Imperial College London

Strategic Development of Pan-European Network without Perfect Foresight and Considering Long-Term uncertainties

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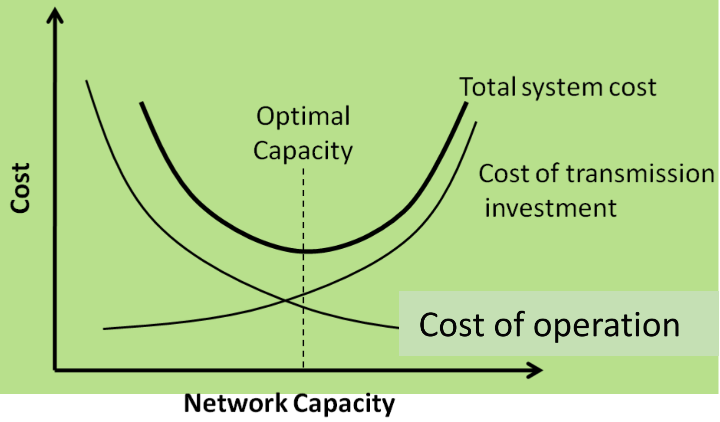
Where, when, what, how much to build?

- Transmission planning is driven by
  - Need to meet peak demand with sufficient reliability.
  - Cost-benefit considerations

$$\max\{\text{social welfare}\} = \min\{\text{total cost}\}$$

- The system evolution is affected by significant uncertainty:
  - **Long-Term Uncertainties** (investment timescale)
    - Location / size/ timing of new generation plants
    - Investment costs of novel technologies (such as storage)
    - Long-term demand growth due to electrification of transport and heat



Why consider uncertainty?

- Capital decisions in power systems are largely **irreversible**.
  This creates the risk of inefficient investment (**stranded assets**).

- There is **learning** regarding future developments (inter-temporal resolution of uncertainty).

- The planner can exert **managerial flexibility** in decision making;
  'Fit-and-forget' vs. 'Wait-and-see'.

- **Time Value of Money** & Value of Delaying for Uncertainty Resolution.

Planning frameworks that consider **uncertainty** are fundamental for identifying **openings for strategic investment action**

System & Objective

- Context
  - Significant Capacity Connections of Renewable sources of Electricity in the Pan-European electricity system
  - Take place under uncertainty in locations, volumes, timing in the deployment of renewables and load-growth

- Key Question:
  - How best to design the European Electricity Transmission system at minimum expected cost, given future uncertainties and considering storage?

- Objective:
  - Identify optimal investments
  - Quantify the Option Value of Storage
  - Conduct sensitivity analyses.

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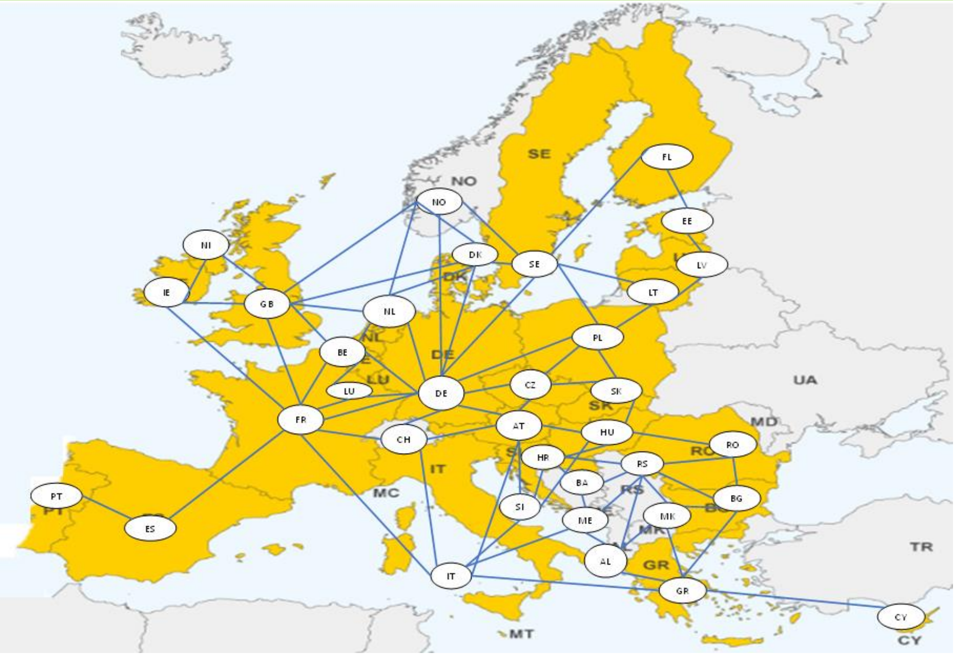
Technologies Modelled

- Electricity Storage:
  - Examples: Compressed Air, Lithium Battery, Pumped Hydro Storage
- Interconnectors
- Generation technologies modelled:
  - OCGT, CCGT, Coal, Nuclear
  - Hydro Reservoir & Run of river
  - Wind, solar PV
  - Other Renewables

