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Robust operation and planning of energy systems under uncertainty

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Structure

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

Types of uncertainty

- 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, $CO2$)

Described via scenarios/ ranges

- **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

Data-driven statistical models

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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. CO_2 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**

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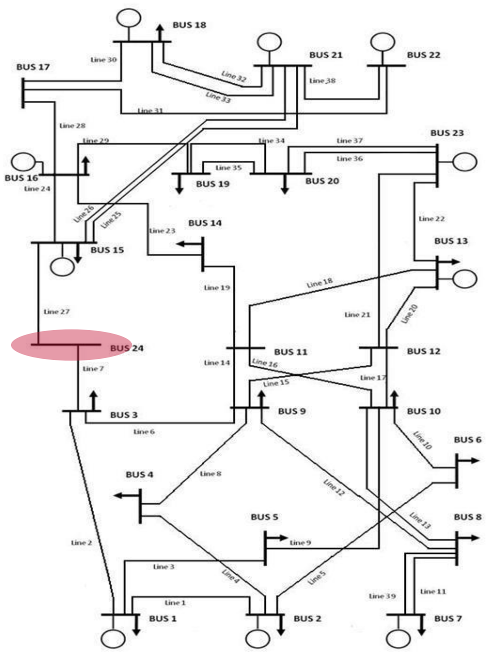
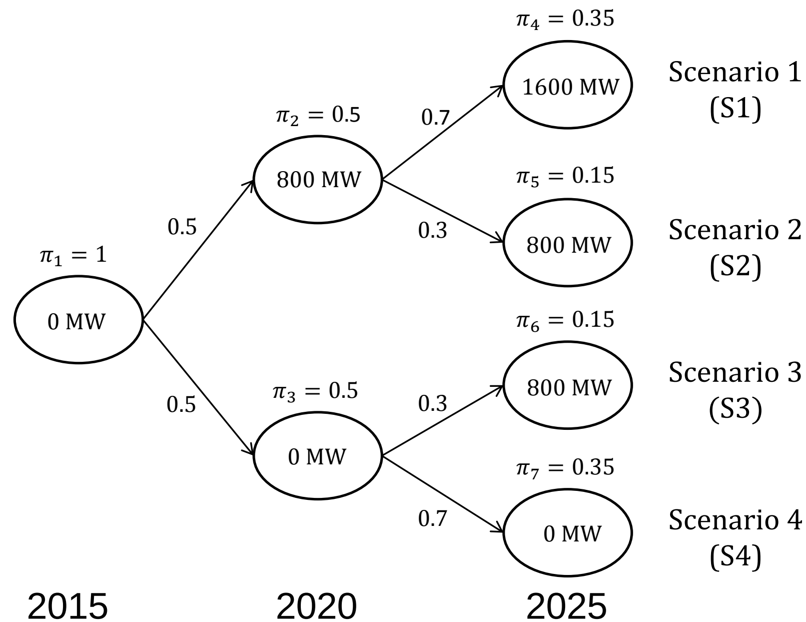
Case study at the transmission level



Uncertainty wrt wind build-out scenario



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.

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IEEE-RTS case study II

Available assets for investment are shown below:

Table I
Transmission Line Reinforcement Options

Asset Type	Reinforcement Capacity [MW]	Annualized Capital Cost [£/year]	Build Time
Option A	200	1,500,000	1 epoch
Option B	400	2,500,000	1 epoch

Table II
Alternative Investment Options

Asset Type	Annualized Capital Cost [£/year]	Build Time
Phase-shifter	600,000	0 epochs
Storage device	15,000,000	0 epochs

QB maximum shift angle: 30°
Storage Charge/Discharge rate: 400MW
Storage Energy Capacity: 1600 MWh

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Deterministic and Stochastic Results

Storage is sub-optimal under full knowledge of the future

		Investment Decisions			Costs (£m)					
		Epoch 1	Epoch2	Epoch 3	IC	OC	TC	E{IC}	E{OC}	E{TC}
D - I	S1	A (3-9), B (3-24), B (15-24)	PS *(3-9)*, PS *(11-14)*	PS *(15-16)*	91.3	4957.4	5048.8			
	S2	A *(3-9)*, A *(3-24)*, A *(15-24)*	PS *(11-14)*	-	52.9	5267.7	5320.6	44.9	5603.8	5648.7
	S3	-	A *(3-9)*, A *(3-24)*, A *(15-24)*	PS *(9-12)*, PS *(10-12)*, PS *(11-13)*	33.6	5834.9	5868.6			
	S4	-	-	-	0.0	6295.1	6295.1			
S - I	S1	B *(3-24)*	A *(1-3)*, A (3-9), A *(14-16)*, B *(15-16)*, B *(15-24)*	-	87.6	5078.7	5166.3			
	S2	B *(3-24)*	A *(1-3)*, A (3-9), A *(14-16)*, B *(15-16)*, B *(15-24)*	-	87.6	5336.5	5424.1	57.4	5665.9	5723.3
	S3	B *(3-24)*	-	-	27.2	5897.1	5924.4			
	S4	B *(3-24)*	-	-	27.2	6295.1	6322.3			
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			
	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			
	S4	-	A *(3-24)*	-	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

