Smart Grids or Microgrids?

Optimal design of future electricity distribution systems

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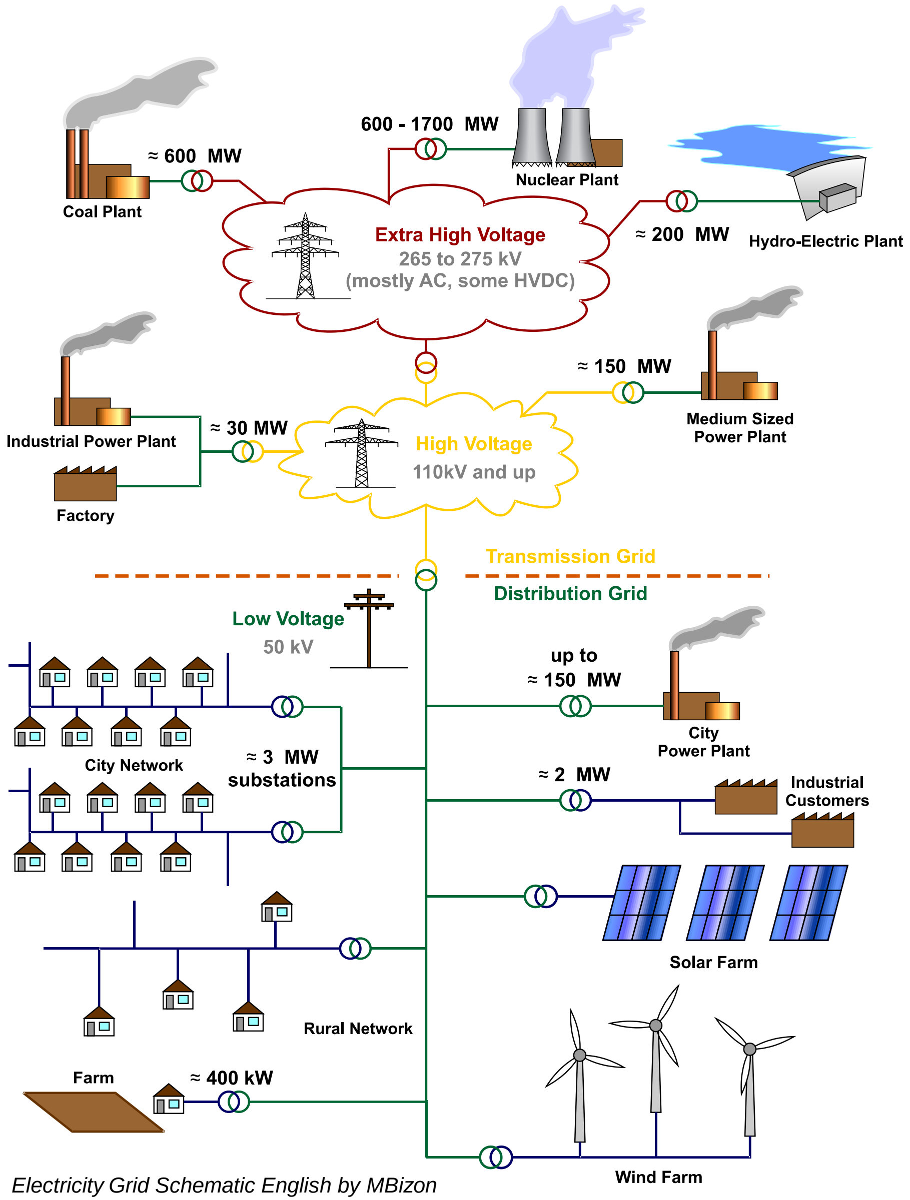
Overview: Trends in the electricity sector

Where we were: Traditional electricity grid

- Large, centralised generation
- Unidirectional power flow
- Flexibility: Fast-ramping plants

Where we're going: Smart Grids

- Communication, computation
- Decentralisation
- Distributed Energy Resources (DER)
  - Wind and solar power
  - Flexible demands (electric vehicles, smart homes)
- New pricing and market schemes

