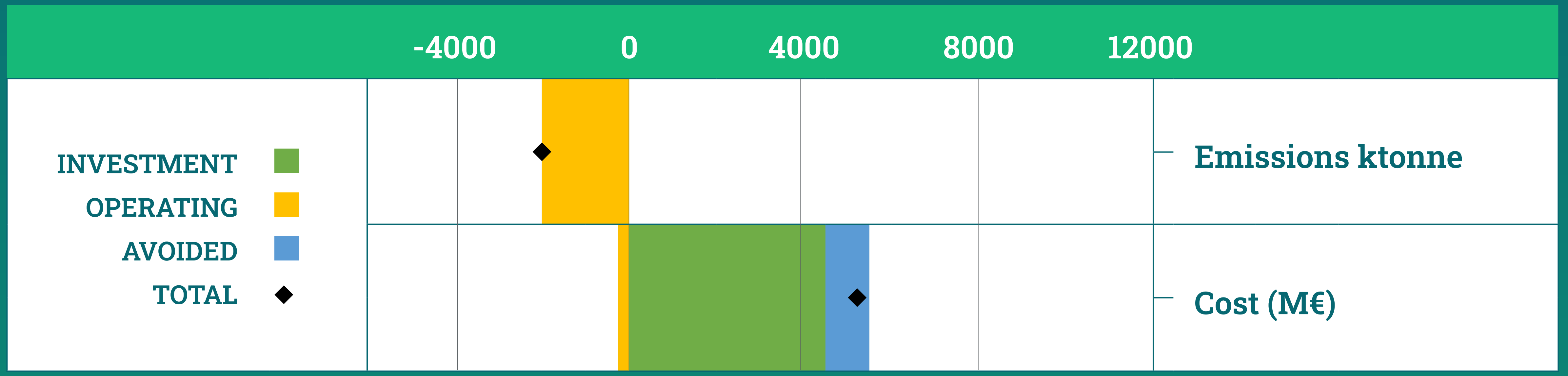
TECHNOLOGY	CAPACITY
SOLAR	15.6 GW
ONSHORE WIND	15.7 GW
OFFSHORE WIND	18.4 GW
H2 GEN	8.9 GW
ELECTROLYSERS	11.5 GW
H2 TANKS	-
SALT CAVERN	3.0 TWh
BATTERIES	3.1 GWH
TRANSMISSION	
Pipelines – Repurposed	575km
Pipelines – New	312km
NG GEN	
NGCCS GEN	
LDES	
BECCS	

HYDROGEN NETWORK

- Large scale gas infrastructure expansion is included in this scenario. A net zero constraint is enforced for the power system, which drives investment decisions.
- Hydrogen production is sufficient to meet the high hydrogen demand, and hydrogen fuelled generation provides most of the dispatchable capacity.
- Significant capacities of additional renewable generation result in 49.7 GW of installed RES, roughly 10% less than in the Electricity Network scenario.
- The expansion of the hydrogen network allows the electrolyser capacities to be more efficiently deployed and dispatched.
- With the introduction of low cost bulk storage (salt cavern), additional hydrogen fuelled generation is favoured over grid scale batteries, with more moderate levels of investments occurring (3.1 GWh).
- The hydrogen network and salt cavern storage displaces more expensive above ground storage.
- As high hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are larger at 2.07 million tonnes of CO2, which results in a more significant negative total for emissions in this scenario.
- Overall costs are significantly reduced compared to the Electricity Network scenario (42% of Electricity Network total), with annualised investment costs accounting for 92% of the overall costs.
- The hydrogen produced to meet the high demand result in M€241.8 of avoided fuel and carbon costs, giving total annualised costs of M€4,904 (35% higher than Business as Usual).
- This scenario demonstrates that large cost reductions and efficiencies can be achieved in a net zero hydrogen based system when large scale infrastructure and low cost bulk storage is available.

