Robust operation and planning of energy systems under uncertainty

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1. Motivation
   • Types of uncertainty
   • Sources of planning uncertainties

2. Motivating examples
   • Transmission planning under uncertainty: the benefit of FACTS and storage
   • Distribution planning under uncertainty: the benefit of controllability

3. Computational Aspects

4. Summary/Discussion
Historically, power system planning has been carried out deterministically, against a certain scenario. However, due to the unbundling of the electricity industry and the rapid growth of renewable energy sources, planning now entails significant uncertainty.

- **Long-Term Uncertainties** (investment timescale)
  - Location, size and technology of new generation plants
  - Investment costs of novel technologies (e.g. storage)
  - Long-term demand growth due to electrification of transport and heat
  - Long-term price trends (e.g. coal, gas, CO2)

- **Short-term Uncertainties** (operational timescale)
  - Power injections from intermittent sources (e.g. wind, solar)
  - Demand patterns due to Electric Vehicles, heat pumps etc.
  - Equipment outages

Described via scenarios/ranges

Data-driven statistical models
Planning uncertainties

Drivers for change in transmission planning:

- **Multiple sources of long-term uncertainty**
  - Generation deployment patterns; What? When? Where?
  - Electrification of heating and transport sectors
  - Technology costs
  - Other policy aspects e.g. CO2 emission targets etc.

- **New technologies** (e.g. energy storage, FACTS):
  - Increase system controllability and provide flexible balancing
  - Do not suffer from lengthy permissioning as conventional reinforcements
  - Can constitute attractive strategic investments for managing uncertainty

- Planning is no longer a straightforward cost-minimisation exercise.

- **Planners** have to optimise across multiple candidate assets while also considering uncertainties i.e. ‘what-if’ strategy vs. schedule
We show the fundamental difference in three approaches:

- **D-I**: Deterministic planning model where all asset types are allowed.
- **S-I**: Stochastic planning model where only investment in line reinforcements is allowed.
- **S-II**: Stochastic planning model where investment in all asset types is allowed.

**Uncertainty wrt wind build-out scenario**

Scenario 1 (S1)

Scenario 2 (S2)

Scenario 3 (S3)

Scenario 4 (S4)
Available assets for investment are shown below:

**Table I**
*Transmission Line Reinforcement Options*

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Reinforcement Capacity [MW]</th>
<th>Annualized Capital Cost [£/year]</th>
<th>Build Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option A</td>
<td>200</td>
<td>1,500,000</td>
<td>1 epoch</td>
</tr>
<tr>
<td>Option B</td>
<td>400</td>
<td>2,500,000</td>
<td>1 epoch</td>
</tr>
</tbody>
</table>

**Table II**
*Alternative Investment Options*

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Annualized Capital Cost [£/year]</th>
<th>Build Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-shifter</td>
<td>600,000</td>
<td>0 epochs</td>
</tr>
<tr>
<td>Storage device</td>
<td>15,000,000</td>
<td>0 epochs</td>
</tr>
</tbody>
</table>

QB maximum shift angle: 30°
Storage Charge/Discharge rate: 400MW
Storage Energy Capacity: 1600 MWh
## Deterministic and Stochastic Results