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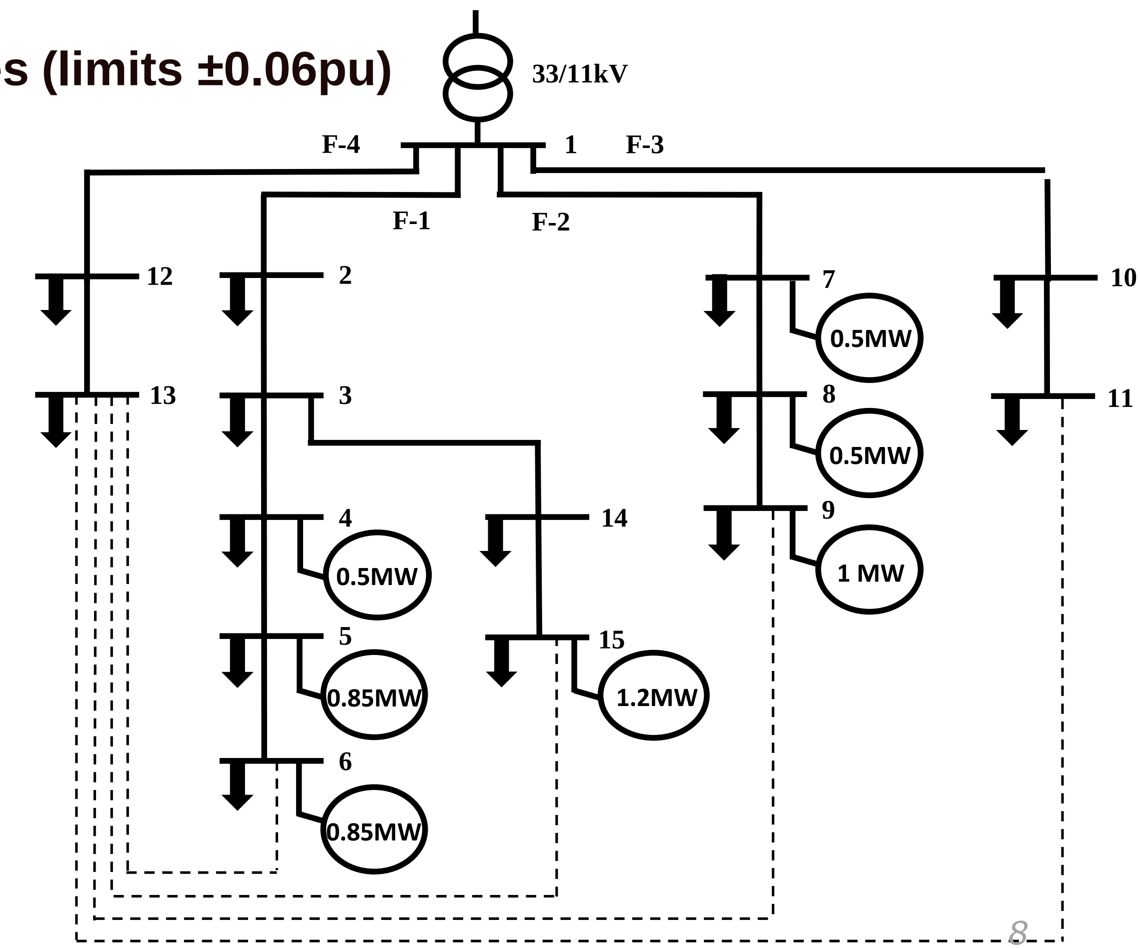
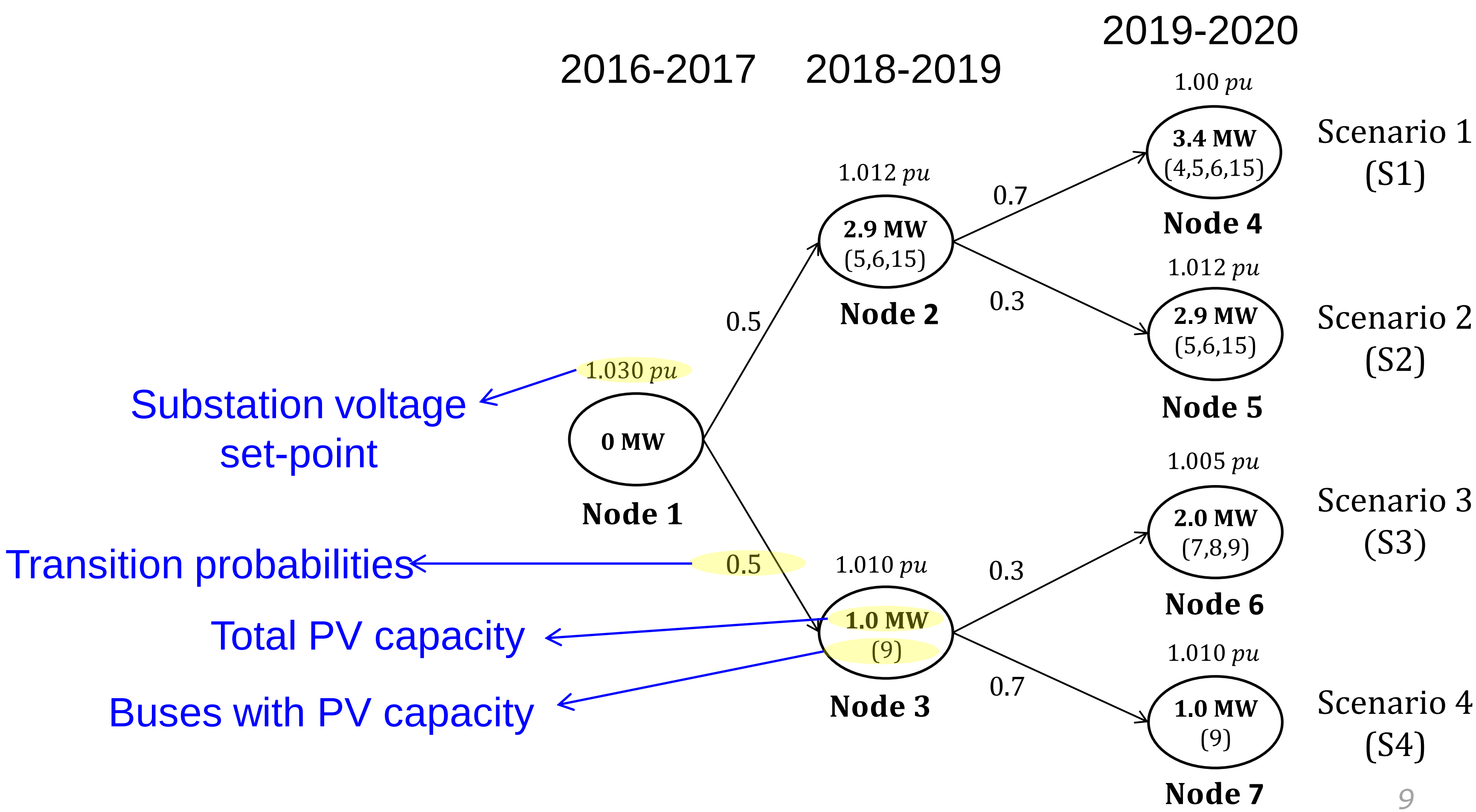
Distribution Network Case Study

- 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:



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]

Technology	Build Time (epochs)	Annualized capital cost (£/yr)
DSR	0	3,200 (per bus)
CVC	0	24,000 (whole system)
SOP	0	29,000 (per NOP)
Reconductoring	1	17,060 (per line)