FULL NETWORK



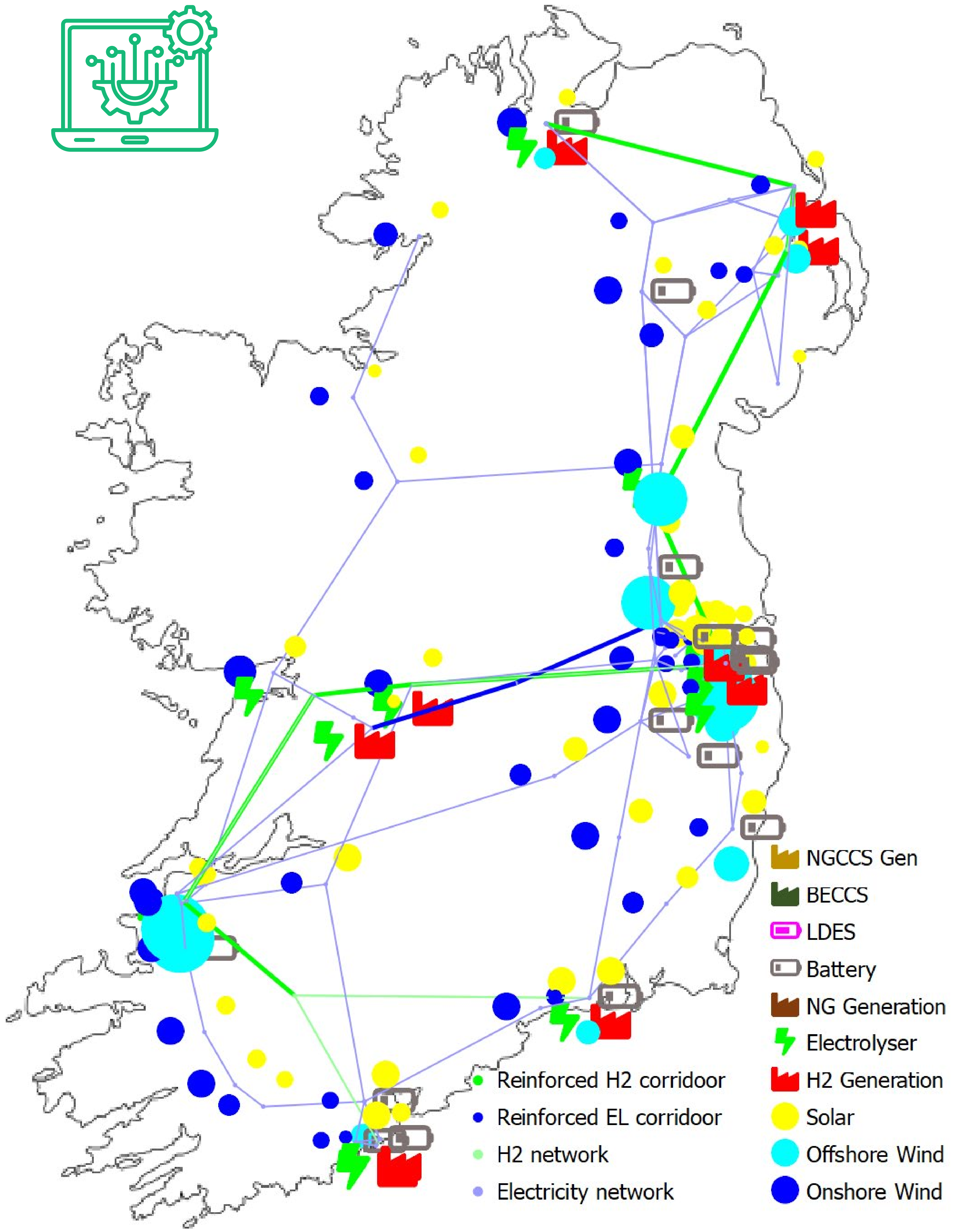


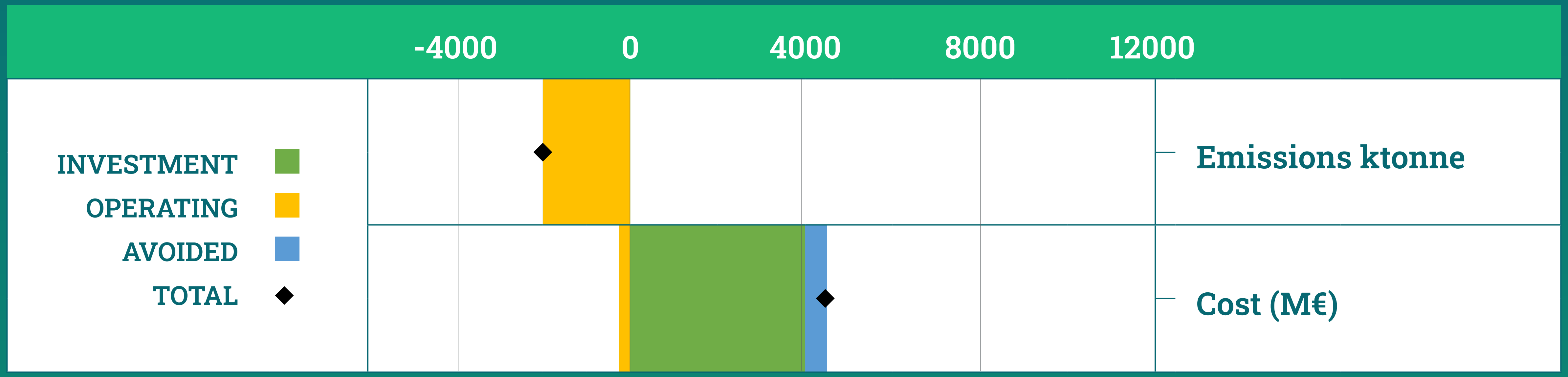
TECHNOLOGY	CAPACITY
SOLAR	15.6 GW
ONSHORE WIND	15.7 GW
OFFSHORE WIND	17.4 GW
H2 GEN	8.6 GW
ELECTROLYSERS	11.6 GW
H2 TANKS	-
SALT CAVERN	3.0 TWh
BATTERIES	1.9 GWH
TRANSMISSION	123.7 km
PIPELINES (Repurposed)	458 km
PIPELINES (New)	253 km
NG GEN	
NGCCS GEN	
LDES	
BECCS	