System & Scope

- Scope:
  - Horizon: 2020 – 2060
  - Topology: European system
- System Representation:
  - A country is represented by a circular bus
  - Two countries linked via an interconnector
  - Focus on Electricity
- Planning:
  - A centralized network planner decides investments based on criterion of smallest expected cost



Problem Formulation

- **min** $\mathbb{E}$\{ Investment Cost + Operational Cost \}, subject to:
- **Investment constraints (MILP)**
- **Operational constraints (LP)**
  - DC Power Flow equations
  - Transmission constraints
  - Generation constraints
  - Storage constraints

- Multi-Stage, multi-year problem
- Investment variables couple the stages
- Stochastic formulation – Uncertainty described by scenario tree
- Consideration of strategic actions and definition of probabilities

Modelling Challenges

Severe challenges related to **problem size:**

- Consideration of large scenario trees - numerous multivariate nodes
  – **Multiple sources of uncertainty** expand tree size exponentially
  – Build times increase importance of **time resolution**
- Novel technologies introduce **coupling** in the problem structure
  - Storage Operation → time coupling

Need for Decomposition & Reformulation

- **Numerous technologies** in addition to traditional assets
  - binary variables

Need for Convexification

- Renewables and demand patterns
  - Expansion of the operational state-space

Optimal choice of representative time points

Traditional optimisation methods are reaching their **computational limits**

Overcoming Modelling Challenges

Computationally Extremely Demanding , making the case for decomposition.

- Undecomposed problem → Intractability.
  - Lack of convergence due to immense state space.
- Classic Benders Decomposition → Intractability.
  - Not enough cut constraints.
- Multi-Cut Benders with Parallel Implementation→ Intractability.
  - Large number of cut constraints, still not leading to convergence.
- Nested Benders Decomposition with the use of Discretization (Typical Days).

Nested Benders decomposition	Forward and backward passes of the formulation increase the accuracy in the selection of Lagrange multipliers.
Multi-Cut Benders decomposition	Numerous cut constraints appended per iteration at the master, aiming towards speed of convergence.
Classic Benders Decomposition	Classic Benders approach involving the generation of a single cut constraint per iteration.

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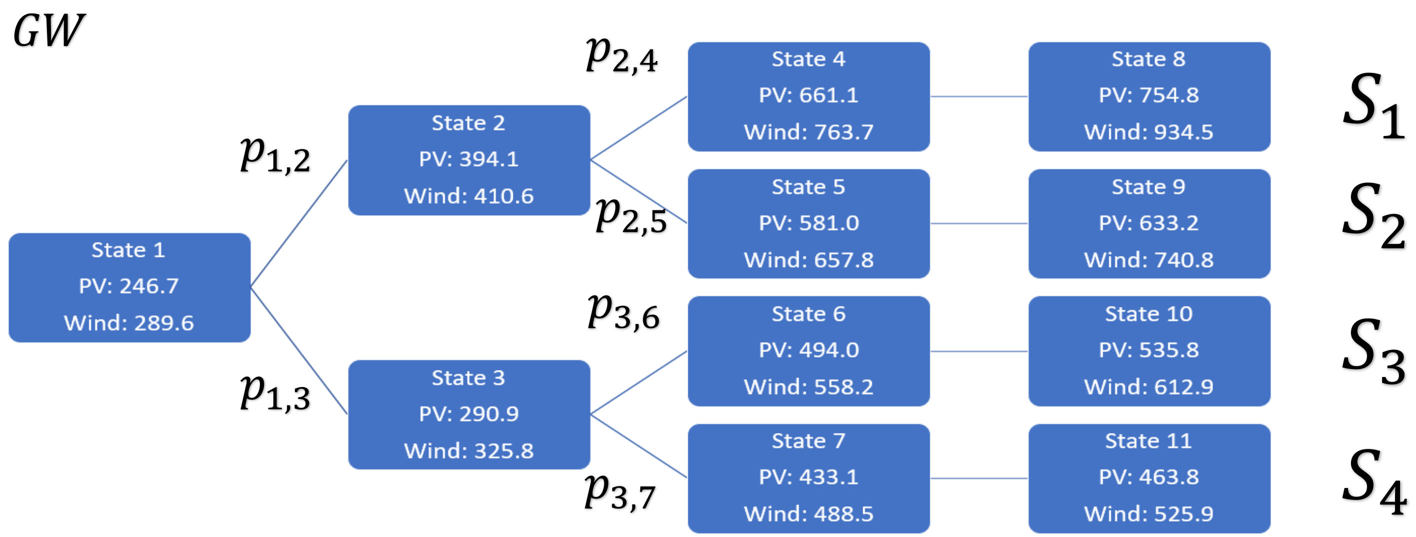
Uncertainty Representation

- Multiple Sources of Uncertainty:
  - Wind deployment & Solar PV deployment
  - Cost of Storage
  - Level of Demand

