Potential of Retrofitting Hydropower Plants in a 2050 Net-Zero European Grid



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The Project, Partners and Modelling Tools

AARHUS UNIVERSITY

The Department of Electrical and Computer Engineering leads STORE2HYDRO's system-level optimisation, assessing the value of retrofitted hydro across Europe.

Store2Hydro

An EU-funded Horizon Europe project involving 11 European partners, aiming to add energy storage capabilities to existing hydropower plants.

EURO DENMARK

EuroCC Denmark

Denmark's national competence centre for high-performance computing, supporting our use of the LUMI supercomputer.

PyPSA GUROBI OPTIMIZATION

The Modelling

The European power system is modelled using PyPSA, and the resulting large-scale optimisation problem is solved using Gurobi.

Talk Overview

1

Europe’s Energy Storage Challenge
Why a power system with high shares of wind and solar needs storage

2

Hydropower & the retrofit idea
Adding pumping capabilities to existing hydropower plants

3

STORE2HYDRO: The Research Question
Where in Europe are retrofitted hydro most valuable?

4

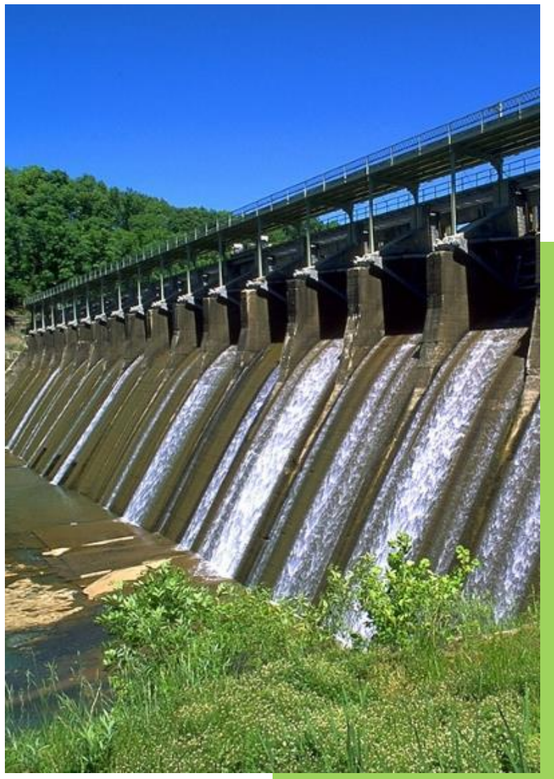
Modelling and High-Performance Computing
Modelling and optimising the European power system

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Value in the Energy Market
How retrofits affect system costs and storage needs

Europe's storage challenge

Why a renewable power system needs somewhere to put its energy.



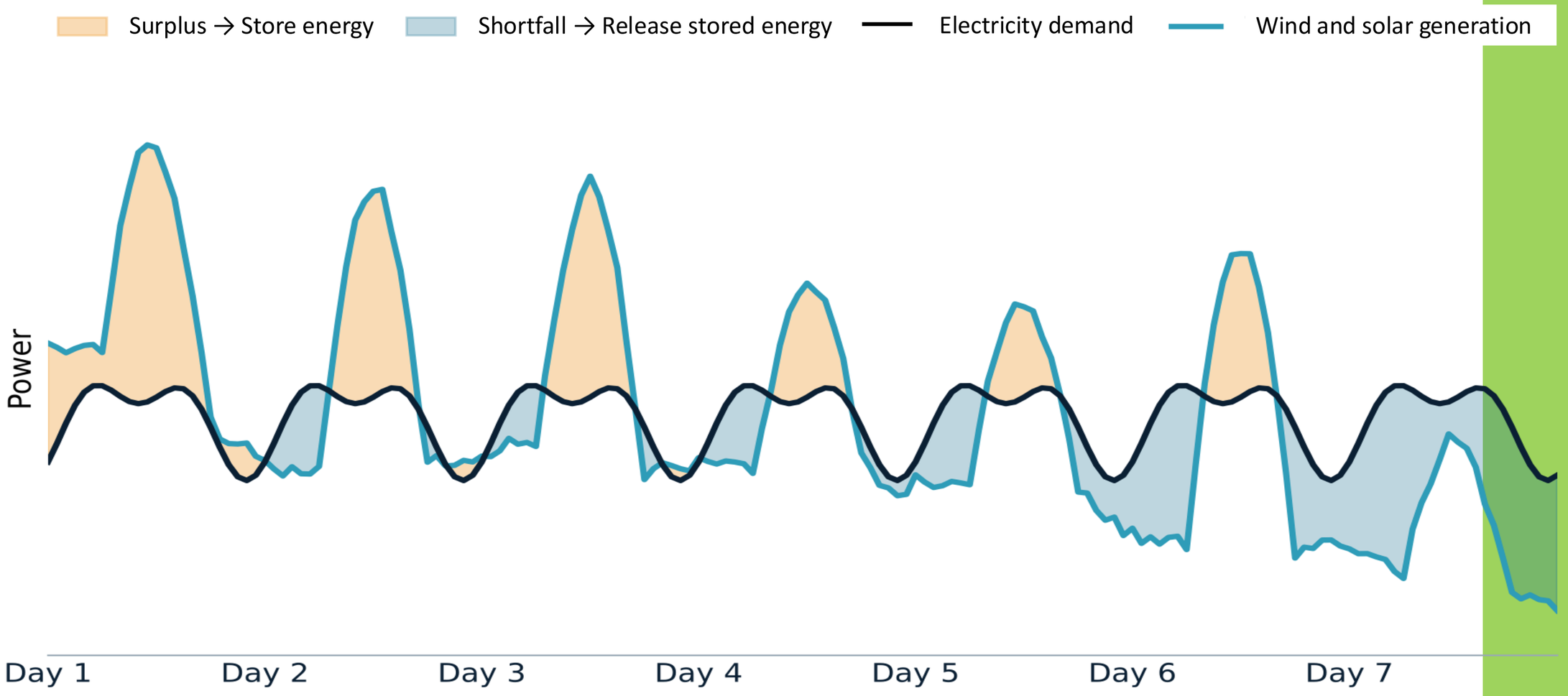
Europe’s Path to Net Zero by 2050

- The European Green Deal sets the goal of EU climate neutrality by 2050.
- Wind and solar are central to this transition, but their output varies with the weather.
- The power system must balance electricity supply and demand at all times.

This study explores a net-zero European power system in 2050.

Wind and Solar Do Not Always Match Demand

Energy storage helps bridge the gap between generation and demand.



Illustrative profiles over one week.

Storage Helps Balance a Renewable Power System

Shifting Energy in Time

Store surplus electricity and release it when generation falls below demand.

Short-Duration Storage

Storage for a few hours helps manage daily variations in solar generation. Batteries are well suited to this role.

Long-Duration Storage

Storage over days, weeks or longer helps manage extended periods of low wind and solar generation.

Key message: Large-scale, long-duration storage is a major challenge—and hydropower can play an important role.

Batteries: Effective for Hours, Costly for Longer Durations

- Lithium-ion batteries are well suited to storing electricity for a few hours.
- Providing terawatt-hours of battery storage can be expensive.
- Costs depend on both power capacity (MW) and energy capacity (MWh).