FULL NETWORK

- Both electricity transmission and large scale hydrogen infrastructure investments are included in this scenario. A net zero constraint is enforced for the power system, driving investment decisions.
- Hydrogen production is sufficient to meet the high Hydrogen demand, and hydrogen fuelled electricity generation provides most of the dispatchable capacity.
- Significant capacities of additional renewable generation result in 48.7 GW of installed RES, 1 GW less than in the Hydrogen Network scenario.
- A modest investment in electricity transmission capacity occurs, coupled with a small drop in battery investments compared to the Hydrogen Network scenario (1.9 vs 3.1 GWh).
- The hydrogen network and salt cavern storage displaces the more expensive above ground storage tanks, with salt cavern capacity matched to the Hydrogen Network scenario.
- As high hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are 2.07 million tonnes of CO2, which results in a negative total for emissions in this scenario.
- Overall costs are reduced slightly (~ 3%) compared to the Hydrogen Network scenario, with annualised investment costs accounting for 91.5 % of the overall costs.
- The hydrogen produced to meet the high demand result in M€241.8 of avoided fuel and carbon costs, giving total annualised costs of M€4,717 (30% higher than Business as Usual).
- This scenario demonstrates that further efficiencies and cost reductions can be achieved when transmission expansion on key lines is facilitated.