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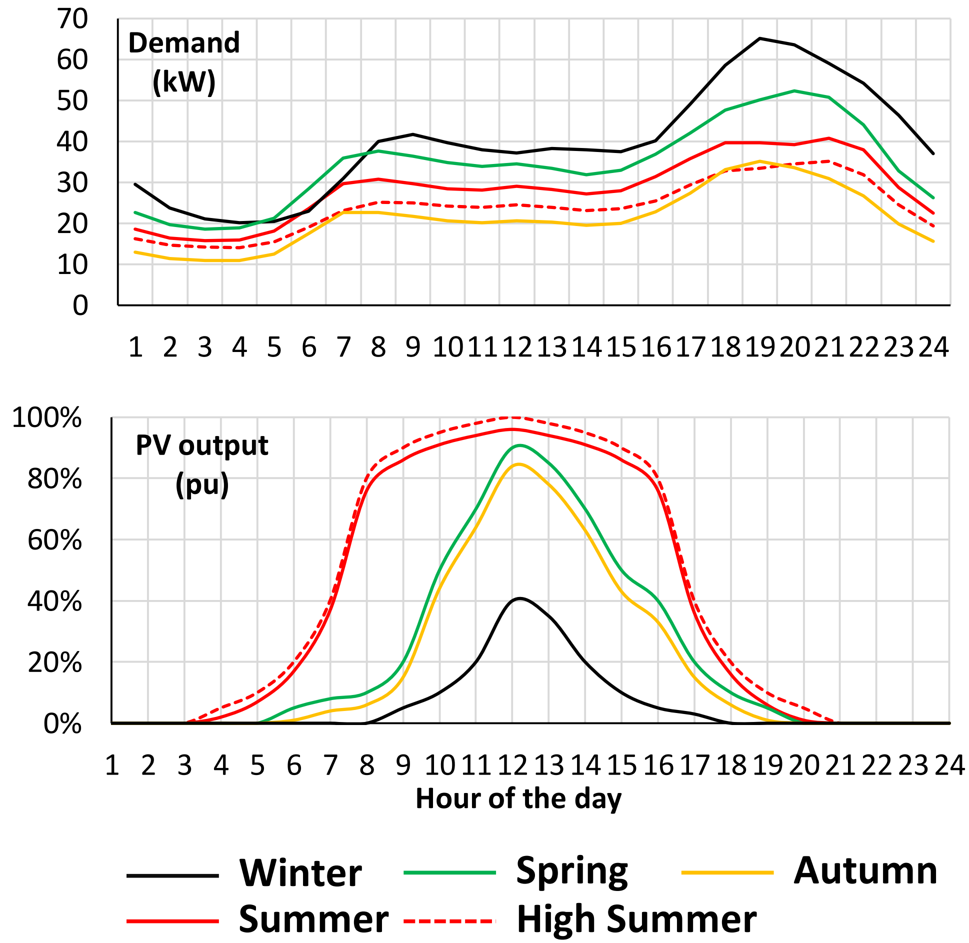
Case Study - Five typical days of operation

- 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 (lo demand & hi PV)
  - Autumn
- Actual data from Low Carbon London trials



Mathematical Formulation I

$$z = min\left\{\sum_{m\in\Omega_M} \pi_m \left(r^{I}_{\varepsilon_m}\omega^{I}_{m} + r^{O}_{\varepsilon_m}\omega^{O}_{m}\right)\right\} \quad (1)$$

Minimization of expected discounted operation and investment cost (social welfare maximisation)

$$\omega^{I}_{m} = \overset{\text{CVC}}{C_m\gamma_C} + \sum_{l\in\Omega_L} \overset{\text{re-conductor}}{B_{m,l}\gamma_B} + \sum_{n\in\Omega_N} \overset{\text{DSR}}{D_{m,n}\gamma_D} + \sum_{c\in\Omega_C} \overset{\text{SOP}}{S_{m,c}\gamma_S} \quad (2)$$

Investment cost per scenario node

$$\omega^{O}_{m} = \sum_{\substack{q\in\Omega_Q\\ t\in\Omega_{T_q}\\ g\in\Omega_{DG}}} \underset{\text{PV curtailment}}{N_q\delta_t c^c\left(P^{max}_{m,g}\zeta_{t,g} - P_{m,t,g}\right)} + \sum_{\substack{q\in\Omega_Q\\ t\in\Omega_{T_q}\\ n\in\Omega_N}} \underset{\text{load curtailment}}{N_q\delta_t\xi^{d}_{m,t,n}\lambda} \quad (3)$$

Operation cost per scenario node

$$\left(P_{m,t,g}\right)^2 + \left(Q_{m,t,g}\right)^2 \leq \left(S^{max}_{m,g}\zeta_{t,g}\right)^2 \quad \forall\, m,t,g\ \Omega_{TH}\ U\ \Omega_{DG} \quad (4)$$

Substation transformer limits

$$\tilde{F}_{m,l} = \sum_{\varphi\in\Phi_{k_L}(m)} B_{\varphi,l}F_{\max} \quad \forall\, m,l\ (5)$$

$$\tilde{B}_{m,l} = \sum_{\varphi\in\Phi_{k_L}(m)} B_{\varphi,l} \quad \forall\, m,l\ (6)$$

Line investment

$$\tilde{C}_{m} = \sum_{\varphi\in\Phi_{k_C}(m)} C_{\varphi} \quad \forall\, m\ (7)$$

CVC investment

$$\tilde{D}_{m,n} = \sum_{\varphi\in\Phi_{k_D}(m)} D_{\varphi,n} \quad \forall\, m,n\ (8)$$

DSR investment

$$\tilde{S}_{m,c} = \sum_{\varphi\in\Phi_{k_S}(m)} S_{\varphi,c} \quad \forall\, m,c\ (9)$$

SOP investment

Path dependency + Build-out time constraints

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Mathematical Formulation II

$$P^{s}_{m,t,l} = (1-\widetilde{B}_{m,l})[V^{2}_{m,t,u_l} g^{A}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{A}_{l} \cdot \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l}) - V_{m,t,u_l} V_{m,t,v_l} b^{A}_{l} \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l})] + \widetilde{B}_{m,l}[V^{2}_{m,t,u_l} g^{N}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{N}_{l} \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l}) - V_{m,t,u_l} V_{m,t,v_l} b^{N}_{l} \cdot \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l})] \quad \forall\, m,t,l \quad (10)$$