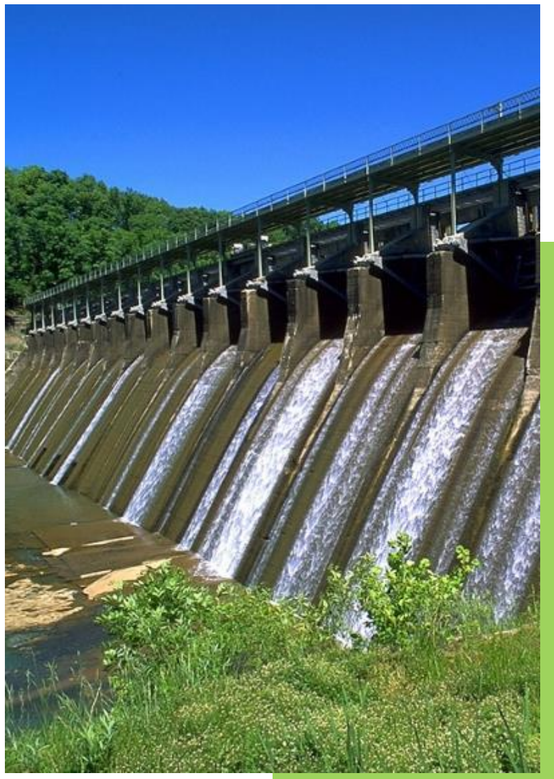
≈ €72,000 per MW per year

Annualised cost of battery power capacity assumed in this study.

Could hydropower provide a more affordable option for large-scale, long-duration storage?

Hydropower & the retrofit idea

Adding pumping capabilities to existing hydropower plants to store surplus electricity.



How Reservoir Hydropower Works

- Water stored behind a dam holds potential energy.
- Releasing water through a turbine generates electricity.
- Reservoir hydropower is dispatchable: its output can be adjusted to help meet demand, within water and operating limits.

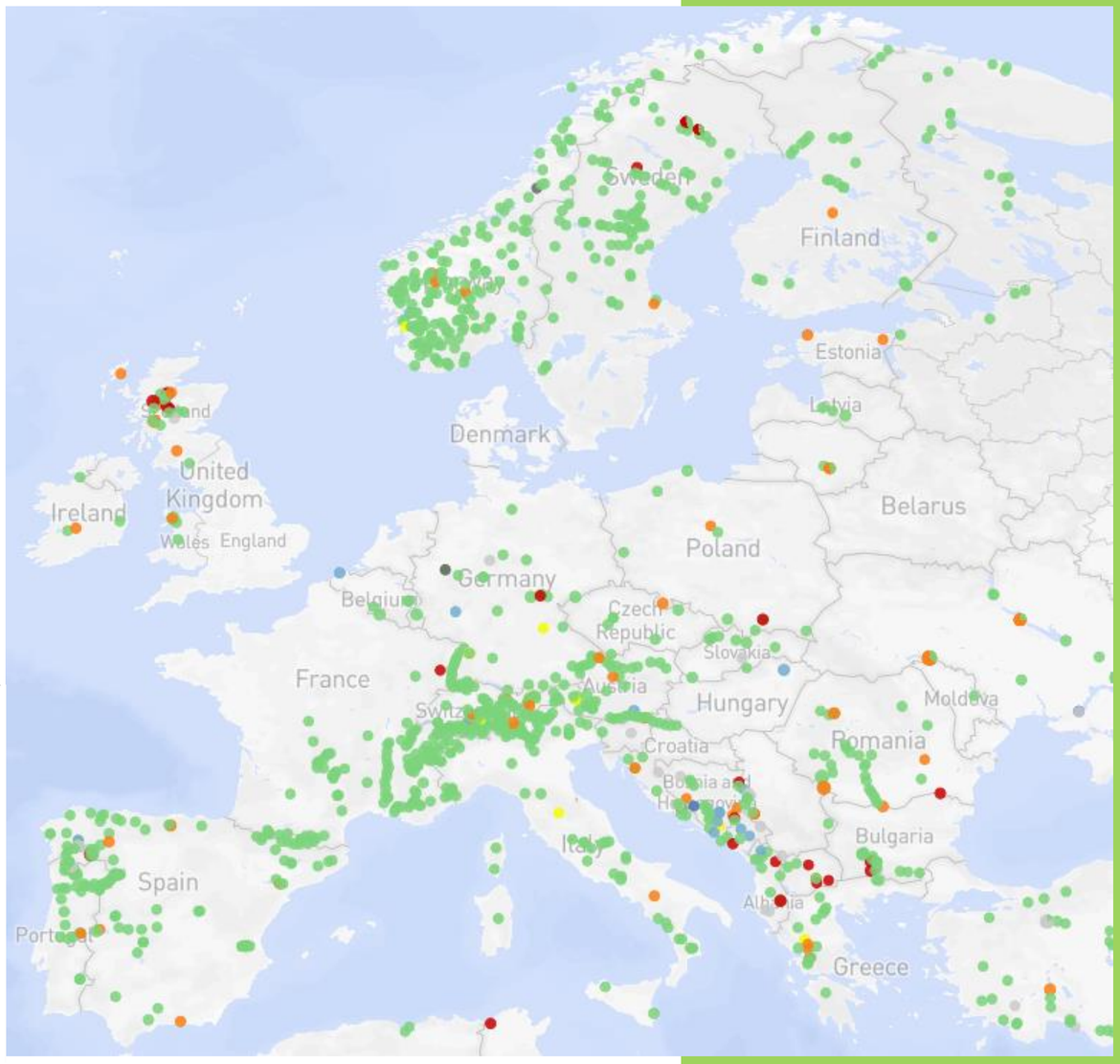
> Hydropower is a major source of renewable electricity in Europe. Reservoirs allow energy to be stored and used when needed.

Hydropower in Europe (2024)

Indicator	Value	Unit
Electricity generation	680	TWh
Installed hydropower capacity	263	GW
Capacity added	544	MW
Installed pumped-storage capacity	56	GW
Pumped-storage capacity added	187	MW

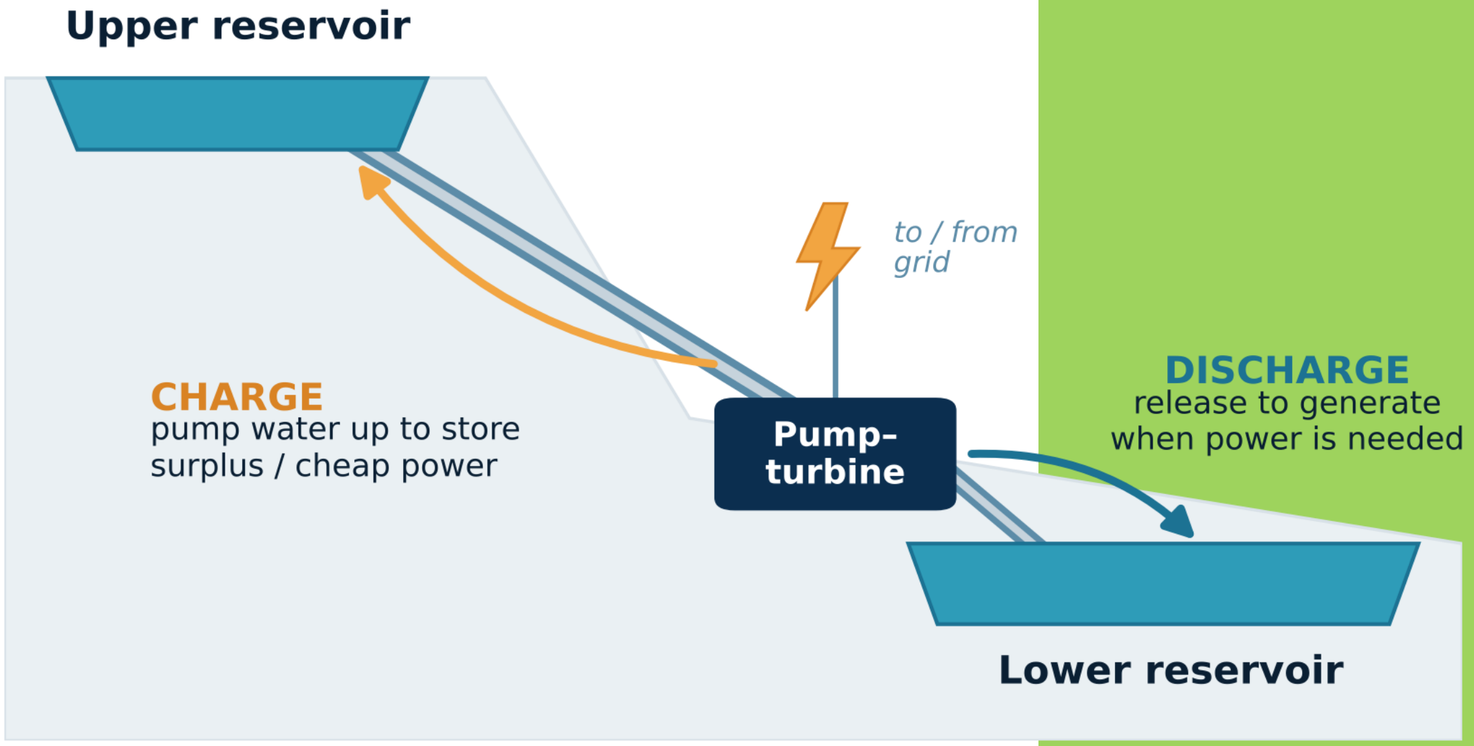
https://www.hydropower.org/region-profiles/europe