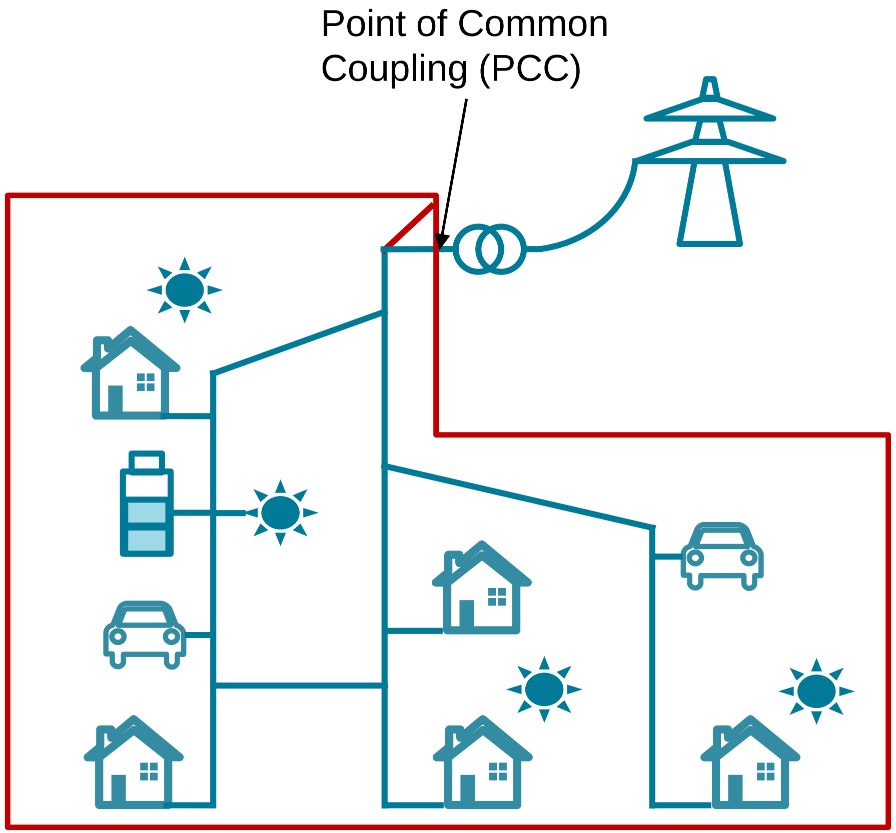


Electricity Grid Schematic English by MBizon

Smart grids and microgrids

- Smart Grids
  - Distributed Energy Resources (DER)
  - New pricing and market schemes
  - Communication, measurements and control