Active power flow (sending end)

$$P^{r}_{m,t,l} = (1-\widetilde{B}_{m,l})[V^{2}_{m,t,v_l} g^{A}_{l} - V_{m,t,v_l} V_{m,t,u_l} g^{A}_{l} \cdot \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l}) - V_{m,t,u_l} V_{m,t,v_l} b^{A}_{l} \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l})] + \widetilde{B}_{m,l}[V^{2}_{m,t,v_l} g^{N}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{N}_{l} \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l}) - V_{m,t,u_l} V_{m,t,v_l} b^{N}_{l} \cdot \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l})] \quad \forall\, m,t,l \quad (11)$$

Active power flow (receiving end)

$$Q^{s}_{m,t,l} = (1-\widetilde{B}_{m,l})[-V^{2}_{m,t,u_l} b^{A}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{A}_{l} \cdot \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l}) + V_{m,t,u_l} V_{m,t,v_l} b^{A}_{l} \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l})] + \widetilde{B}_{m,l}[-V^{2}_{m,t,u_l} b^{N}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{N}_{l} \sin(\theta_{m,t,u_l} - \theta_{m,t,v_l}) + V_{m,t,u_l} V_{m,t,v_l} b^{N}_{l} \cos(\theta_{m,t,u_l} - \theta_{m,t,v_l})] \quad \forall\, m,t,l \quad (12)$$

Reactive power flow (sending end)

$$Q^{r}_{m,t,l} = (1-\widetilde{B}_{m,l})[-V^{2}_{m,t,v_l} b^{A}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{A}_{l} \cdot \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l}) + V_{m,t,u_l} V_{m,t,v_l} b^{A}_{l} \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l})] + \widetilde{B}_{m,l}[-V^{2}_{m,t,v_l} b^{N}_{l} - V_{m,t,u_l} V_{m,t,v_l} g^{N}_{l} \sin(\theta_{m,t,v_l} - \theta_{m,t,u_l}) + V_{m,t,u_l} V_{m,t,v_l} b^{N}_{l} \cos(\theta_{m,t,v_l} - \theta_{m,t,u_l})] \quad \forall\, m,t,l \quad (13)$$

Reactive power flow (receiving end)

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Mathematical Formulation III

$$(P^{s}_{m,t,l})^2 + (Q^{s}_{m,t,l})^2 \leq [F_l + \tilde{F}_{m,l}]^2 \qquad \forall\, m,t,l \quad (14)$$

Power limits

$$(P^{r}_{m,t,l})^2 + (Q^{r}_{m,t,l})^2 \leq [F_l + \tilde{F}_{m,l}]^2 \qquad \forall\, m,t,l \quad (15)$$

$$V_{min} \leq V_{m,t,n} \leq V_{max} \qquad \forall\, m,t,n-\{1\} \quad (16)$$

Voltage limits

$$V_{m,t,1} = V^{cvc}_{m,t} + V^{noc}_{m,t} \qquad \forall\, m,t \quad (17)$$

Substation voltage

$$V^{cvc}_{min} \cdot \tilde{C}_m \leq V^{cvc}_{m,t} \leq V^{cvc}_{max} \cdot \tilde{C}_m \qquad \forall\, m,t \quad (18)$$

$$V^{noc}_{m,t} = V_{set_m} \cdot (1 - \tilde{C}_m) \qquad \forall\, m,t \quad (19)$$

CVC voltage regulation

$$\sum_{t\in\Omega_{T_q}} (\xi^{d}_{m,t,n} - \xi^{c}_{m,t,n}) = 0 \qquad \forall\, m,n,q \quad (20)$$

DSR energy equation

$$\xi^{d}_{m,t,n} \leq \widetilde{D}_{m,n} \cdot f_{t,n} \cdot d_{t,n} \qquad \forall\, m,t,n \quad (21)$$

$$\xi^{c}_{m,t,n} \leq \widetilde{D}_{m,n} \overline{D}_{t,n} \qquad \forall\, m,t,n \quad (22)$$

Bounds on shift-able load

$$R_{m,t,c} \leq P^{max}_{c} \cdot \tilde{S}_{m,c} \qquad \forall\, m,t,c \quad (23)$$

SOP active power transfer limits

$$H_{m,t,c} \leq P^{max}_{c} \cdot \tilde{S}_{m,c} \qquad \forall\, m,t,c \quad (24)$$

$$|H^{Q}_{m,t,c,n}| \leq Q^{max}_{c} \cdot \tilde{S}_{m,c} \qquad \forall\, m,t,c \quad (25)$$

SOP reactive power bound

Mathematical Formulation III

$$\sum_{g \in \Omega_{Dg} \cup \Omega_{TH}} P_{m,t,g} I_{n,g} - \sum_{l \in \{\Omega_L | v_l = n\}} P^r_{m,t,l} - \sum_{l \in \{\Omega_L | u_l = n\}} P^s_{m,t,l} =$$
$$+ d_{t,n} + \xi^d_{m,t,n} - \xi^c_{m,t,n} + \sum_{c \in \{\Omega_C | n = n^a_c\}} (H_{m,t,c} - R_{m,t,c} \eta_f)$$
$$+ \sum_{c \in \{\Omega_C | n = n^b_c\}} (R_{m,t,c} - H_{m,t,c} \eta_f) \qquad \forall\, m,t,n \quad (26)$$

Active power system balance equation

$$\sum_{g \in \Omega_{Dg} \cup \Omega_{TH}} Q_{m,t,g} I_{n,g} - \sum_{l \in \{\Omega_L | v_l = n\}} Q^r_{m,t,l} - \sum_{l \in \{\Omega_L | u_l = n\}} Q^s_{m,t,l} =$$
$$+ \Psi_{n,t} (d_{t,n} + \xi^d_{m,t,n} - \xi^c_{m,t,n})$$
$$+ \sum_{c \in \{\Omega_C | n = n^a_c \text{ or } n = n^b_c\}} H^Q_{m,t,c,n} \qquad \forall m,t,n \quad (27)$$

Reactive power system balance equation

Case Study - Optimal Deterministic Investment plans (D-I)