Distribution of Potential and Existing Hydropower Plants in Europe



Pumped Hydropower: A “Water Battery”

- Two reservoirs at different elevations.
- Water is pumped uphill to store energy.
- Water flows downhill through a turbine to generate electricity.
- Round-trip efficiency: approximately 75–80%.

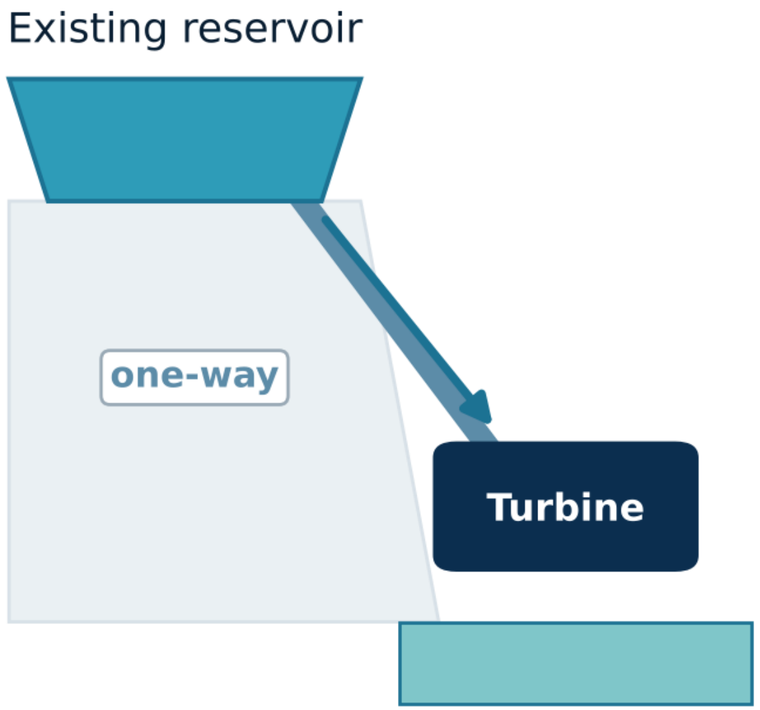


Pumped Hydropower: An Established Storage Technology

- A proven technology for large-scale energy storage.
- Long operating life and potentially low storage costs.
- New projects can face lengthy approval processes and environmental constraints.

> Can pumped storage be expanded by upgrading existing hydropower plants?

STORE2HYDRO: Adding Storage to Existing Hydropower Plants

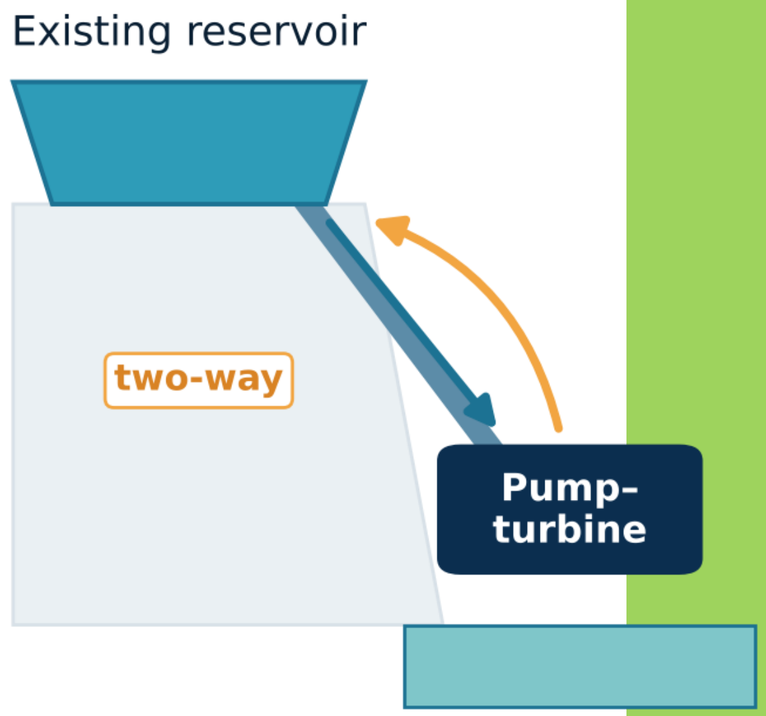


Conventional hydropower

Water flows downhill through a turbine to generate electricity.

RETROFIT

Reuse the existing dam, reservoir and grid connection.



Retrofitted: reversible pump-turbine

Water can also be pumped uphill to store energy for later use.

Why Retrofit Existing Hydropower Plants?

Reuse Existing Infrastructure

Make use of existing reservoirs, dams and grid connections.

Lower Investment Costs

Reusing infrastructure can reduce costs compared with building new storage facilities.

Shorter Development Times

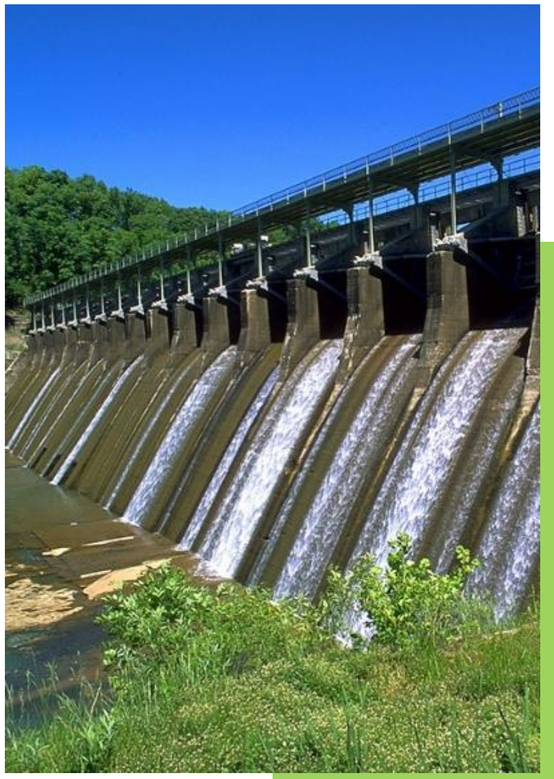
Upgrading an existing plant can be faster than building a new facility.

Reduced Environmental Impact

Avoid creating new reservoirs, while respecting water-use and environmental limits.

STORE2HYDRO: The Research Question

Assessing the value of hydropower retrofits for the European power system.



The STORE2HYDRO Project

€4.3 million
Horizon Europe research and innovation funding

48 months
Project duration

11
Partner organisations

7
European countries

New Energy Storage Technologies for Flexible Hydropower

- Adds reversible pump-turbines to existing European hydropower plants.
- Combines turbine technology, digital twins, life-cycle assessment and cost analysis.
- Coordinated by Luleå University of Technology, Sweden. Aarhus University leads the power system modelling.