TECHNOLOGY BREAKTHROUGH



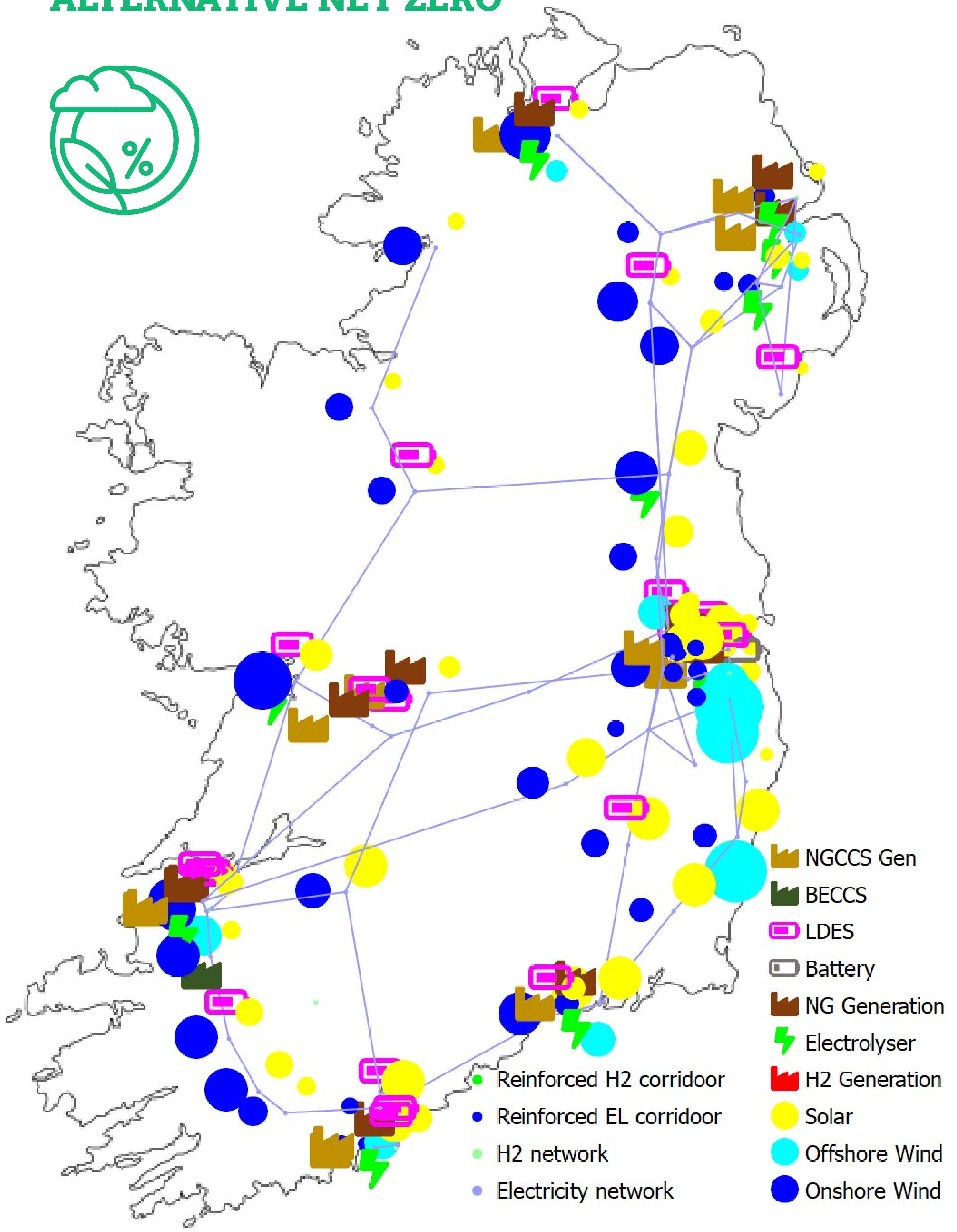


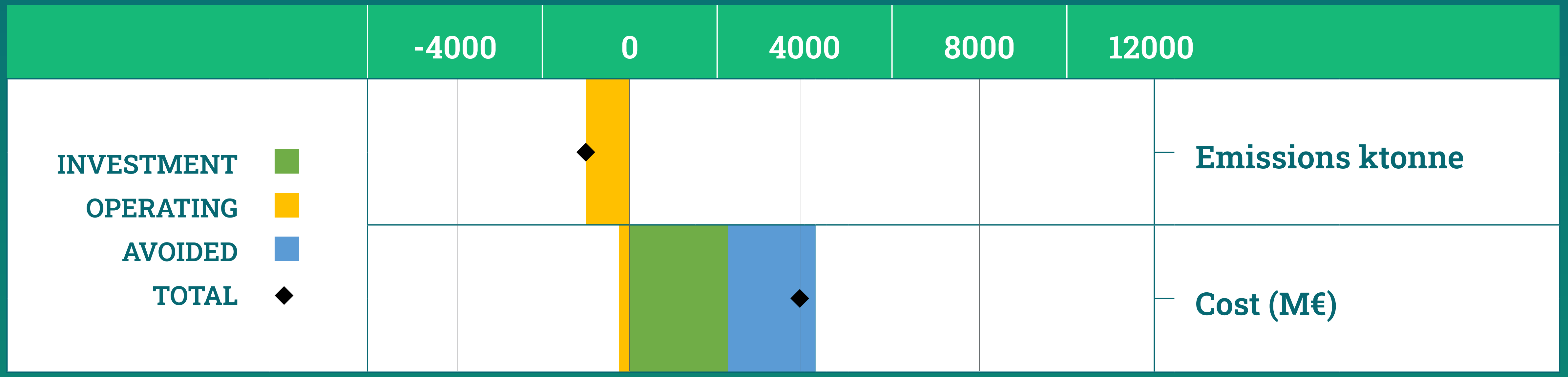
TECHNOLOGY	CAPACITY
SOLAR	15.6 GW
ONSHORE WIND	15.7 GW
OFFSHORE WIND	17.6 GW
H2 GEN	8.6 GW
ELECTROLYSERS	12.1 GW
H2 TANKS	-
SALT CAVERN	4.1 TWh
BATTERIES	0.6 GWH
TRANSMISSION	153.9 km
PIPELINES (Repurposed)	458 km
PIPELINES (New)	292 km
NG GEN	
NGCCS GEN	
LDES	
BECCS	

TECHNOLOGY BREAKTHROUGH

- Both electricity transmission and large scale hydrogen infrastructure investments are included in this scenario. A net zero constraint is enforced for the power system, driving investment decisions.
- Lower costs and increased efficiencies are assumed for the hydrogen technologies.
- Hydrogen production is sufficient to meet the high Hydrogen demand, and hydrogen fuelled electricity generation provides most of the dispatchable capacity.
- Significant capacities of additional renewable generation result in 48.9 GW of installed RES, similar to the Full Network scenario.
- A modest investment in transmission capacity occurs, coupled with a further drop in battery investments compared to the Full Network scenario (0.6 vs 1.9 GWh).
- Additional investments in both electrolysers (+ 5%) and salt cavern storage (+ 39%) occur compared to the Full Network scenario.
- As high hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are 2.07 million tonnes of CO2, which results in a negative total for emissions in this scenario.
- Overall costs are reduced considerably (~ 9%) compared to the Full Network scenario, with annualised investment costs accounting for 90 % of the overall costs.
- The hydrogen produced to meet the high demand result in M€241.8 of avoided fuel and carbon costs, giving total annualised costs of M€4,291 (18% higher than Business as Usual).
- This scenario demonstrates that if the more ambitious targets are reached for hydrogen technology costs and efficiencies, overall costs move closer to the Business as Usual scenario, with overall reduced emissions.