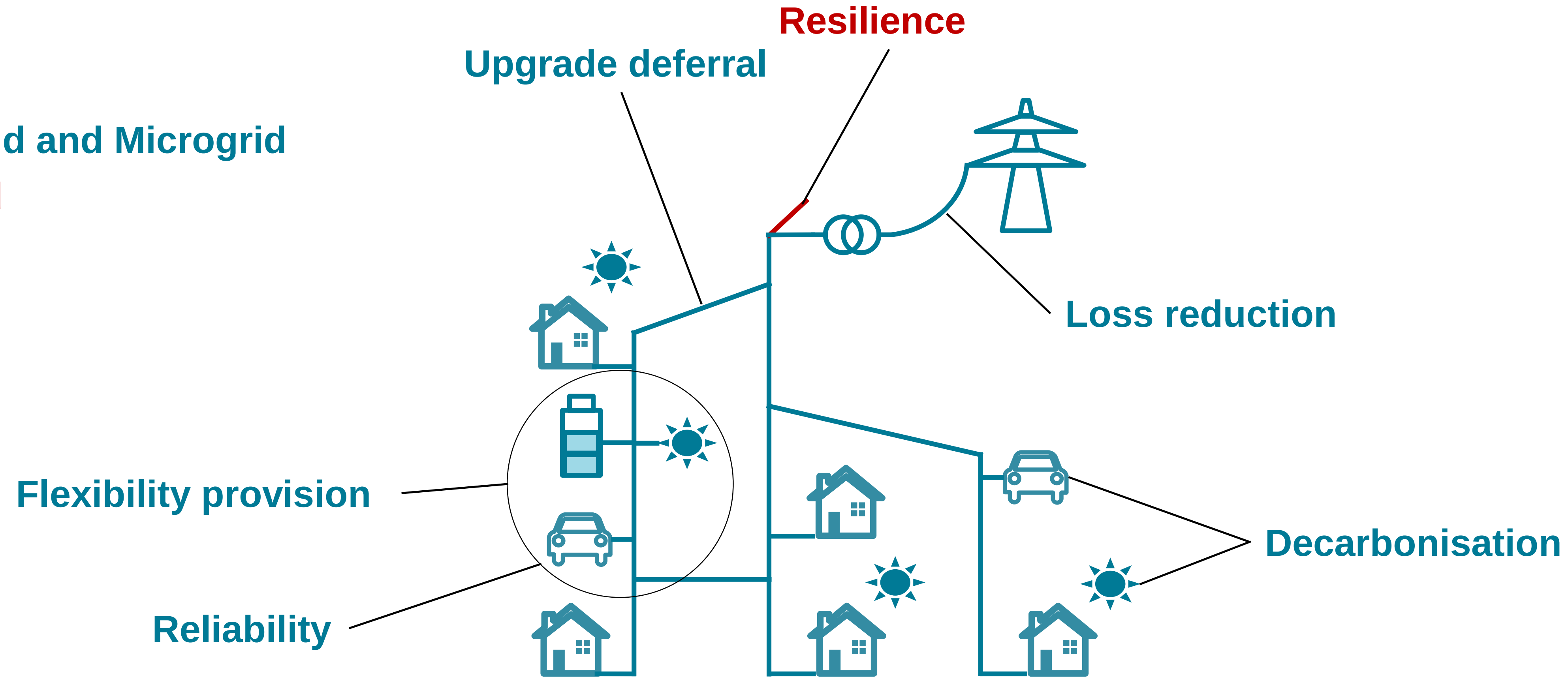
- Microgrids: Islands
  - Sufficient DER
  - Coordination within clearly defined boundaries
  - Communication, protection and control



Proposed Benefits

Smart Grid and Microgrid

Microgrid



Research questions

Which benefits justify upgrading current grids
to active distribution networks or microgrids?

- How to optimise microgrid design for cost, reliability and resilience?
- What are current incentives and drivers towards smart grids or microgrids?
- Which solution(s) could be preferred in the future?

Mathematical (MILP)
+ Optimality guarantee

Optimisation method

Metaheuristic
+ Nonlinearities (exact power flow)

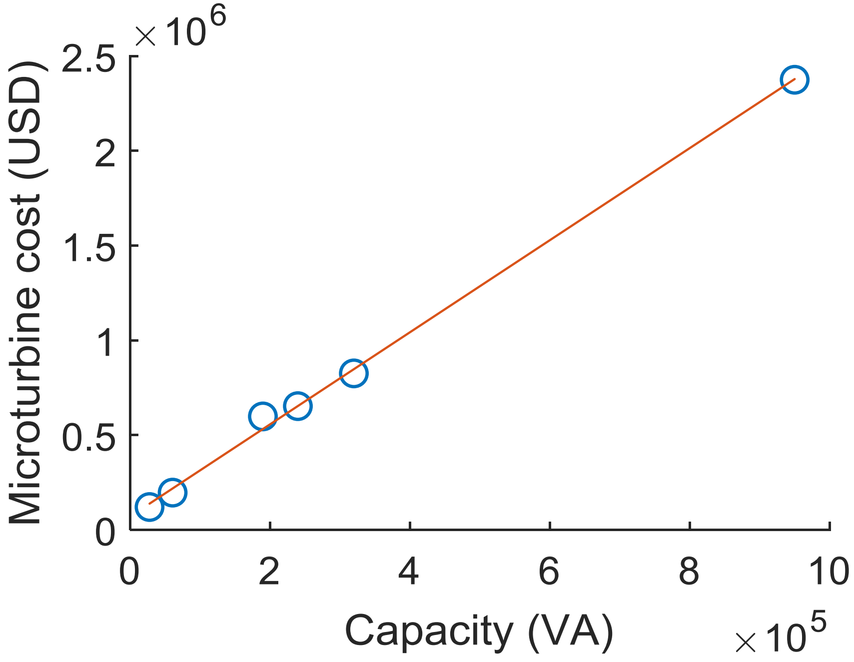
$$\min c^T x$$
$$subject\ to\ Ax \leq b$$
$$x_R \in \mathbb{R}$$
$$x_I \in \mathbb{Z}$$
Notation: Binary $y \in \{0,1\}$