Project aim: Enable at least 22 TWh of electricity storage per year across Europe through hydropower retrofits.

Store2Hydro

Two Key Innovations

Reversible pump-turbine

A design for upgrading existing hydropower plants to both pump water and generate electricity, with a focus on flexible operation, high efficiency and reduced cavitation.

Digital twin

A virtual model of a plant’s water flows and sediment behaviour, supporting safe and flexible operation.

Life-cycle assessment and investment and operating cost analysis evaluate both technologies. Aarhus University assesses their value for the European power system.

What Is the Value of Retrofitted Hydro—and Where?

System-Level Optimisation

Assessing the value of retrofitted hydro for a net-zero European power system in 2050.

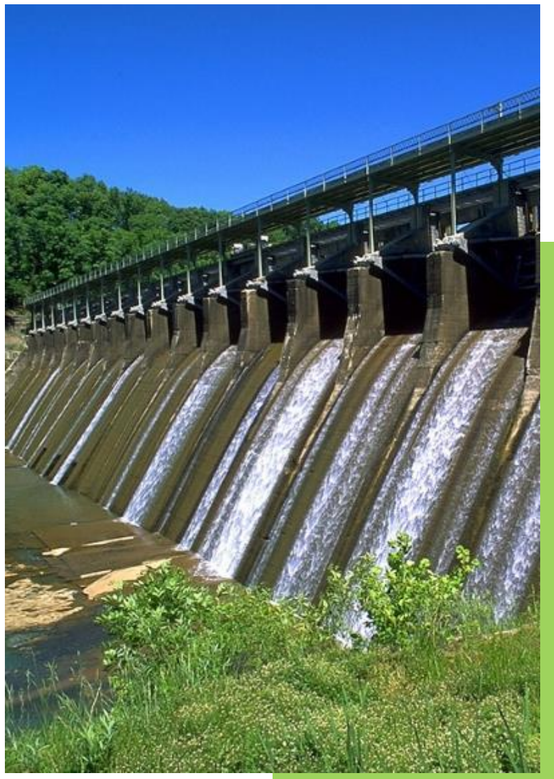
Reducing System Costs
How much could retrofits reduce total power system costs?

Reducing Other Storage Needs
How much could retrofits reduce the need for other storage technologies, especially batteries?

Understanding Grid Constraints
Where do transmission limits restrict the benefits of retrofits?

Modelling Europe’s Power System: Why HPC Is Needed

Solving a large-scale optimisation problem for the interconnected European grid.



Assessing Retrofit Value Across Europe

The model identifies the lowest-cost European power system that meets demand and a net-zero emissions target in 2050. Scenarios with and without hydropower retrofits are then compared.

Represent the Power System

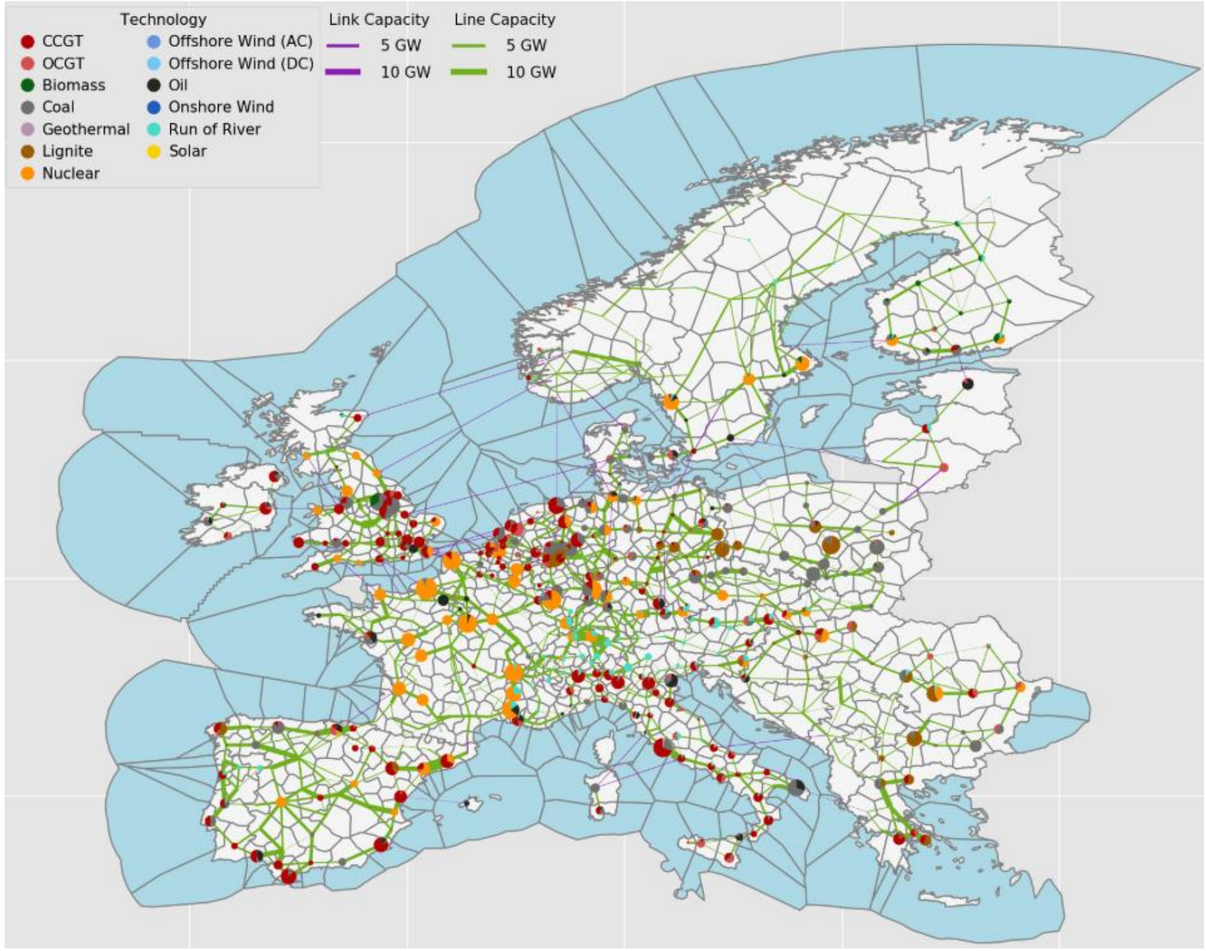
Include electricity demand, generation, storage and transmission connections across Europe.

Find the Lowest-Cost Solution

Optimise investment and operation while meeting demand and respecting emissions and technical limits.

Compare Scenarios

Compare total system costs with and without retrofits to quantify their value.