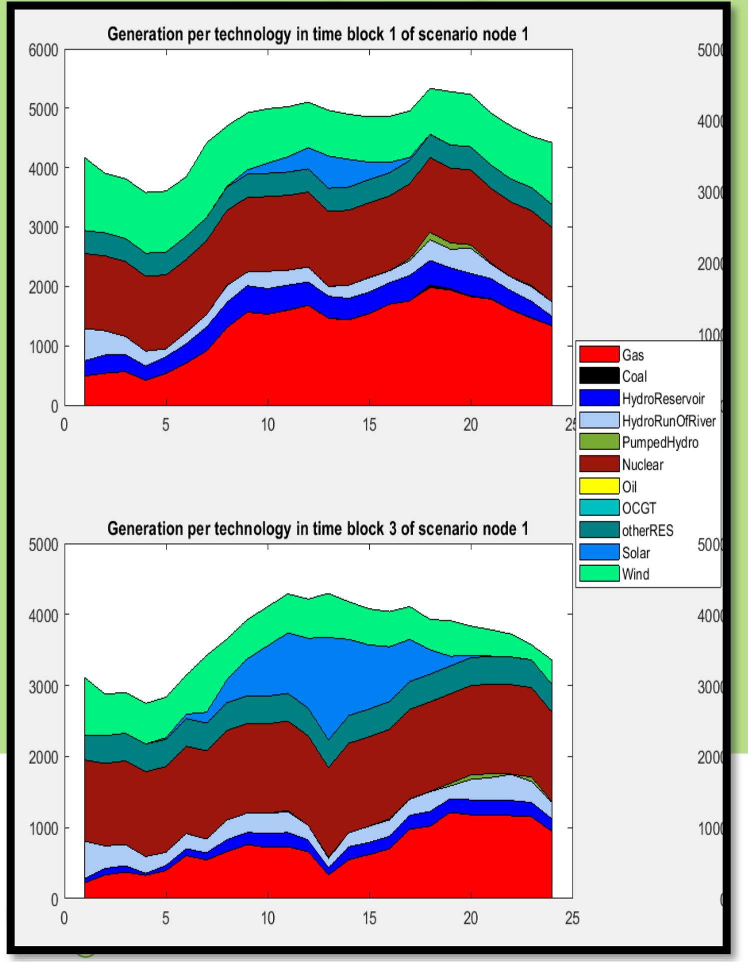
- Many Dimensions of Uncertainty:
  - Magnitude (How much)
  - Location (Where)
  - Timing (When)

- 10-year epochs, starting from 2020.