ALTERNATIVE NET ZERO



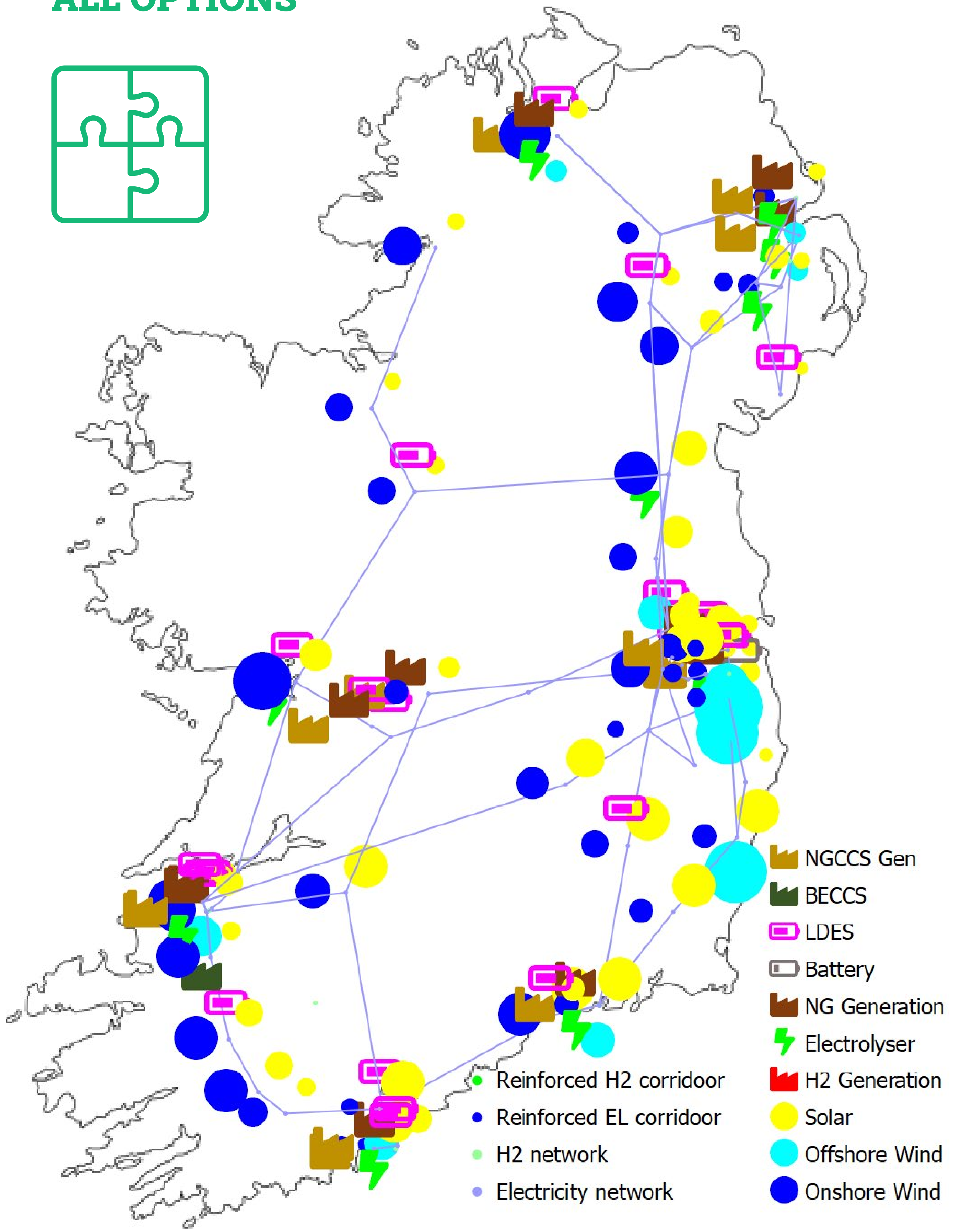


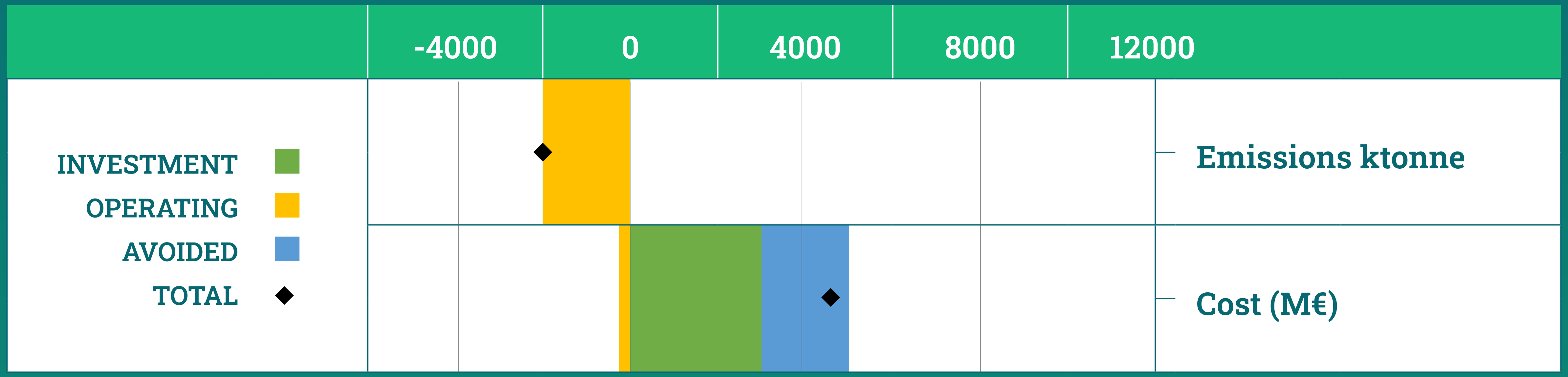
TECHNOLOGY	CAPACITY
SOLAR	13.4 GW
ONSHORE WIND	14.0 GW
OFFSHORE WIND	5.4 GW
H2 GEN	-
ELECTROLYSERS	1.0 GW
H2 TANKS	3.8 GWH
SALT CAVERN	
BATTERIES	0.12 GWH
TRANSMISSION	
PIPELINES	
NG GEN	2.3 GW
NGCCS GEN	6.4 GW
LDES	47.6 GWh
BECCS	300 MW

ALTERNATIVE NET ZERO

- A net zero constraint is enforced for the power system. While electricity transmission investments are allowed, no large scale hydrogen infrastructure is included.
- Fossil fuel generation (with or without CCS), LDES and. BECCS can all be selected.
- Hydrogen production is sufficient to meet the low Hydrogen demand, while no hydrogen fuelled electricity generation is selected in the absence of large scale infrastructure.
- Modest capacities of additional renewable generation result in 32.8 GW of installed RES, 3.3 GW more than the Business as Usual scenario.
- As with the Business as Usual scenario, the base portfolio and the 1 GW of electrolysers required to meet the low hydrogen demand provides most of the short term flexibility requirements for the system, with a small capacity of battery investments (0.12 GWh).