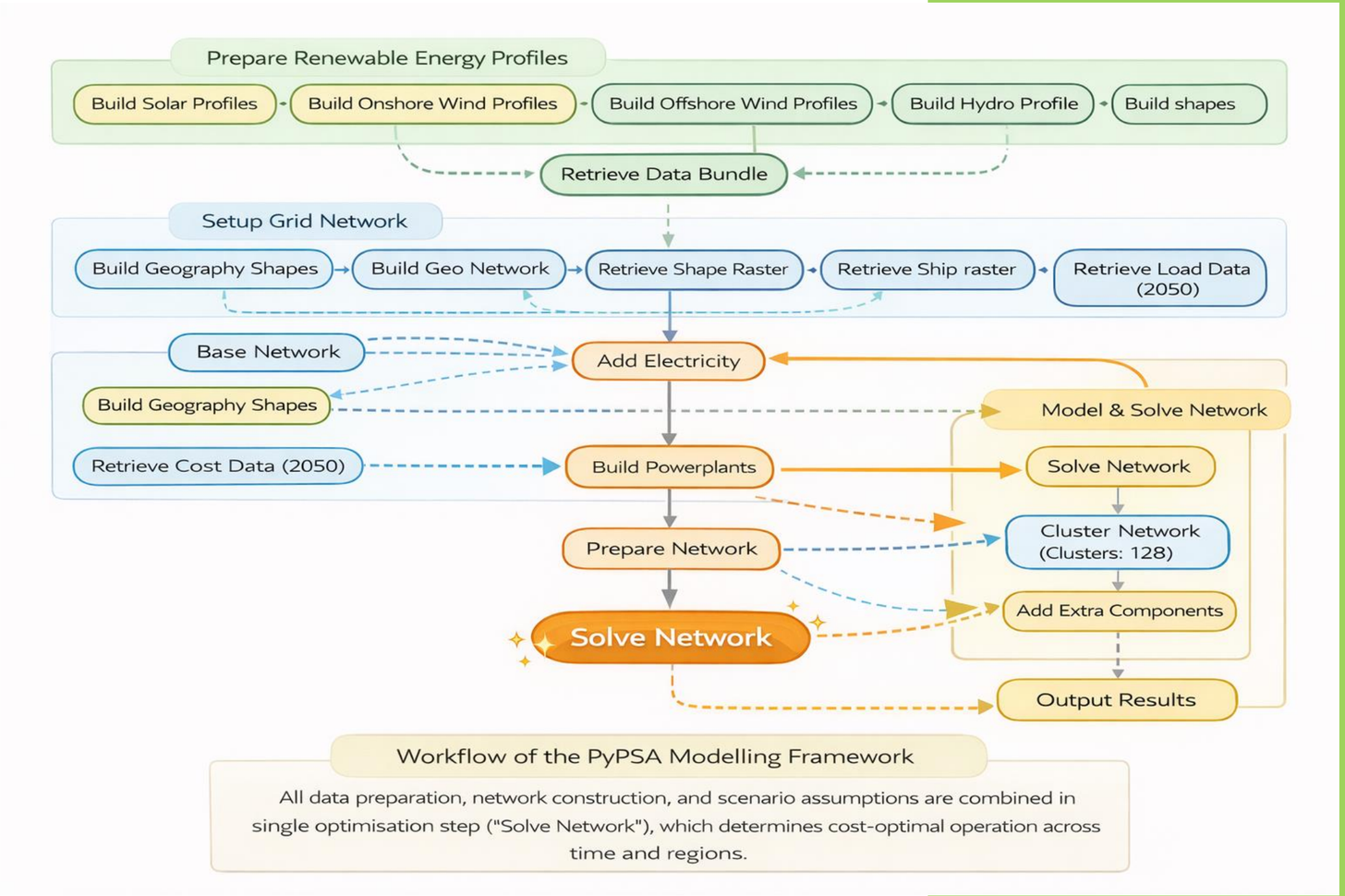


PyPSA: Open-Source Power System Modelling

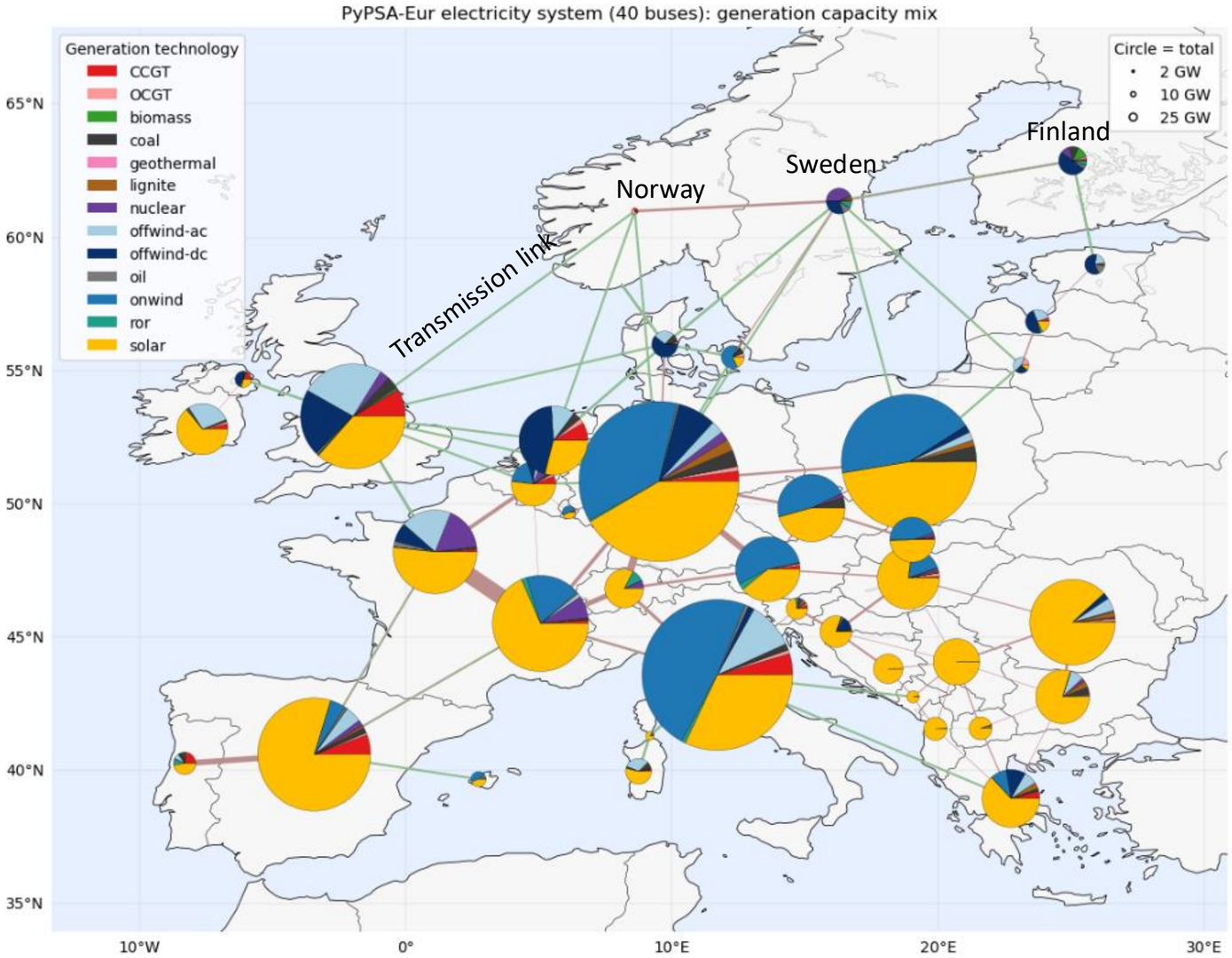
- PyPSA stands for Python for Power System Analysis.
- In this study, it formulates a large linear optimisation problem to find the lowest-cost investments and operation.
- Open code and documented assumptions support transparent and reproducible results.

PyPSA

An open-source workflow for building European power system models using data on demand, generation, storage and transmission networks.



The European Power System Model at a Glance



39 Nodes

Representing regions across the European power system.

2,920 Time Steps

One full year at three-hour intervals.

Planning Year: 2050

A future European power system.

Net-Zero CO_2 Constraint

A system-wide limit on net CO_2 emissions.

Joint Optimisation

Investment, generation, storage operation, power flows and hydropower retrofits.

Four Decisions Optimised Together

Generation Investment

How much wind, solar and other generation capacity to build in each region.

Storage Operation

When to charge and discharge batteries and pumped hydropower at each time step.

Transmission Flows

How electricity flows between regions through the grid.