Design Optimisation

Optimal DER and grid design

- Approximate investment with fixed and capacity-dependent costs
  - Binary investment decision y_{Inv}^{DER}
  - Cost proportional to capacity S_{max}^{DER}

- Equivalent annual cost
  - Parameters: Discount rate and life time
  - Compare assets with different life times
  - Compare investment and operation cost

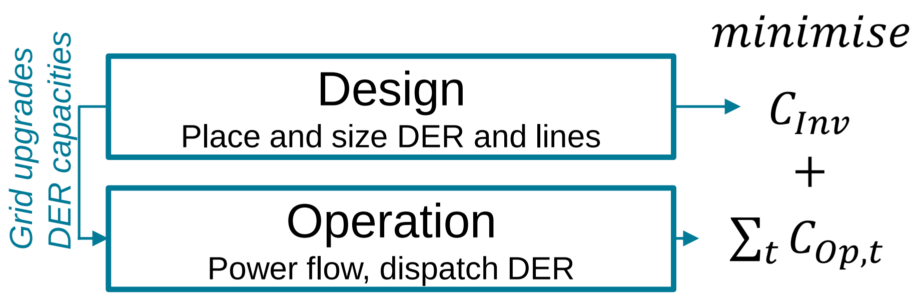


Optimal Operation

Objective

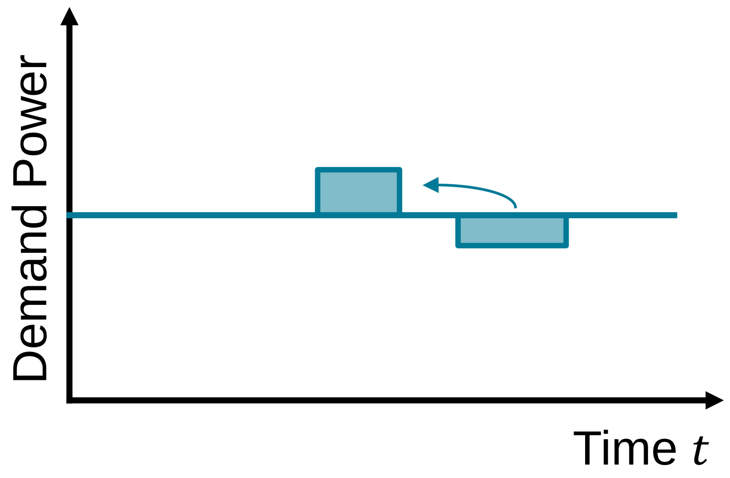
$$C_{Op,t} = c_t^{PCC} * P_t^{PCC} + \sum_{DER} c_{Op}^{DER} * P_t^{DER} + \sum_{RG} c_{Curt}^{RG}\left(P_{t,Avl}^{RG} - P_t^{RG}\right)$$

Imports — Fuel cost — Renewable curtailment



Operating constraints

- Equipment capacity (lines, DER)
- Available solar radiation
- Demand flexibility limits
- Linearised DistFlow [Baran & Wu 1989]
- Storage
  - State of charge constraints
  - Cycling limit (aging)