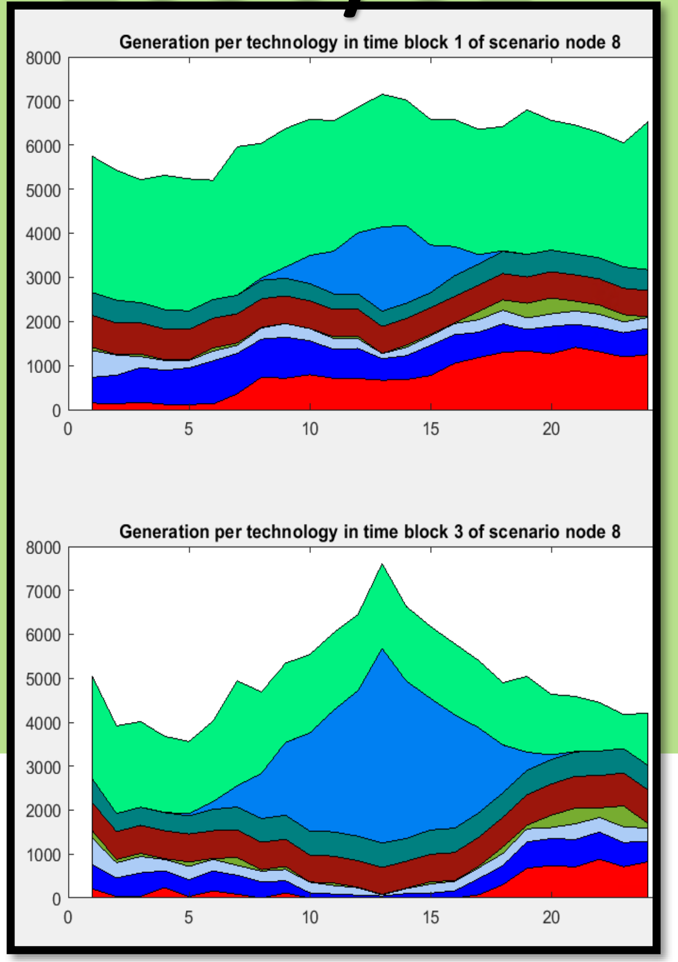


Generation mix evolution

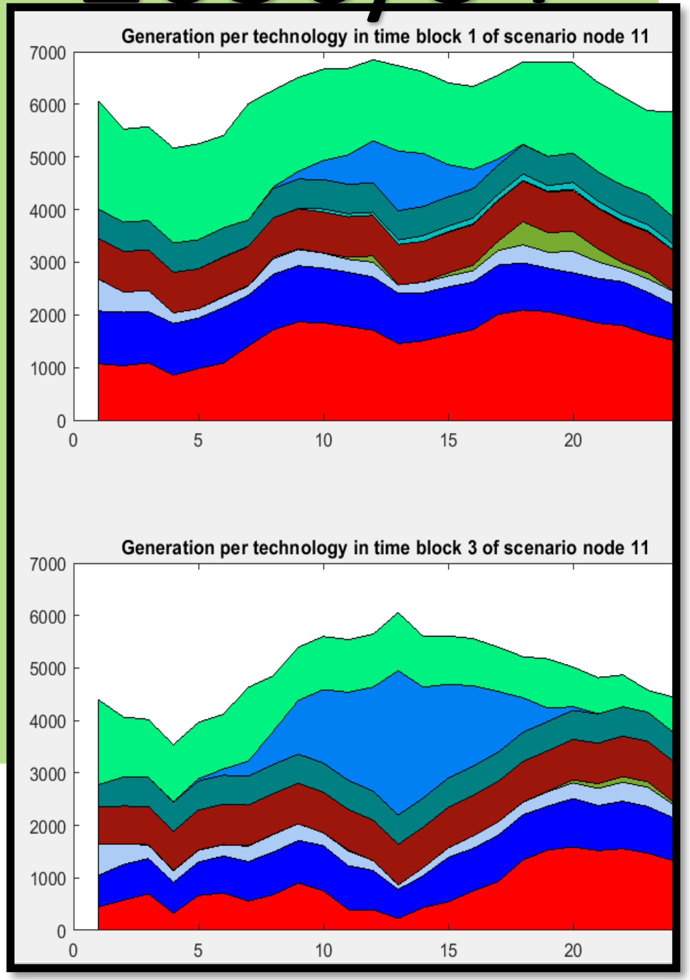
2020



2050/S1



2050/S4



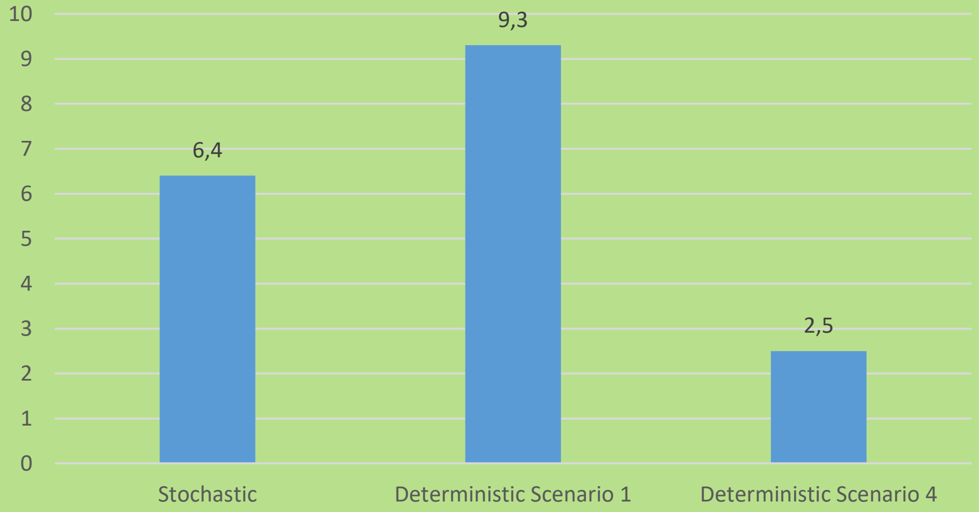
Electricity Storage & Transmission Investment

- Deploying storage leads to 15% reduced transmission investment or 4 billion euros savings (expected values).
- Energy Storage is deployed so that its optimal operation can aim towards the increased integration of renewables.

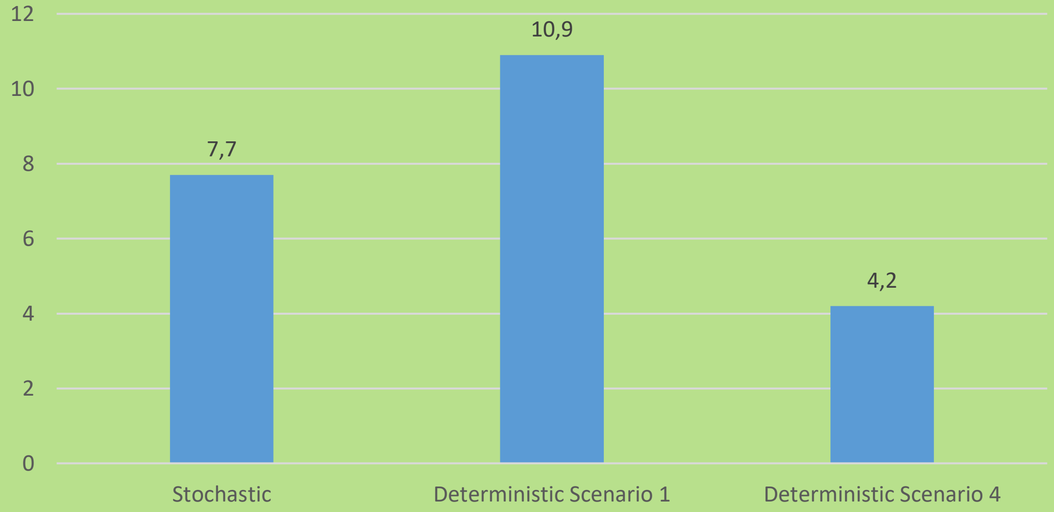
Cases $p_{1,2} - p_{1,3}$	Expected Reduction in transmission investment cost when Storage is being deployed compared to when it is not		Expected Transmission Investment (GW) reduction
90-10	30%	7 bn euros	10
70-30	15%	4 bn euros	5