Retrofit decisions

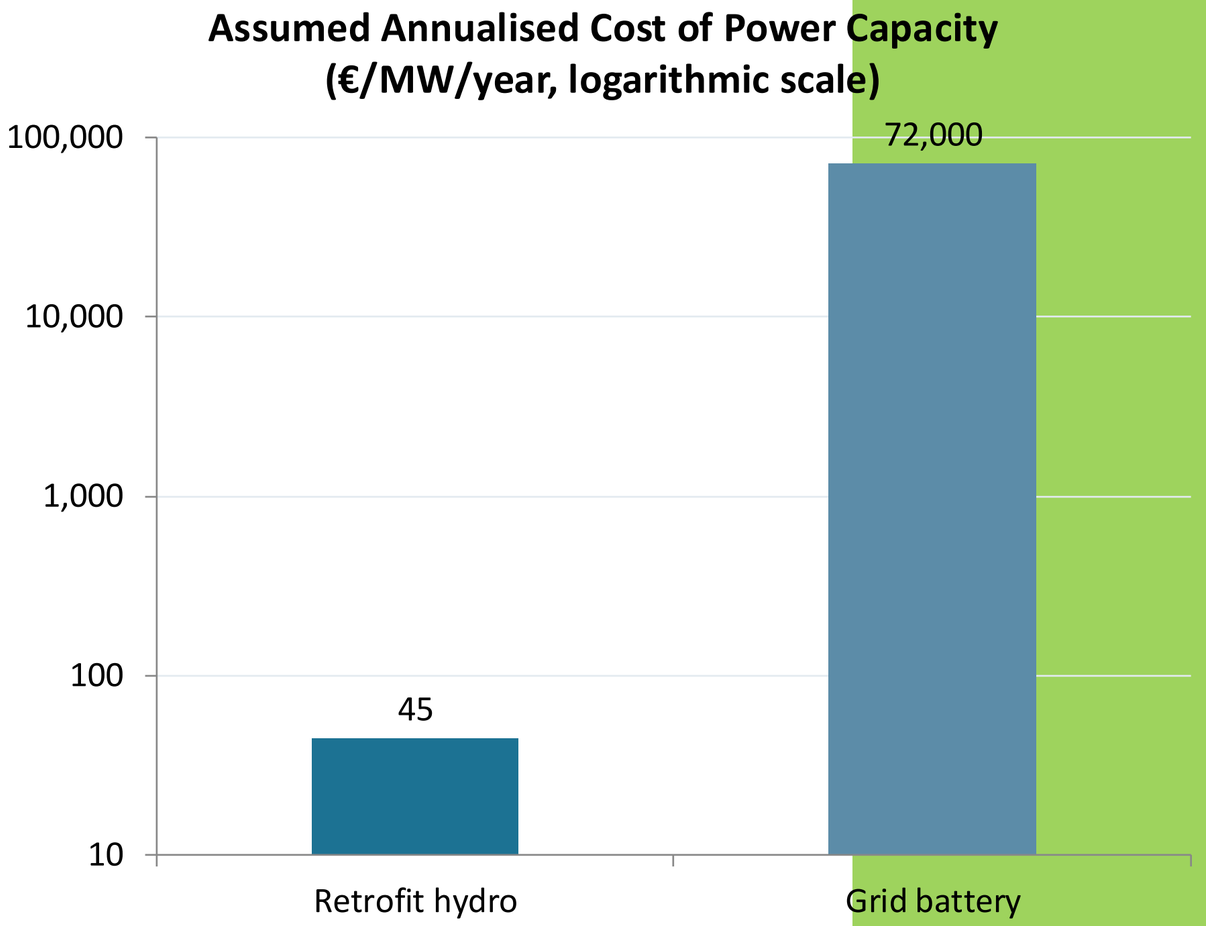
Where to add pumping capability and how much capacity to install.

Joint optimisation considers all four together to find the lowest total system cost.

How Retrofitted Hydro Are Modelled

- Pumping capability can be added at eligible hydropower plants.
- Retrofit capacity is limited to 30% of the plant’s existing capacity.
- The model compares retrofits with batteries and other investment options.

45 €/MW·yr — assumed annualised cost of retrofit power capacity.



A Large and Interconnected Optimisation Problem

Hundreds of thousands of decision variables

Millions of constraints

39 regions × 2,920 time steps

Multiple scenarios to compare

All regions, technologies and time steps are optimised together. Investment decisions, storage operation and the annual CO_2 limit connect the entire year, so individual time steps cannot be solved independently.

European model → **Linear optimisation problem** → **Gurobi solver** → **Results and shadow prices**

Why More Computing Power Is Needed

Limitations of the Local Workstation

- Insufficient memory for the full model.
- A single scenario can take days or fail to finish.
- Limited capacity to compare multiple scenarios.

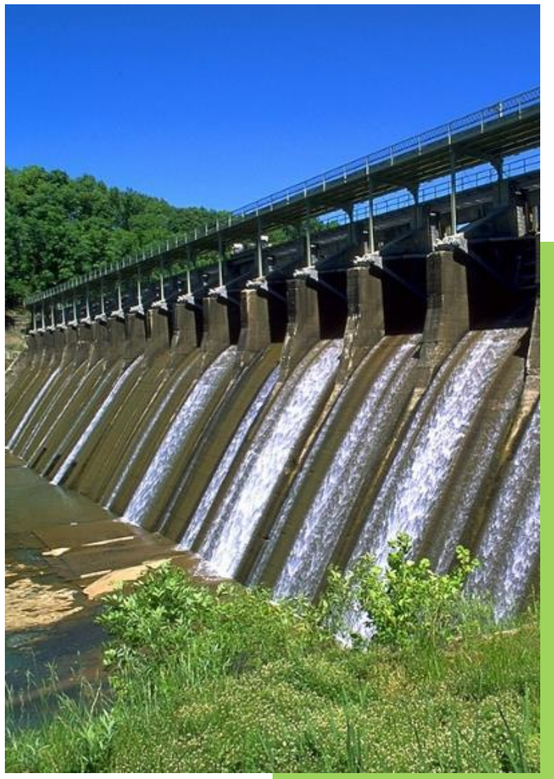
Computing Requirements

- Full-year optimisation at the chosen model resolution.
- Reliable shadow prices for economic analysis.
- Faster runs across multiple scenarios.

Reliable economic analysis requires a well-converged solution and carefully checked shadow prices.

The Value of Retrofitted Hydro in the Energy Market

How retrofits affect electricity generation, storage operation and total system costs.