- As low hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are modest at 0.85 million tonnes of CO2, which results in a small negative total for emissions in this scenario.
- Overall costs are the lowest of the net zero scenarios, with annualised investment costs accounting for 51 % of the overall costs.
- The hydrogen produced to meet the low demand result in M€100.2 of avoided fuel and carbon costs, giving total annualised costs of M€4,144 (14% higher than Business as Usual).
- This scenario demonstrates that if alternative low carbon technologies become viable, such as carbon capture and storage and alternative LDES technologies, a lower cost net zero electricity system can be achieved. However, there is uncertainty surrounding both the LDES and CCS assumptions. In addition in the absence of hydrogen infrastructure there is less potential for the decarbonisation of the wider energy system.

ALL OPTIONS





TECHNOLOGY		CAPACITY
SOLAR		15.6 GW
ONSHORE WIND		15.7 GW
OFFSHORE WIND		6.6 GW
H2 GEN		2.9 GW
ELECTROLYSERS		5.0 GW
H2 TANKS		-
SALT CAVERN		0.65 TWh
BATTERIES		0.95 GWH
TRANSMISSION		
PIPELINES	Repurposed	458 km
	New	292 km
NG GEN		0.4 GW
NGCCS GEN		5.6 GW
LDES		
BECCS		300 MW