### Storage is sub-optimal under full knowledge of the future

<table>
<thead>
<tr>
<th>D-I</th>
<th>S1</th>
<th>A (3-9), B (3-24), B (15-24), PS (3-9), PS (11-14)</th>
<th>-</th>
<th>PS (15-16)</th>
<th>91.3</th>
<th>4957.4</th>
<th>5048.8</th>
<th>44.9</th>
<th>5603.8</th>
<th>5648.7</th>
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</thead>
<tbody>
<tr>
<td>S2</td>
<td>A (3-9), A (3-24), A (15-24)</td>
<td>PS (11-14)</td>
<td>-</td>
<td>-</td>
<td>52.9</td>
<td>5267.7</td>
<td>5320.6</td>
<td>4.9</td>
<td>5603.8</td>
<td>5648.7</td>
</tr>
<tr>
<td>S3</td>
<td>A (3-9), A (3-24), A (15-24)</td>
<td>-</td>
<td>PS (9-12), PS (10-12), PS (11-13)</td>
<td>33.6</td>
<td>5834.9</td>
<td>5868.6</td>
<td>0.0</td>
<td>6295.1</td>
<td>6295.1</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0</td>
<td>6295.1</td>
<td>6295.1</td>
<td>0.0</td>
<td>6295.1</td>
<td>6295.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S-I</th>
<th>S1</th>
<th>B (3-24)</th>
<th>A (1-3), A (3-9), A (14-16), B (15-16), B (15-24)</th>
<th>-</th>
<th>-</th>
<th>87.6</th>
<th>5078.7</th>
<th>5166.3</th>
<th>57.4</th>
<th>5665.9</th>
<th>5723.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>B (3-24)</td>
<td>A (1-3), A (3-9), A (14-16), B (15-16), B (15-24)</td>
<td>-</td>
<td>-</td>
<td>87.6</td>
<td>5336.5</td>
<td>5424.1</td>
<td>27.2</td>
<td>5897.1</td>
<td>5924.4</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>B (3-24)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>27.2</td>
<td>6295.1</td>
<td>6322.3</td>
<td>27.2</td>
<td>6295.1</td>
<td>6322.3</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>B (3-24)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>27.2</td>
<td>6295.1</td>
<td>6322.3</td>
<td>27.2</td>
<td>6295.1</td>
<td>6322.3</td>
<td></td>
</tr>
</tbody>
</table>

| S-II | S1 | A (3-9), B (3-24), B (15-24), PS (12-13), PS (16-19), STOR (24) | PS (3-9), PS (8-9), PS (16-17) | 149.2 | 5009.9 | 5159.1 | 79.6 | 5626.1 | 5705.7 |
|----|----|-----------------------------------------------|---------|--------|--------|------|--------|--------|
| S2 | A (3-9), B (3-24), B (15-24), PS (12-13), PS (16-19), STOR (24) | PS (9-11), PS (10-12) | 147.6 | 5253.7 | 5401.3 | 79.6 | 5626.1 | 5705.7 |
| S3 | A (3-24) | PS (9-11), PS (13-23) | 12.9 | 5875.4 | 5888.3 | 9.5 | 6295.1 | 6304.6 |
| S4 | A (3-24) | - | 9.5 | 6295.1 | 6304.6 | 9.5 | 6295.1 | 6304.6 |

### Conservative first-stage commitments to conventional reinforcements

### Ability to invest in storage defers long-term commitments to second stage (conditional on high-growth scenarios)

### Option Value of Flexible Assets

- STOR (24)
- PS (12-13), PS (16-19)
- PS (3-9), PS (8-9), PS (16-17)
- PS (9-11), PS (10-12)
- PS (9-11), PS (13-23)
- 11kV distribution network with 13 bus-bars arranged on four feeders.
- Uncertain PV build-out
- Potential voltage rise issues (limits ±0.06pu)
Scenario Trees for Uncertainty Description

Uncertainty wrt future PV build-out:

- **0 MW**
  - Node 1
  - Transition probabilities:
    - 0.5
    - 1.030 pu

- **1.0 MW** (9)
  - Node 3
  - Transition probabilities:
    - 0.5
    - 1.010 pu

- **2.9 MW** (5,6,15)
  - Node 2
  - Transition probabilities:
    - 0.7
    - 1.012 pu

- **3.4 MW** (4,5,6,15)
  - Node 4
  - 1.00 pu

- **2.9 MW** (5,6,15)
  - Node 5
  - 1.005 pu

- **2.0 MW** (7,8,9)
  - Node 6
  - 0.7

- **1.0 MW** (9)
  - Node 7
  - 0.3


**Transition probabilities for 2019-2020**: 2019-2020

- Scenario 1 (S1)
- Scenario 2 (S2)
- Scenario 3 (S3)
- Scenario 4 (S4)

**Buses with PV capacity**: 4, 5, 6, 15

**Substation voltage set-point**
Case Study - Investment Options

Three smart and one conventional investment options of different build time/cost are considered:

- **Demand Side Response (DSR)** allows the optimal intra-day shifting of flexible load (30% at each bus with 100% energy payback)
- **Coordinated Voltage Control (CVC)** measures actual voltage values at buses enabling the optimal regulation of the substation voltage.
- **Soft Open Point (SOP)** technology allows optimal control of active power flow and reactive compensation [135kW/135kVAr capacity @ 90% efficiency]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Build Time (epochs)</th>
<th>Annualized capital cost (£/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSR</td>
<td>0</td>
<td>3,200 (per bus)</td>
</tr>
<tr>
<td>CVC</td>
<td>0</td>
<td>24,000 (whole system)</td>
</tr>
<tr>
<td>SOP</td>
<td>0</td>
<td>29,000 (per NOP)</td>
</tr>
<tr>
<td>Reconductoring</td>
<td>1</td>
<td>17,060 (per line)</td>
</tr>
</tbody>
</table>
Case Study - Five typical days of operation