Comparing Two Scenarios

S1 — Baseline

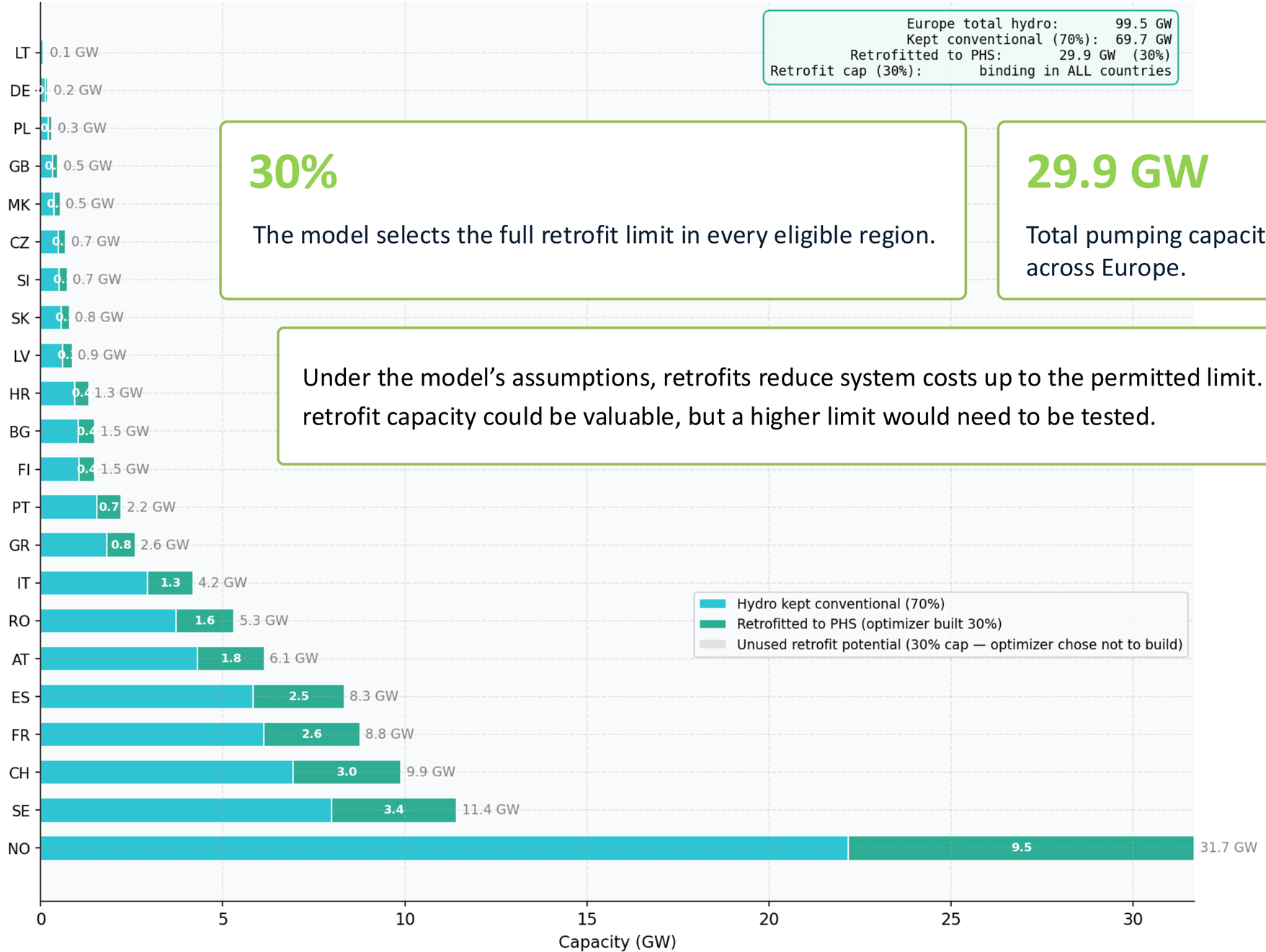
- A net-zero European power system in 2050.
- Flexibility is provided by batteries, existing hydropower and other available technologies.
- Hydropower retrofits are not allowed.

S2 — Retrofit

- The same power system and assumptions as S1.
- Pumping capacity can be added to eligible hydropower plants.
- Retrofit capacity is limited to 30% of existing plant capacity.

Comparing the total system costs of S1 and S2 shows the value of allowing hydropower retrofits.

Result 1 — The Model Selects the Maximum Allowed Retrofit Capacity



30%

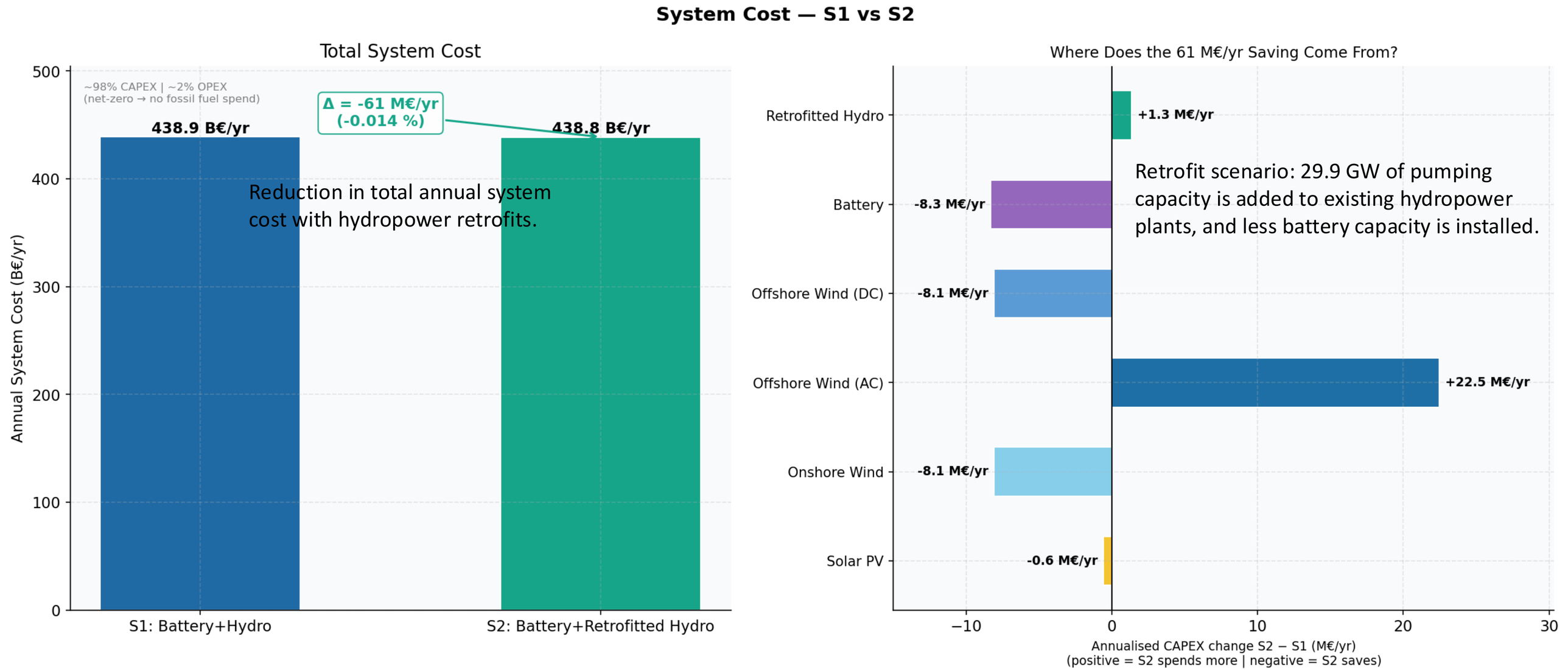
The model selects the full retrofit limit in every eligible region.

29.9 GW

Total pumping capacity added to existing hydropower plants across Europe.

Under the model's assumptions, retrofits reduce system costs up to the permitted limit. This suggests that additional retrofit capacity could be valuable, but a higher limit would need to be tested.