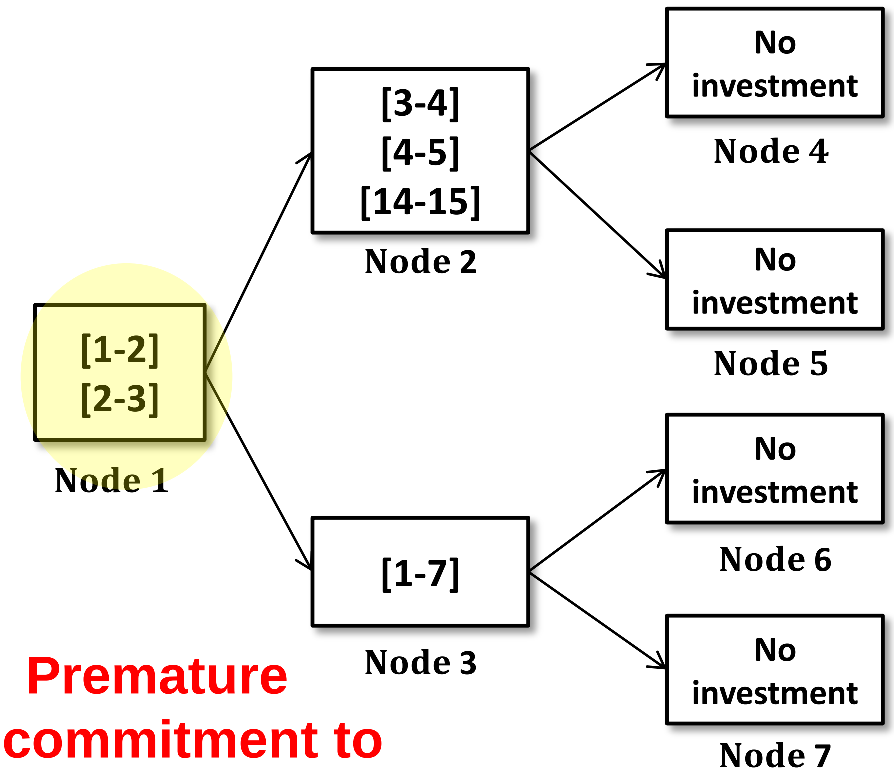
Exclusive reliance on network reinforcement (economies of scale)

Smart options are completely ignored!

				T Cost	I Cost	O Cost	PV Curt
[1-2] [2-3] [3-4] [4-5] [14-15] Node 1	No investment Node 2	No investment Node 4	S1	£478.9k	£454.9k	£23.9k	2.5%
[1-2] [2-3] [3-4] [4-5] [14-15] Node 1	No investment Node 2	No investment Node 5	S2	£501.0k	£455.9k	£45.1k	5.0%
[8-9] Node 1	[1-7] Node 3	No investment Node 6	S3	£168.7k	£148.5k	£20.2k	6.0%
[8-9] Node 1	No investment Node 3	No investment Node 7	S4	£129.4k	£90.6k	£38.8k	12.0%

Case Study - Optimal Stochastic Investment strategy (S-I)

No possibility for smart asset investment



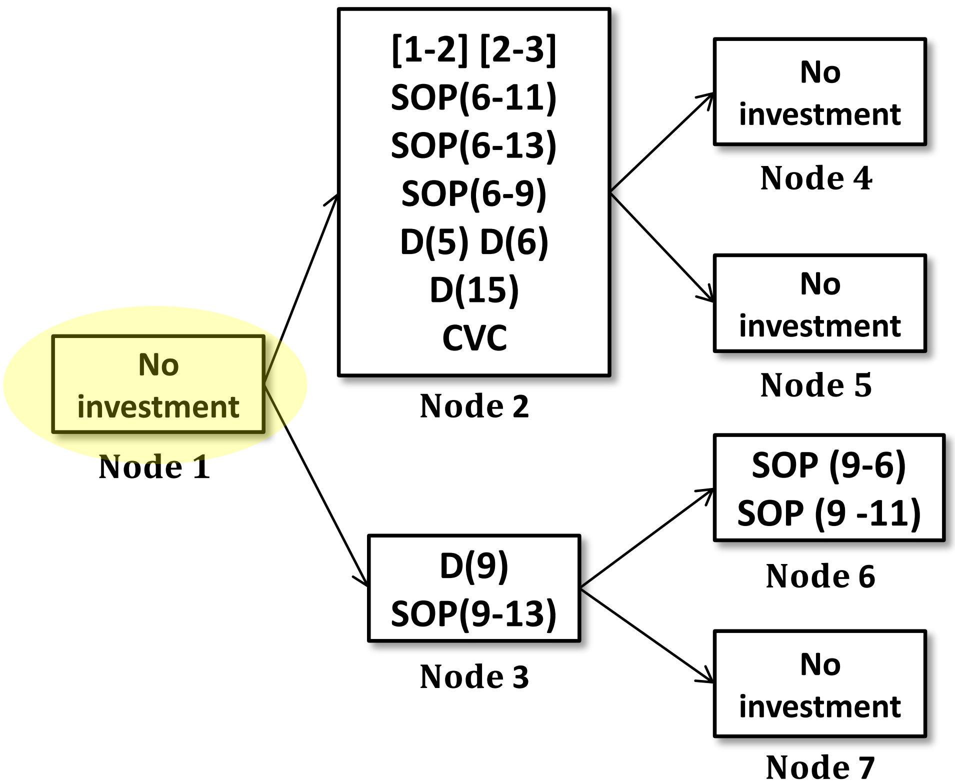
	T Cost	I Cost	O Cost	PV Curt
S1	£666.7k	£354.6k	£312.1k	14.4%
S2	£660.1k	£354.6k	£305.5k	16.0%
S3	£379.6k	£239.4k	£140.2k	14.2%
S4	£339.4k	£239.4k	£100.0k	14.8%
	£508.1k	£297.0k	£211.1k	14.8%

Premature commitment to conventional reinforcements

Case Study - Optimal Stochastic Investment strategy (S-II)

Ability to invest in smart technologies radically alters strategy:

Deferral of all first-stage commitments!