- For computational tractability, cost-benefit analysis is on the basis of repeated typical days.
- Five typical day profiles have been used to characterise the possible operating conditions (Elexon definition):
  - Winter
  - Spring
  - Summer
  - High summer (low demand & high PV)
  - Autumn
- Actual data from Low Carbon London trials
Mathematical Formulation I

(1) \[ z = \min \left\{ \sum_{m \in \Omega_M} \pi_m (r^I_{e_m} \omega^I_m + r^O_{e_m} \omega^O_m) \right\} \]

(2) \[ \omega^I_m = \sum_{q \in \Omega Q} \sum_{t \in \Omega T_q} C_{VQ} \delta_{t,c} c \left( (P_{m,t,g}^{\max} \zeta_{t,g} - P_{m,t,g}) \right) + \sum_{c \in \Omega C} SOP S_{m,c} \gamma_S \]

(3) \[ \omega^O_m = \sum_{q \in \Omega Q} \sum_{t \in \Omega T_q} \sum_{n \in \Omega N} D_{m,n} \gamma_D + \sum_{n \in \Omega N} \sum_{c \in \Omega C} SOP S_{m,c} \gamma_S \]

(4) \[ (P_{m,t,g})^2 + (Q_{m,t,g})^2 \leq (S_{m,t,g}^{\max} \zeta_{t,g})^2 \quad \forall m,t,g \Omega_{TH} U \Omega_{DG} \]

(5) \[ \tilde{F}_{m,l} = \sum_{\varphi \in \Phi_{KL}(m)} B_{\varphi,l} F_{\text{max}} \]

(6) \[ \tilde{B}_{m,l} = \sum_{\varphi \in \Phi_{KL}(m)} B_{\varphi,l} \]

(7) \[ \tilde{C}_m = \sum_{\varphi \in \Phi_{KL}(m)} C_{\varphi} \]

(8) \[ \tilde{D}_{m,n} = \sum_{\varphi \in \Phi_{KL}(m)} D_{\varphi,n} \]

(9) \[ \tilde{S}_{m,c} = \sum_{\varphi \in \Phi_{KL}(m)} S_{\varphi,c} \]

- Minimization of expected discounted operation and investment cost (social welfare maximisation)
- Investment cost per scenario node
- Operation cost per scenario node
- Substation transformer limits
- Path dependency
- Build-out time constraints
- Line investment
- CVC investment
- DSR investment
- SOP investment
Mathematical Formulation II

\[ P_{m,t,l}^s = (1 - \tilde{B}_{m,l})[V_{m,t,u_l}^2 g_i^A - V_{m,t,u_l} V_{m,t,v_l} g_i^A \cdot \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l}) - V_{m,t,u_l} V_{m,t,v_l} b_i^A \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l})] + V_{m,t,u_l} V_{m,t,v_l} b_i^N \cdot \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l}) \] \quad \forall m, t, l (10)

\[ P_{m,t,l}^r = (1 - \tilde{B}_{m,l})[V_{m,t,v_l}^2 g_i^A - V_{m,t,v_l} V_{m,t,u_l} g_i^A \cdot \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l}) - V_{m,t,v_l} V_{m,t,u_l} b_i^A \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l})] + V_{m,t,v_l} V_{m,t,u_l} b_i^N \cdot \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l}) \] \quad \forall m, t, l (11)

\[ Q_{m,t,l}^s = (1 - \tilde{B}_{m,l})[-V_{m,t,u_l}^2 b_i^A - V_{m,t,u_l} V_{m,t,v_l} g_i^A \cdot \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l}) + V_{m,t,u_l} V_{m,t,v_l} b_i^A \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l})] + V_{m,t,u_l} V_{m,t,v_l} b_i^N \cdot \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l}) \] \quad \forall m, t, l (12)