Case Study

IEEE 37 Bus system

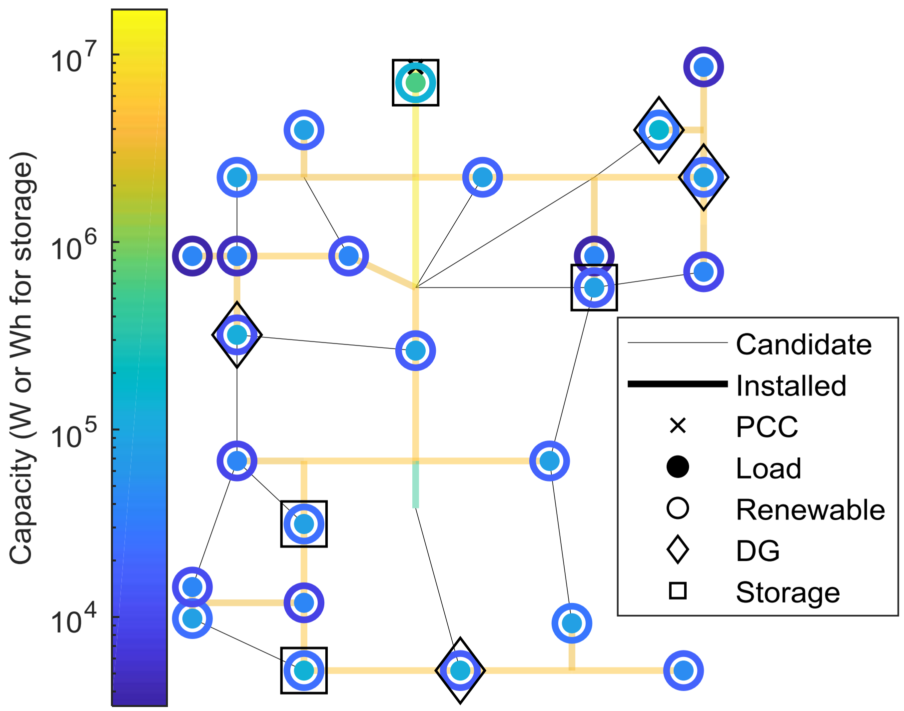
Location	California
Demand	2.7 MW peak
Solar PV	0.5 MW peak
Demand types	Residential, commercial
Electric Vehicles	0.07 MW peak

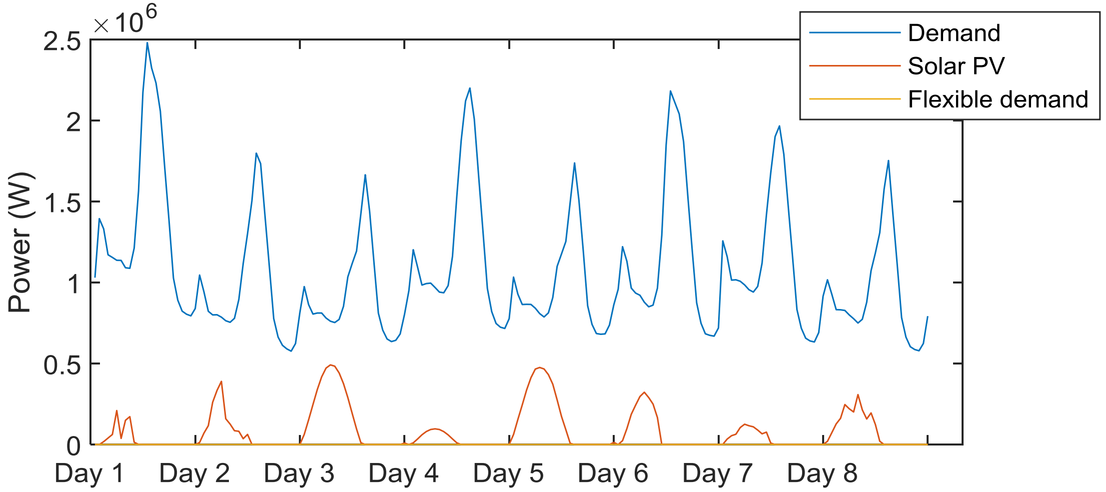
Expansion Options

- New lines
- Distributed Generator (DG): Biogas microturbine
- Battery storage

Time horizon

- 1 year (8 representative days)