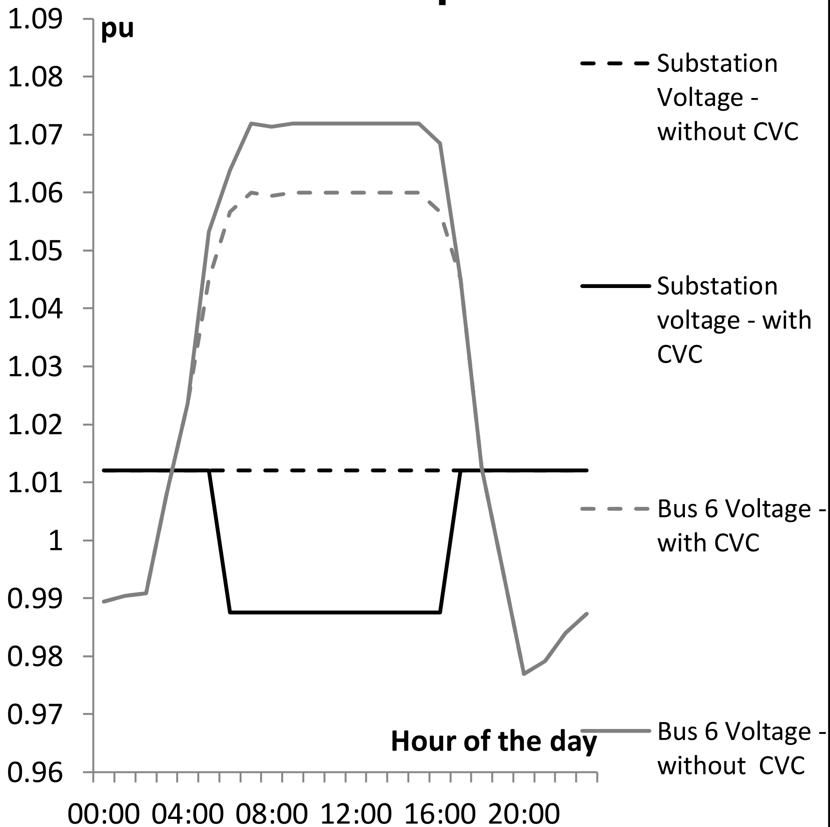
	T Cost	I Cost	O Cost	PV Curt
S1	£742.2k	£488.7k	£253.4k	11.8%
S2	£721.5k	£488.7k	£232.8k	11.7%
S3	£207.1k	£168.9k	£38.2k	3.9%
S4	£128.9k	£91.8k	£37.1k	5.6%
	£444.2k	£301.8k	£142.4k	8.4%

Strategic value of smart = £508.1k - £444.2k = £63.9k

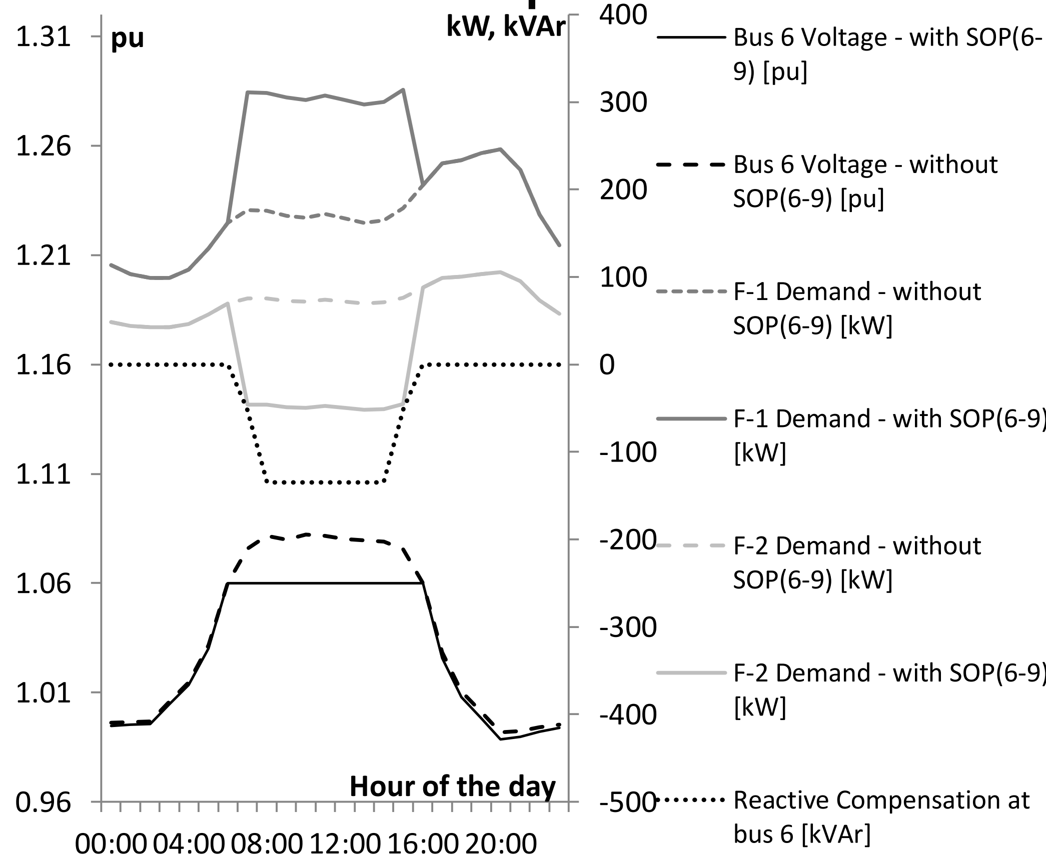
Operation examples

Smart technologies offer increased controllability and resolve voltage constraints