\[ Q_{m,t,l}^r = (1 - \tilde{B}_{m,l})[-V_{m,t,v_l}^2 b_i^A - V_{m,t,v_l} V_{m,t,u_l} g_i^A \cdot \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l}) + V_{m,t,v_l} V_{m,t,u_l} b_i^A \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l})] + V_{m,t,v_l} V_{m,t,u_l} b_i^N \cdot \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l}) \] \quad \forall m, t, l (13)
Mathematical Formulation III

\[
\left( P_{m,t,l}^s \right)^2 + \left( Q_{m,t,l}^s \right)^2 \leq \left[ F_l + f_{m,l} \right]^2
\]
\[
\left( P_{m,t,l}^r \right)^2 + \left( Q_{m,t,l}^r \right)^2 \leq \left[ F_l + f_{m,l} \right]^2
\]
\[
V_{m,t,n} \leq V_{\text{max}}
\]
\[
V_{m,t,1} = V_{m,t}^{c\text{vc}} + V_{m,t}^{\text{noc}}
\]
\[
V_{m,t,n} \leq V_{m,t}^{c\text{vc}} \leq V_{\text{max}}^{c\text{vc}} \cdot \mathcal{C}_{m}
\]
\[
V_{m,t}^{\text{noc}} = V_{\text{set}} - (1 - \mathcal{C}_{m})
\]
\[
\sum_{t \in \Omega_{t,q}} (\xi_{m,t,n}^d - \xi_{m,t,n}^c) = 0
\]
\[
\xi_{m,t,n}^d \leq \tilde{D}_{m,n} \cdot f_{t,n} \cdot d_{t,n}
\]
\[
\xi_{m,t,n}^c \leq \tilde{D}_{m,n} \cdot \bar{D}_{t,n}
\]
\[
R_{m,t,c} \leq p_{c}^{\text{max}} \cdot \mathcal{S}_{m,c}
\]
\[
|H_{m,t,c,n}^Q| \leq Q_{c}^{\text{max}} \cdot \mathcal{S}_{m,c}
\]

\[\forall m, t, l \quad (14)\]
\[\forall m, t, l \quad (15)\]
\[\forall m, t, n - \{1\} \quad (16)\]
\[\forall m, t \quad (17)\]
\[\forall m, t \quad (18)\]
\[\forall m, t \quad (19)\]
\[\forall m, n, q \quad (20)\]
\[\forall m, t, n \quad (21)\]
\[\forall m, t, n \quad (22)\]
\[\forall m, t, c \quad (23)\]
\[\forall m, t, c \quad (24)\]
\[\forall m, t, c \quad (25)\]

- Power limits
- Voltage limits
- Substation voltage
- CVC voltage regulation
- DSR energy equation
- Bounds on shift-able load
- SOP active power transfer limits
- SOP reactive power bound
Mathematical Formulation III

Active power system balance equation

\[
\sum_{g \in \Omega_{DS \cup \Omega_{TH}}} P_{m,t,g} I_{n,g} - \sum_{i \in \Omega_L | v_i = n} P_{m,t,i}^r - \sum_{i \in \Omega_L | u_i = n} P_{m,t,i}^s = \]
\[
+ d_{t,n} + \xi_{m,t,n}^d - \xi_{m,t,n}^c + \sum_{c \in \Omega_C | n = n_c^a} (H_{m,t,c} - R_{m,t,c} \eta_f) \\
\sum_{c \in \Omega_C | n = n_c^b} (R_{m,t,c} - H_{m,t,c} \eta_f) \quad \forall \ m, t, n \quad (26)
\]

Reactive power system balance equation

\[
\sum_{g \in \Omega_{DS \cup \Omega_{TH}}} Q_{m,t,g} I_{n,g} - \sum_{i \in \Omega_L | v_i = n} Q_{m,t,i}^r - \sum_{i \in \Omega_L | u_i = n} Q_{m,t,i}^s = H_{m,t,c,n}^q \\
\sum_{c \in \Omega_C | n = n_c^a \text{ or } n = n_c^b} \quad \forall m, t, n \quad (27)
\]
Case Study - Optimal Deterministic Investment plans (D-I)

Exclusive reliance on network reinforcement (economies of scale)
Smart options are completely ignored!