ALL OPTIONS

- A net zero constraint is enforced for the power system with both large scale hydrogen infrastructure and CCS investments allowed.
- Hydrogen production is sufficient to meet the high hydrogen demand, with a combination of hydrogen fuelled natural gas (primarily with CCS) electricity generation selected.
- Large capacities of additional renewable generation result in 37.9 GW of installed RES, between the Alternative Net Zero and Hydrogen Network scenarios.
- Electrolyser capacities also lie between the Alternative Net Zero and the Hydrogen Network scenarios at 5 GW, meeting the high hydrogen demand some of the hydrogen generation capacity.
- The short term flexibility requirements for the system increase compared to Alternative Net Zero and an increase in battery capacity is seen (0.95 vs 0.12 GWh).
- As high hydrogen demand is included in this scenario, avoided emissions from the industry and transport sectors are 2.07 million tonnes of CO2, which results in a negative total for emissions in this scenario.
- Overall costs are comparable to the Technology Breakthrough scenario, with annualised investment costs accounting for 58 % of the overall costs.
- The hydrogen produced to meet the high demand result in M€241.8 of avoided fuel and carbon costs, giving total annualised costs of M€4,291 (18% higher than Business as Usual).
- This scenario demonstrates that a combination of technologies , including large scale hydrogen production, can achieve efficient solutions for the power system, while also achieving significant emission reductions in the wider energy system.

5. FLEXIBILITY & RELIABILITY ASSESSMENTS

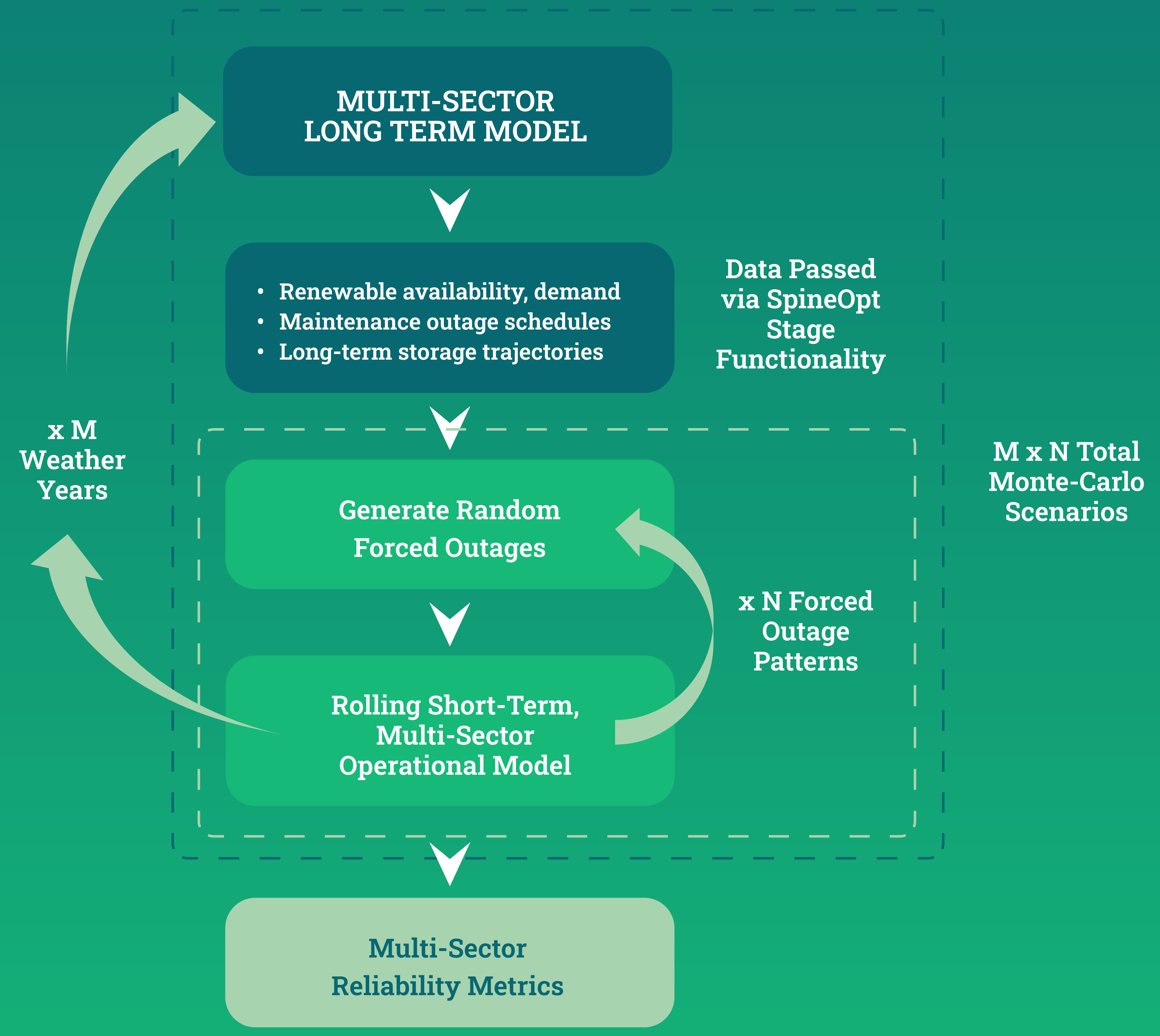
The **Flexibility** and **Reliability Models** were used to further assess the portfolios produced by the **Pathways Model.** The **Flexibility Model** assesses the operability of the system over a full continuous year, with more operational detail. To demonstrate this capability to carry out flexibility assessments, the **Hydrogen Network** scenario was evaluated. This incorporates a long-term model which optimises long-duration storage usage which is passed to a rolling operations model allowing the hydrogen to be appropriately valued while allowing the freedom for deviations according to short-term system needs. The flexibility assessment confirmed the capability of the portfolio to meet the system inertia and reserve requirements, with no loss of load.