CVC operation

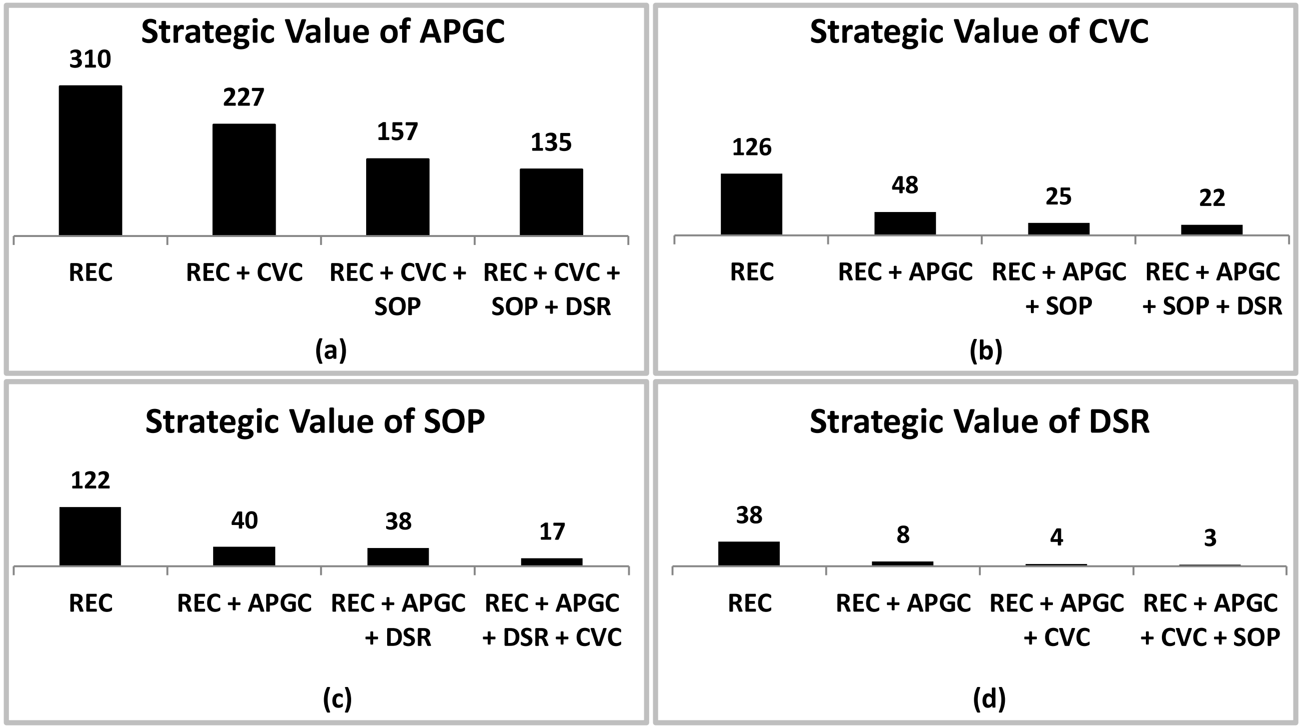


SOP operation



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

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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

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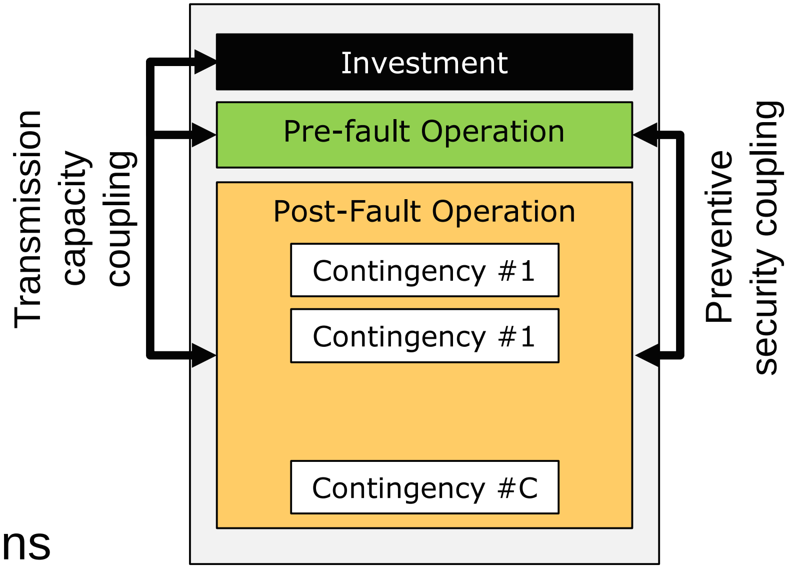
General Planning Problem Form

min{ Investment Cost + Operation Cost + 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



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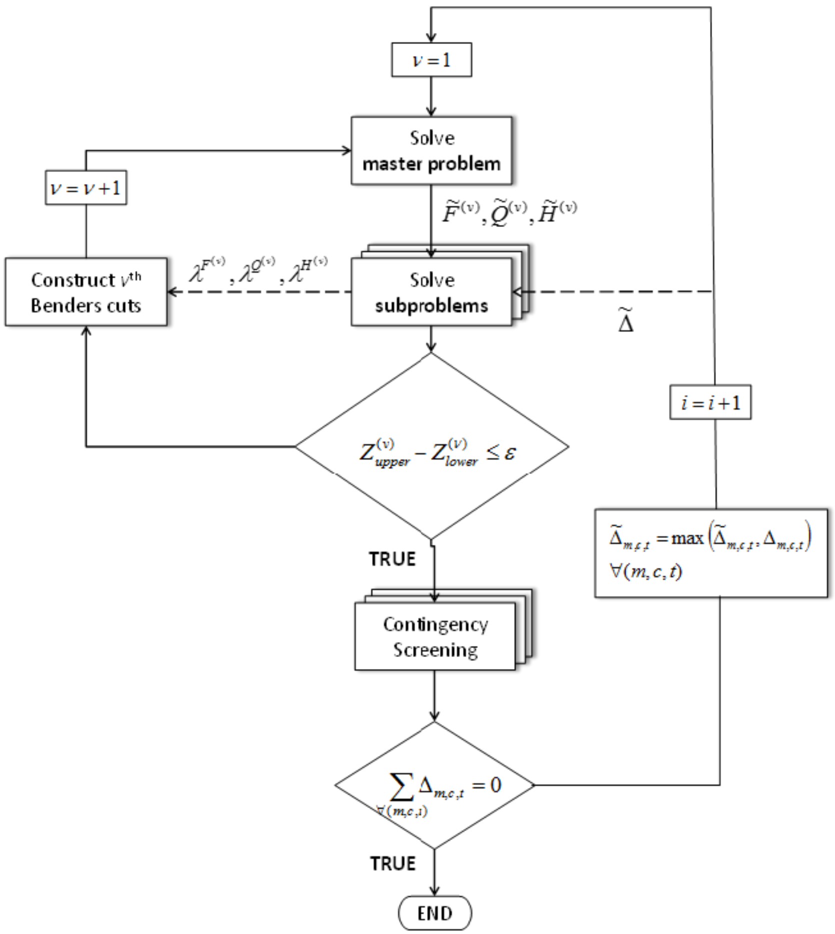
Hierarchical Decomposition Scheme