[S1]  
Node 1: [1-2] [2-3] [3-4] [4-5] [14-15]  
Node 2: No investment  
Node 3: No investment  
Node 4: No investment  
Node 5: No investment  
Node 6: No investment  
Node 7: No investment  

[S2]  
Node 1: [8-9]  
Node 2: No investment  
Node 3: No investment  
Node 4: No investment  

[S3]  
Node 1: [1-2] [2-3] [3-4] [4-5] [14-15]  
Node 2: No investment  
Node 3: No investment  
Node 4: No investment  
Node 5: No investment  
Node 6: No investment  
Node 7: No investment  

[S4]  
Node 1: [8-9]  
Node 2: No investment  
Node 3: No investment  
Node 4: No investment  

T Cost  I Cost  O Cost  PV Curt
---  ---  ---  ---
[S1] £478.9k  £454.9k  £23.9k  2.5%
[S2] £501.0k  £455.9k  £45.1k  5.0%
[S3] £168.7k  £148.5k  £20.2k  6.0%
[S4] £129.4k  £90.6k  £38.8k  12.0%
Case Study - Optimal Stochastic Investment strategy (S-I)

No possibility for smart asset investment

Node 1

- [1-2]
- [2-3]

Node 2

- [3-4]
- [4-5]
- [14-15]

Node 3

- [1-7]

Node 4

No investment

Node 5

No investment

Node 6

No investment

Node 7

Premature commitment to conventional reinforcements

<table>
<thead>
<tr>
<th></th>
<th>T Cost</th>
<th>I Cost</th>
<th>O Cost</th>
<th>PV Curt</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>£666.7k</td>
<td>£354.6k</td>
<td>£312.1k</td>
<td>14.4%</td>
</tr>
<tr>
<td>S2</td>
<td>£660.1k</td>
<td>£354.6k</td>
<td>£305.5k</td>
<td>16.0%</td>
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<tr>
<td>S3</td>
<td>£379.6k</td>
<td>£239.4k</td>
<td>£140.2k</td>
<td>14.2%</td>
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<tr>
<td>S4</td>
<td>£339.4k</td>
<td>£239.4k</td>
<td>£100.0k</td>
<td>14.8%</td>
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<tr>
<td></td>
<td>£508.1k</td>
<td>£297.0k</td>
<td>£211.1k</td>
<td></td>
</tr>
</tbody>
</table>
Ability to invest in smart technologies radically alters strategy:
Deferral of all first-stage commitments!

Strategic value of smart = £508.1k - £444.2k = £63.9k
Smart technologies offer increased controllability and resolve voltage constraints

**CVC operation**

- Substation Voltage - without CVC
- Substation Voltage - with CVC
- Bus 6 Voltage - without CVC

**SOP operation**

- Bus 6 Voltage - with SOP(6-9) [pu]
- Bus 6 Voltage - without SOP(6-9) [pu]
- F-1 Demand - without SOP(6-9) [kW]
- F-1 Demand - with SOP(6-9) [kW]
- F-2 Demand - without SOP(6-9) [kW]
- F-2 Demand - with SOP(6-9) [kW]
- Reactive Compensation at bus 6 [kVar]
Strategic Value of Smart Technology Options

Framework enables the computation of technology strategic value under different conditions -> explore technology complementarity and impact

| REC: reconductoring, CVC: coordinated voltage control, SOP: soft open points, DSR: demand-side response, APGC: active power generation curtailment | Strategic Value of APGC |
|---|---|---|---|---|
| REC | 310 | REC + CVC | 227 | REC + CVC + SOP | 157 | REC + CVC + SOP + DSR | 135 |

| Strategic Value of SOP |
|---|---|---|---|---|
| REC | 122 | REC + APGC | 40 | REC + APGC + DSR | 38 | REC + APGC + DSR + CVC | 17 |

| Strategic Value of CVC |
|---|---|---|---|---|
| REC | 126 | REC + APGC | 48 | REC + APGC + SOP | 25 | REC + APGC + SOP + DSR | 22 |

| Strategic Value of DSR |
|---|---|---|---|---|
| REC | 38 | REC + APGC | 8 | REC + APGC + CVC | 4 | REC + APGC + CVC + SOP | 3 |
Computational Challenges

Planning problems are becoming increasingly complex:

• Need to consider **multiple long-term uncertainties** → large scenario trees

• Multiple technology candidates → numerous binary variables

• Project of different building times; fast deployable storage/FACTS vs. large line requiring planning permission → many stages