A state-of-the-art, generalised **Reliability Model** was developed specifically for this project which implements resource adequacy assessment suitable for a future integrated energy system with long term storage and high shares of variable renewables. Reliability is assessed for portfolios from the **Hydrogen Network** scenarios, considering 30 weather years and multiple outage patterns while fully considering the contribution of long-term storage. The implementation involved adding monte-carlo capabilities to the SpineOpt energy system modelling framework allowing a wide variety of assessments to be carried out efficiently.

The model was employed to evaluate multi-sector resource adequacy of the **Hydrogen Network** scenario demonstrating the capability of the framework. Results highlighted the need to consider resource adequacy at the portfolio optimisation stage. The potential of hydrogen imports or back-up fuels to increase the reliability of a hydrogen-based system can also be assessed. This can be the subject of future work. More details are available in the Spine H2-IRL Final Report and the open model is available online at **www.energyreform.ie**.

6. DISCUSSION & RECOMMENDATIONS

- A suite of state-of-the-art open models has been developed allowing comprehensive assessment of the transition to a net-zero integrated electricity system. The models have been used to implement 7 future energy system scenarios, providing useful insights regarding the development of the future system and the modelling methodologies required to adequately study the energy transition
- Hydrogen technologies have the potential to provide the backbone of a net-zero power system, as well as playing a role in the decarbonisation of the wider energy system.
- To adequately capture the complex interactions across space and time, a modelling approach is required that can simultaneously optimise investments while capturing seasonality of long-term storage and the impact of detailed operations.
- Low-cost hydrogen storage and large-scale infrastructure play an important role in the roll-out of a cost-effective hydrogen-based energy system.
- A hydrogen-based energy system can integrate very large shares of renewable generation and provide stability services for the power system.
- The future system can integrate large shares of renewable generation with limited transmission upgrades when investment decisions are optimised and location specific. This highlights the importance of considering regional resources and networks at the portfolio optimisation stage.
- Very large capacities of renewable generation are required to achieve a net-zero power system based primarily on hydrogen technologies.
- Results from the All Options scenario demonstrate that significant efficiencies can be achieved by providing some energy capacity from alternative sources.
- While the future role of carbon capture and storage is uncertain, other options should be considered for providing baseload and system stability services, including low inertia systems / alternative sources of inertia.
- The Spine H2-IRL open models can be leveraged to consider a broader range of scenarios and sensitivities for future net zero options.



RECOMMENDED FUTURE WORK INCLUDES:

Primarily, the focus of this project was on the development of open models along with a complimentary analysis demonstrating how they can be used. The analysis is not intended to be exhaustive, or definitive. It is our hope that the models are exploited to study the transition and carry out further analysis. Some specific opportunities for further work are outlined below.

- A comprehensive multi-sector reliability assessment framework has been developed which considers adequacy in a future integrated energy system with variable renewables and long-term storage. Framing of resulting constraints to be included in the pathways phase can be the subject of future work.
- The modelling outcomes represent a high degree of optimisation of instantaneous production across the network to mitigate constraints and meet demand across multiple sectors. Exploring the operability of the power system with co-optimised dispatch of distributed generation, storage and hydrogen production is an area for further investigation.
- The results show the high value of locationally optimal investment decisions. Further work should explore how this could be realised in practice.
- Dynamics and stability have not been considered. The potential of grid-forming technology and future low-inertia power systems / alternative inertia sources should be studied along with the implications for a hydrogen-based power system.
- The role of interconnection was not extensively explored in this work. Future work could consider alternative interconnection capacities and alternative evolutions of the broader European power system.
- Future work could explore the development of an established international hydrogen market and the potential role of large-scale imports /exports of hydrogen and hydrogen-based fuels.
- Additionally, future work could consider broader sensitivity analysis including the following areas:
  - Low inertia systems / alternative sources of inertia
  - Available capacities of flexible demand/EV operation
  - Alternative CAPEX assumptions
  - Alternative fuel price assumptions
  - The integration of heat networks