- 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



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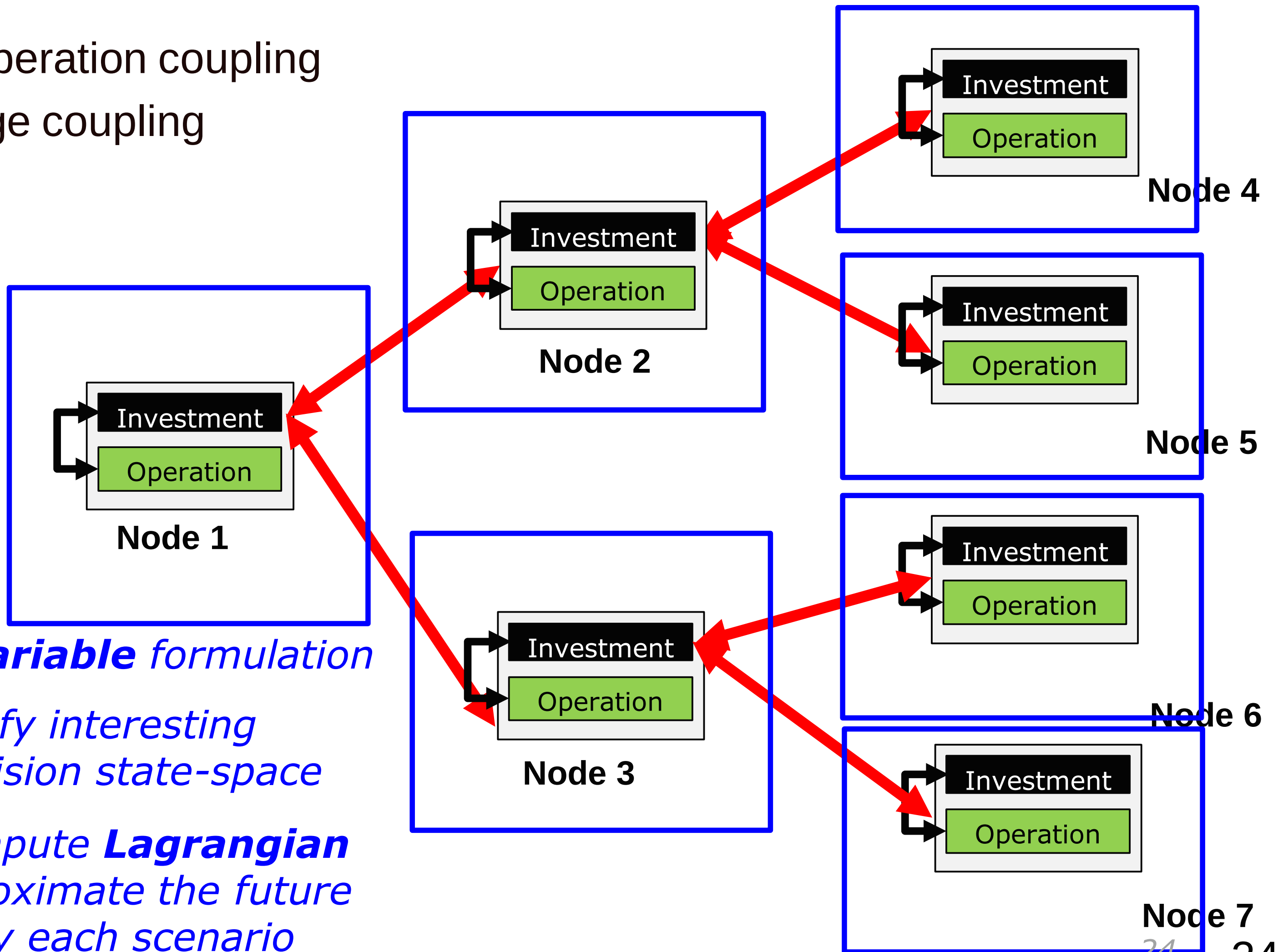
Temporal Decomposition Scheme

Investment/operation coupling

Scenario/stage coupling



*We utilize a **node variable** formulation*

<u>Forward pass</u>: identify interesting points (trials) in decision state-space

*<u>Backward pass</u>: compute **Lagrangian multipliers** to approximate the future cost function seen by each scenario node*

24-bus IEEE RTS Case Study - Computational Performance

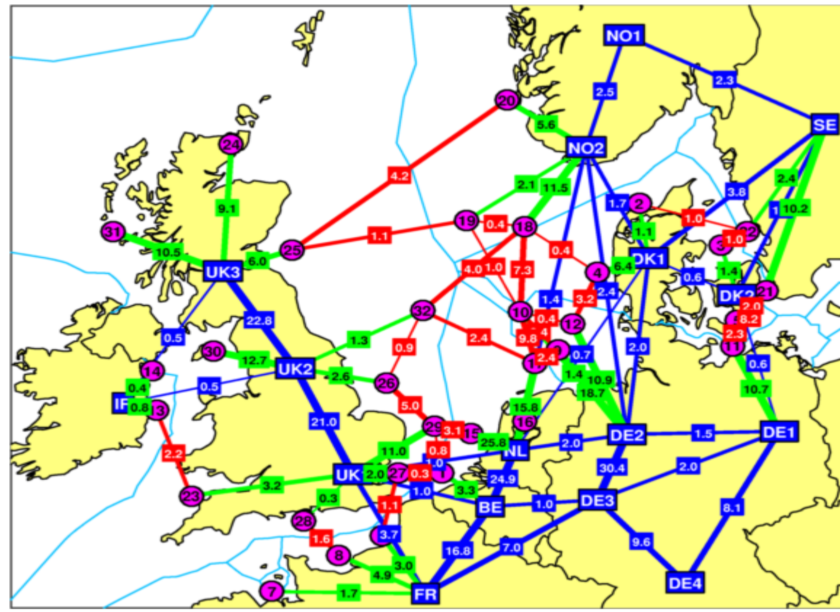
Nodes	No. of Iterations	CPU Time	Cost lower bound (£m)	Cost upper bound (£m)	Gap
Benders Decomposition					
15	12	55s	6436.3	6346.3	0%
31	15	5m 52s	6917.1	6917.1	0%
63	11	3d 19h 39m	7309.5	7328.5	0.26%
127	6	15d 14h 35m	7559.8	7642.9	1.08%
255	7	21d 7h	7585.3	7674.4	1.17%
Nested Benders Decomposition					
15	13	1m 58s	6301.3	6348.8	0.74%
31	14	4m 28s	6840.8	6922.8	1.18%
63	16	10m 39s	7219.7	7316.9	1.32%
127	12	16m 13s	7449.2	7612.3	2.12%
255	12	28m 28s	7464.9	7637.4	2.26%

45X

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



- <u>Example application to North Sea electricity network: </u>Studies have shown that flexible assets such as offshore-offshore connections could hedge against the high uncertainty that characterizes offshore wind deployment.

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Summary/Discussion

- 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.

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References

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Thank you!

Questions?