Stochastic versus Deterministic Optimization

Transmission Investment at node 1, when storage is available (GW)

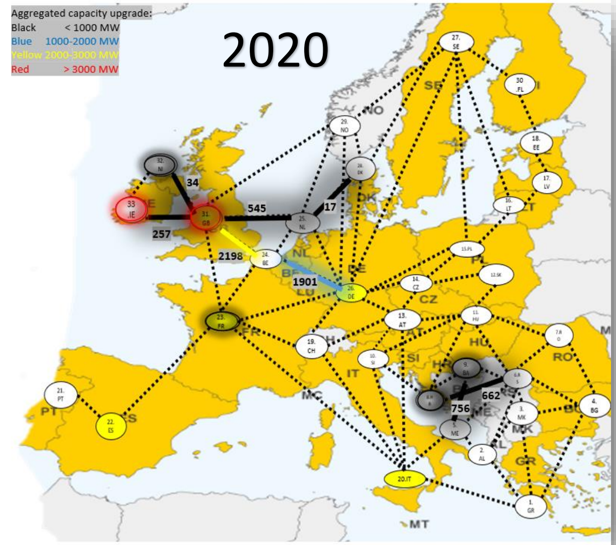


Transmission investment at node1, when storage is not available (GW)

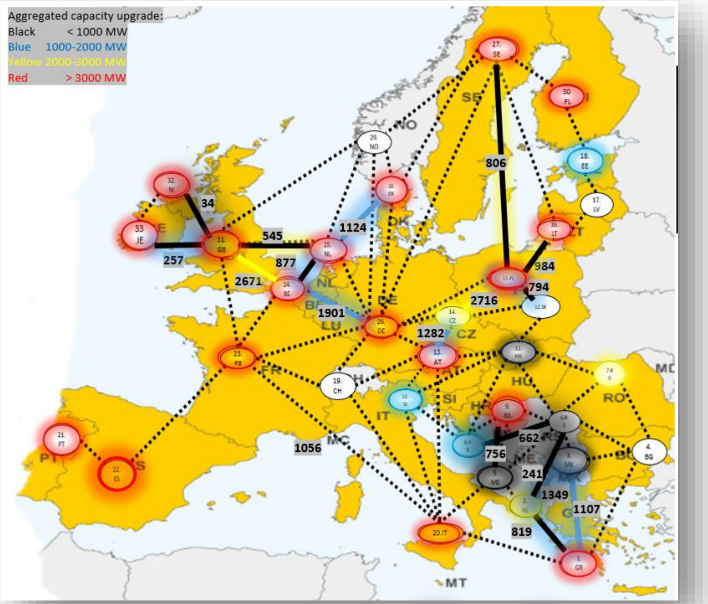


WITH STORAGE

- Transmission Investment: 6.4 GW
- Storage: 9.8 GW



2050 – SCENARIO 1

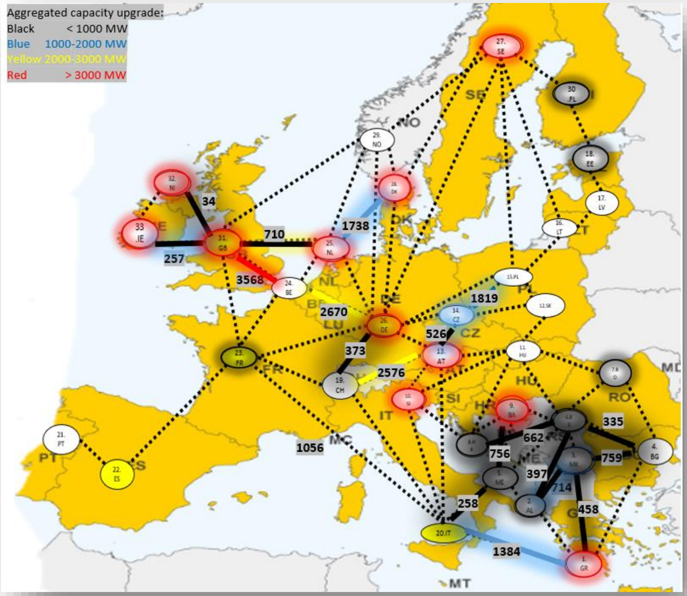


- Transmission Investment: 16 GW
- Storage: 450 GW

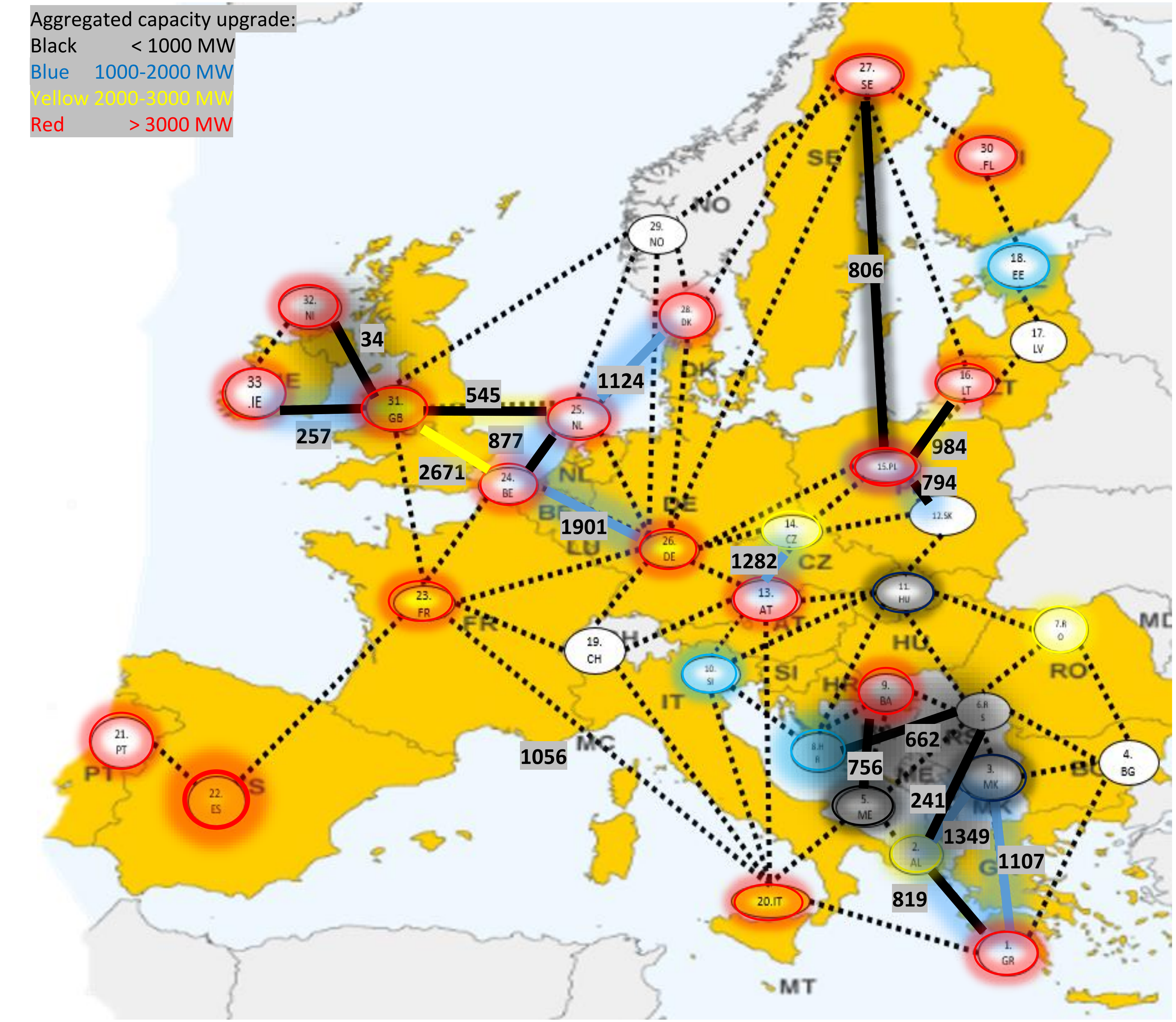
Greater investment in Storage across S1 (low cost) to facilitate the higher Renewables capacity.

Lower investment in Storage across S4 (high cost) and more transmission investment to allow renewables.

2050 – SCENARIO 4



- Transmission Investment: 20 GW
- Storage: 85 GW



=========Epoch 4 aggregate capacities ======

1.January. 2050: decision point. Applies until: 31.dec.2059. I.e. 10 years

Dotted lines: have their initial capacity . They have not been upgraded.