Result 2 — Lower System Costs and Less Battery Capacity



Result 3 — More Stable Prices and Better Use of Renewables

More Stable Electricity Prices

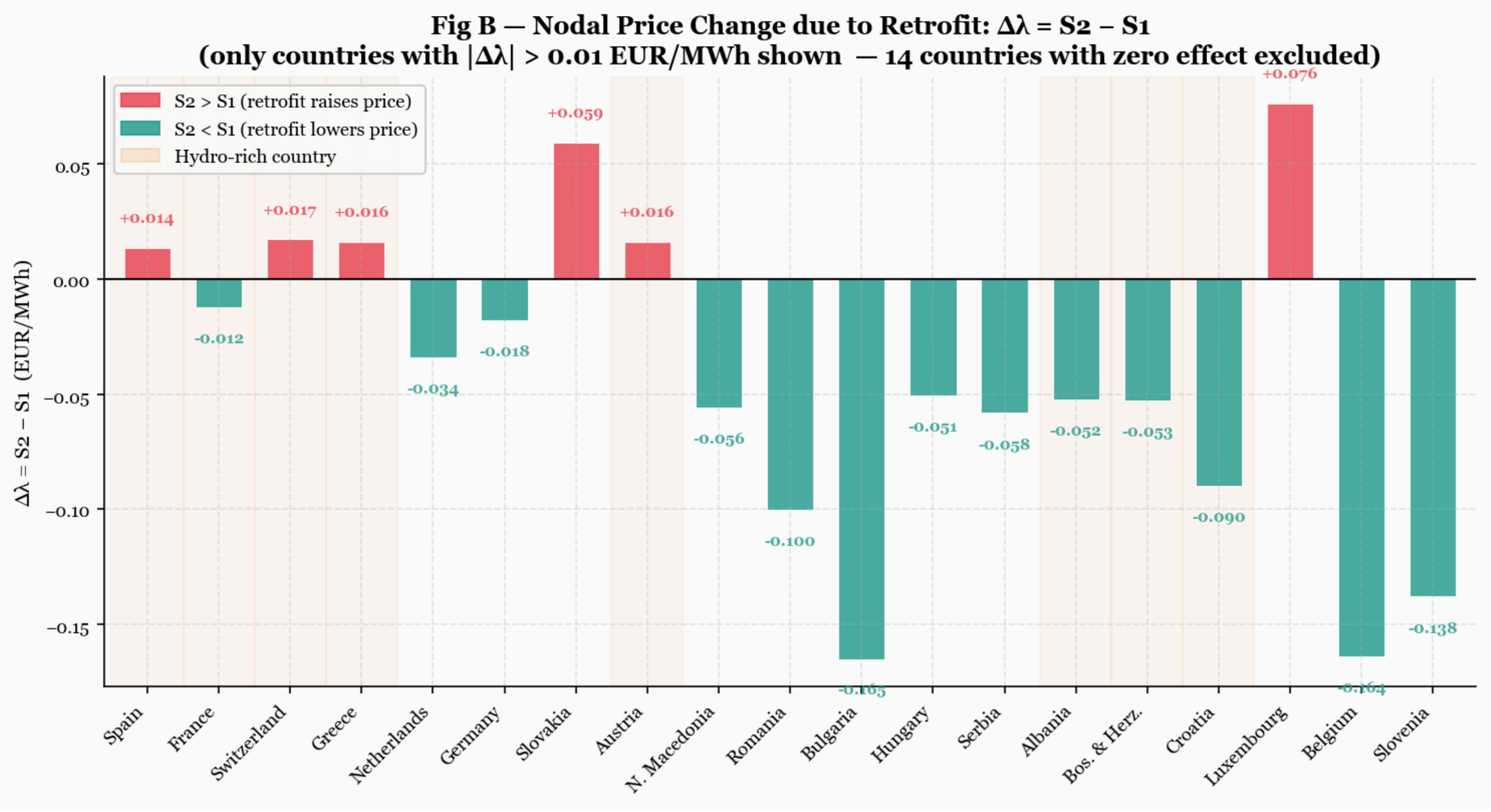
Electricity prices become less variable, particularly in Spain and Portugal, where storage helps balance changes in solar generation.

Better Use of Renewable Energy

Retrofits use surplus wind and solar electricity to pump water uphill, making that energy available later.

The Role of Transmission

The model identifies where transmission limits restrict the benefits of retrofits and where grid reinforcement could increase their value.



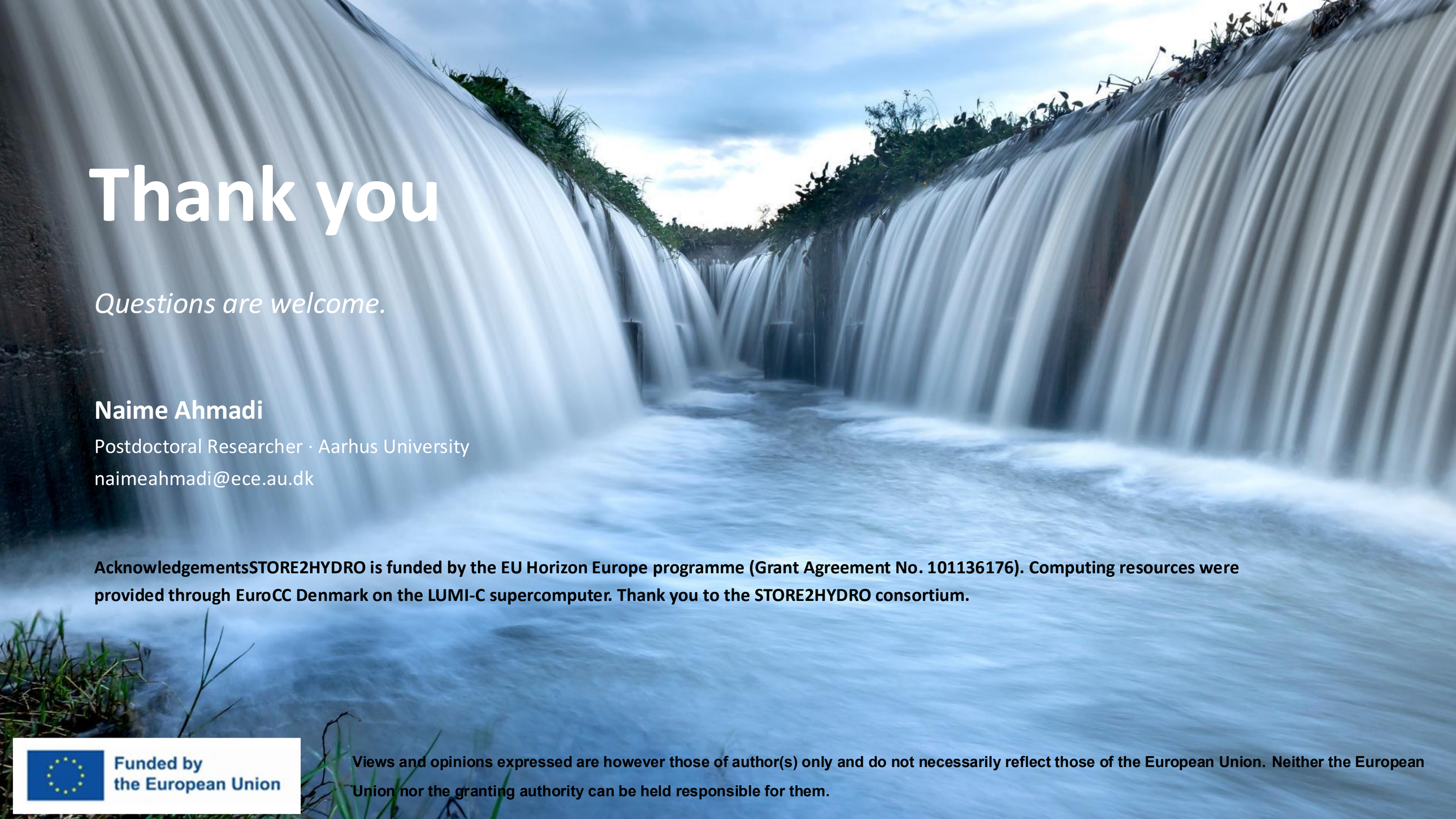
What High-Performance Computing Made Possible

- Solving the model for a full year at the chosen three-hour resolution.
- Comparing multiple retrofit scenarios and reserve market designs.
- Obtaining shadow prices for economic analysis.

Key message: With support from EuroCC Denmark, LUMI-C provided the computing resources needed to run the large-scale European model and compare scenarios.

Key Takeaways

- Retrofitting existing hydropower plants can provide additional large-scale energy storage by reusing existing infrastructure.
- In the modelled net-zero European system, retrofits are selected up to the permitted limit in all eligible regions.
- Retrofits reduce total system costs and the need for battery capacity. They can also help make electricity prices more stable.
- The model helps identify where transmission constraints limit the benefits of retrofits.
- High-performance computing, supported by EuroCC Denmark, made the energy and reserve analysis possible.



Thank you

Questions are welcome.

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