• Non-sequential state equations due to building times

**Strategic investment requires the solution of very large MILPs**

**Effective decomposition methods are essential**
General Planning Problem Form

\[
\text{min}\{ \text{Investment Cost} + \text{Operation Cost} + \text{Lost Load} \}
\]

subject to

- Investment constraints (MILP)
- Operational constraints (LP)
  - Power Flow equations
  - Transmission constraints
  - Generation constraints
  - Pre-fault system energy balance equations
  - Post-fault system energy balance equations
Hierarchical Decomposition Scheme

- Concentrate all planning decisions in one problem

- Concentrate all operational decisions to a number of subproblems

- Iterate until the optimal solution is found (e.g. Benders decomposition)

- Through offline validation, identify offending post-fault operating points and add them as operating constraints
We utilize a **node variable** formulation.

**Forward pass:** identify interesting points (trials) in decision state-space

**Backward pass:** compute **Lagrangian multipliers** to approximate the future cost function seen by each scenario node.
## 24-bus IEEE RTS Case Study - Computational Performance

<table>
<thead>
<tr>
<th>Nodes</th>
<th>No. of Iterations</th>
<th>CPU Time</th>
<th>Cost lower bound (£m)</th>
<th>Cost upper bound (£m)</th>
<th>Gap</th>
</tr>
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<tbody>
<tr>
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<tr>
<td>Benders Decomposition</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>55s</td>
<td>6436.3</td>
<td>6346.3</td>
<td>0%</td>
</tr>
<tr>
<td>31</td>
<td>15</td>
<td>5m 52s</td>
<td>6917.1</td>
<td>6917.1</td>
<td>0%</td>
</tr>
<tr>
<td>63</td>
<td>11</td>
<td>3d 19h 39m</td>
<td>7309.5</td>
<td>7328.5</td>
<td>0.26%</td>
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<tr>
<td>127</td>
<td>6</td>
<td>15d 14h 35m</td>
<td>7559.8</td>
<td>7642.9</td>
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<tr>
<td>255</td>
<td>7</td>
<td>21d 7h</td>
<td>7585.3</td>
<td>7674.4</td>
<td>1.17%</td>
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<tr>
<td>Nested Benders Decomposition</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>1m 58s</td>
<td>6301.3</td>
<td>6348.8</td>
<td>0.74%</td>
</tr>
<tr>
<td>31</td>
<td>14</td>
<td>4m 28s</td>
<td>6840.8</td>
<td>6922.8</td>
<td>1.18%</td>
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<tr>
<td>63</td>
<td>16</td>
<td>10m 39s</td>
<td>7219.7</td>
<td>7316.9</td>
<td>1.32%</td>
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<tr>
<td>127</td>
<td>12</td>
<td>16m 13s</td>
<td>7449.2</td>
<td>7612.3</td>
<td>2.12%</td>
</tr>
<tr>
<td>255</td>
<td>12</td>
<td>28m 28s</td>
<td>7464.9</td>
<td>7637.4</td>
<td>2.26%</td>
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</table>
Min-max regret planning

- An alternative decision criterion is the **minimization of the maximum regret** experienced across all considered scenarios.

- This approach **foregoes the use of probabilities** and ensures that the worst case (NOT defined a priori) does not lead to exceedingly high costs.

- **Example application to North Sea electricity network:** Studies have shown that flexible assets such as offshore-offshore connections could hedge against the high uncertainty that characterizes offshore wind deployment.
Evidence shows that flexible/smart technologies can play an important role in managing interim uncertainty:

- They entail **faster commissioning times**
- They enable an **increase in controllability (pre and post fault)** rendering them more immune to siting uncertainties
- Many of these technologies are **relocatable**

Industry and regulators are increasingly recognizing the need to manage uncertainty, but a **conceptual/methodological gap still persists**.

We present a **methodological framework** for:

- Identifying the **optimal investment strategy** under uncertainty which moves beyond scale economies and rewards operational flexibility
- Computing the **option value** of different technologies under uncertainty

These methods will **grow in importance** as the integration across energy vectors increases due to:

- **Electrification trajectory is still highly uncertain**
- It presents expanded opportunities for **operational flexibility** (EVs, heat pumps etc.)

There is an **active debate** on stochastic vs. min-max **decision criteria**

Extension to the multi-energy case requires the deployment of efficient **decomposition and linearization** techniques.


Thank you!

Questions?