Black lines: are the lines whose capacity is decided to be upgraded

Circles: are the buses where storage is decided to be upgraded

storage device 1: Greece : 19862.3 MWh / 19862.3 MW
storage device 2: Albania : 2590.52 MWh /2590.52 MW
storage device 3: Macedonia : 854.37 MWh /854.37 MW
storage device 5: Montenegro: 844.46 MWh /844.46 MW
storage device 7: Romania : 2324.17MWh / 2324.17MW
storage device 8: Croatia : 1596.16MWh / 1596.16 MW
storage device 9: Bosnia : 9744.96 MWh / 9744.96 MW
storage device 10: Slovenia : 1782.69 MWh /1782.69 MW
storage device 11: Hungary : 758.01 MWh / 758.01 MW
storage device 13: Austria : 7539.63 MWh / 7539.63 MW
storage device 14: Czech Republic : 2010.25MWh / 2010.25 MW
storage device 15: Poland : 25716.61 MWh / 25716.61 MW
storage device 16: Lithuania : 7727.93MWh / 7727.93 MW
storage device 18: Estonia : 1176.01 MWh / 1176.01 MW
storage device 20: Italy : 13255.4 MWh/ 13255.4 MW
storage device 21: Portugal : 22151.36 MWh / 22151.36 MW
storage device 22: Spain : 78663.14MWh / 78663.14MW
storage device 23: France : 31552.80 MWh / 31552.80MW
storage device 24: Belgium : 4819.84 MWh / 4819.84 MW
storage device 25: Netherlands : 69494.94 MWh / 69494.94 MW
storage device 26: Germany : 42617.9 MWh / 42617.9 MW
storage device 27: Sweden : 9646.15MWh / 9646.15 MW
storage device 28: Denmark : 32598.99MWh /32598.99 MW
storage device 30: Finland : 6285.51 MWh / 6285.51 MW
storage device 31: GB : 15538.1 MWh / 15538.1 MW
storage device 32: N. Ireland : 22555.45 MWh / 22555.45 MW
storage device 33: Ireland : 57893.8 MWh / 57893.8MW

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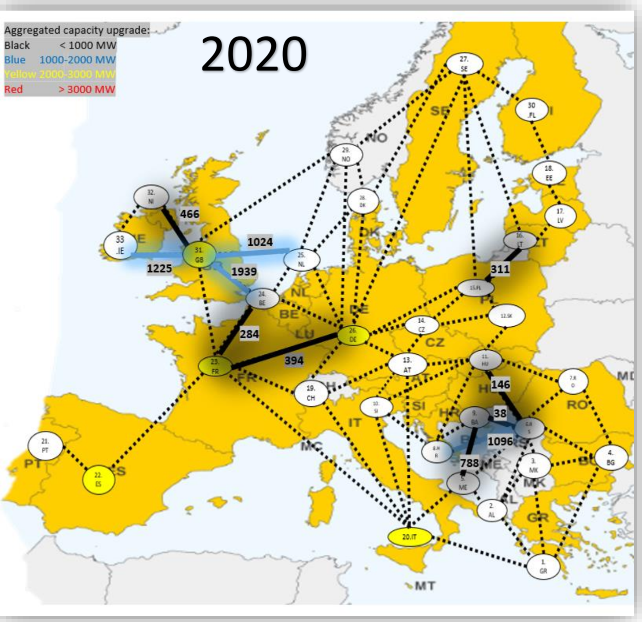
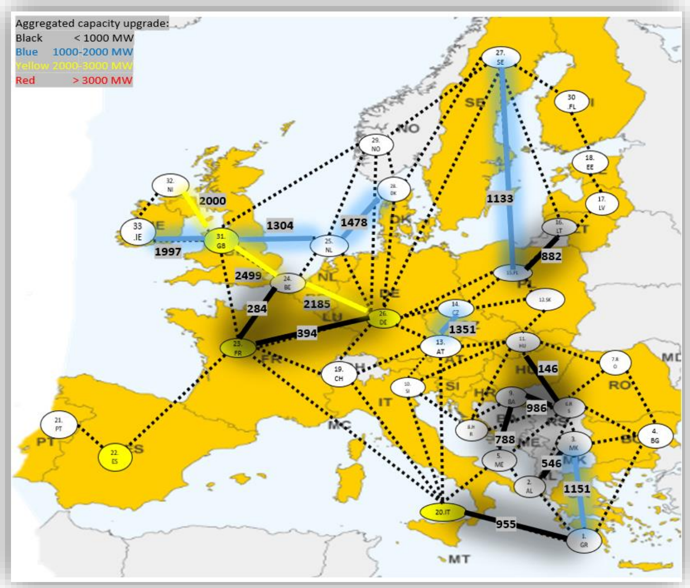
WITHOUT STORAGE

- Transmission Investment: **7.7** GW

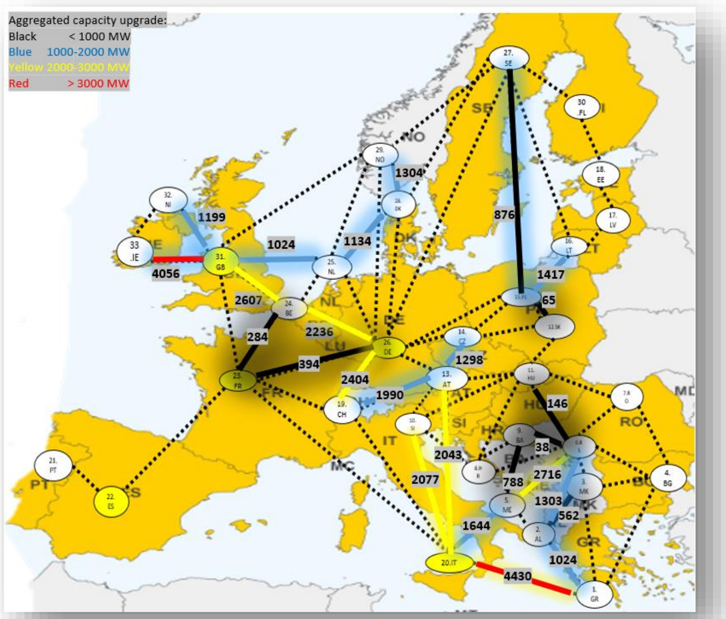


2050 – SCENARIO 1



Transmission : 21 GW

2050 – SCENARIO 4



No storage investment.

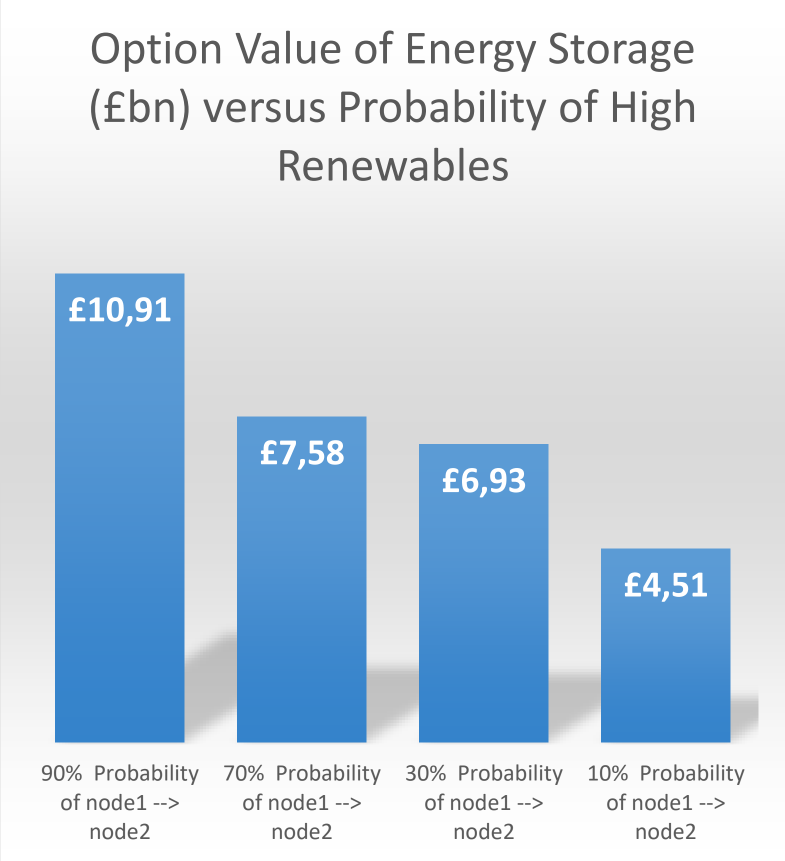
Given lower renewables across S4, than across S1, the planner attempts to reduce operational cost by investing more in interconnection to allow low-cost thermal generation (eg CCS gas)

Transmission : 40 GW

Option Value of Storage

- Option Value of Energy Storage
  - Net Economic Savings from Investing In Energy Storage Under Uncertainty.
  - Calculation: Solving Stochastic Optimization

- Sensitivity Analysis on Probability of having Large Renewables into the System.
  - Probabilities significantly affect the Option Value.
  - The more likely it is for Large Renewables to connect, the higher the Option Value of Storage.
  - Under Large Renewables Integration, the Energy Storage has greater potential to contribute positively to system economics as it enables higher use of Renewables.



Key Messages

- This Electricity transmission planning study covers the horizon 2020 – 2060 and focuses on 33 European countries, where significant amount of renewables will be connected in the coming decades.
- The objective of the study is to yield the optimal investments in Energy Storage and in upgrading Interconnectors, under uncertainty that surrounds Wind & Solar installed capacities, Energy Storage investment cost and peak demand, via a 4-stage scenario tree.
- The Option Value of energy Storage reflects the net economic benefit accrued from investing in Storage under uncertainty.
- It is found that Storage has significant Option Value which increases with the likelihood of connecting more renewables, as well as with higher demand in the system. In these cases, Energy Storage has higher scope for generating savings under uncertainty.
- The tool involves an Advanced Decomposed Optimisation Model, using Stochastic Optimization. It generates a complete investment output and a range of graphs. It can be used to perform energy investment analysis under multiple sources of uncertainty under different dimensions.

❑Thank you!