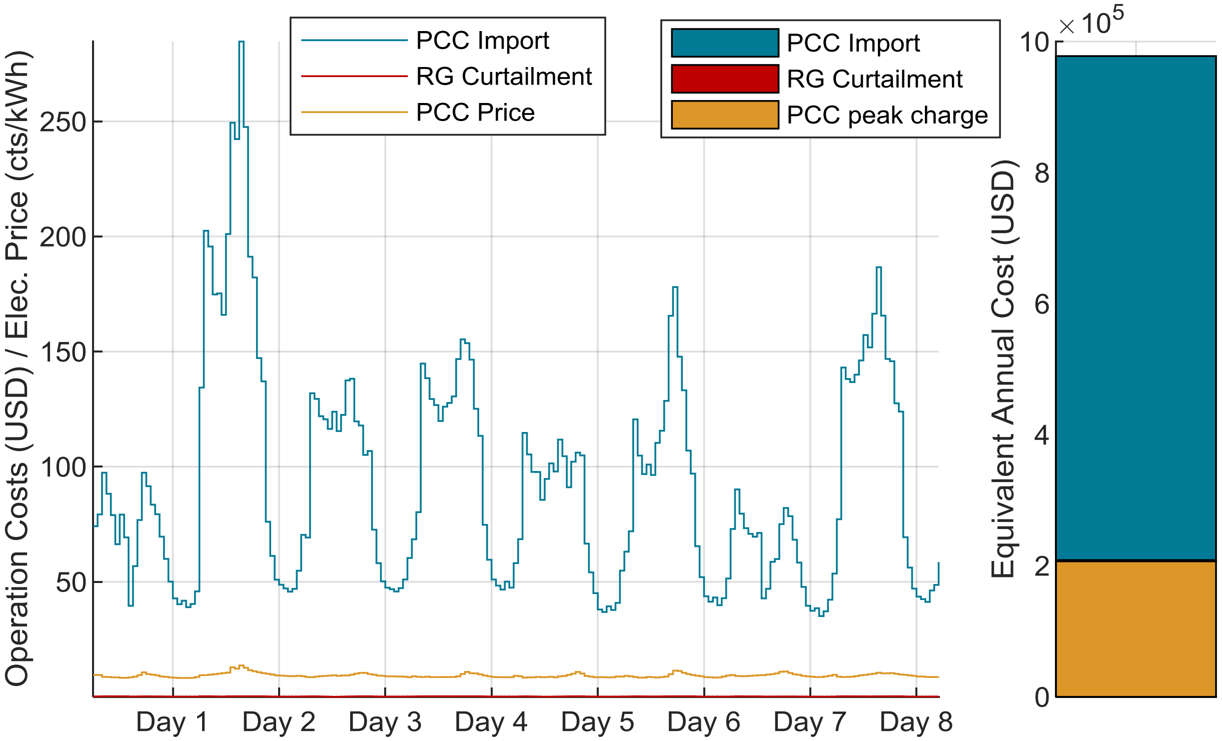




Smart grid or Microgrid for profit?

- No new lines or DER
- Flexible demand shifted to low price periods

➡ Arbitrage does not justify DER investments



Operational Objective

Total Objective

Reliability and Resilience

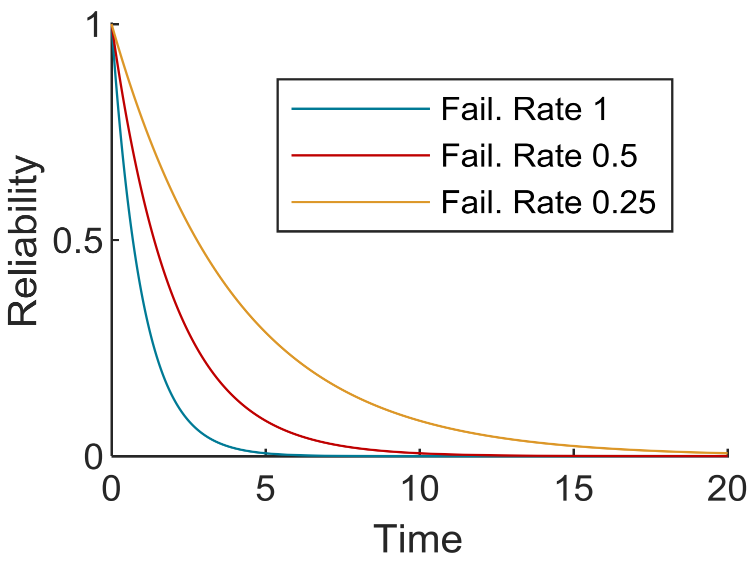
Reliability

Definition

- «Reliability is a *characteristic* of an item, expressed by the *probability* that the item will perform its *required functions* under given conditions *for a stated time interval*» [Birolini 2004]

Simple model

- Constant failure rate λ (1/year)



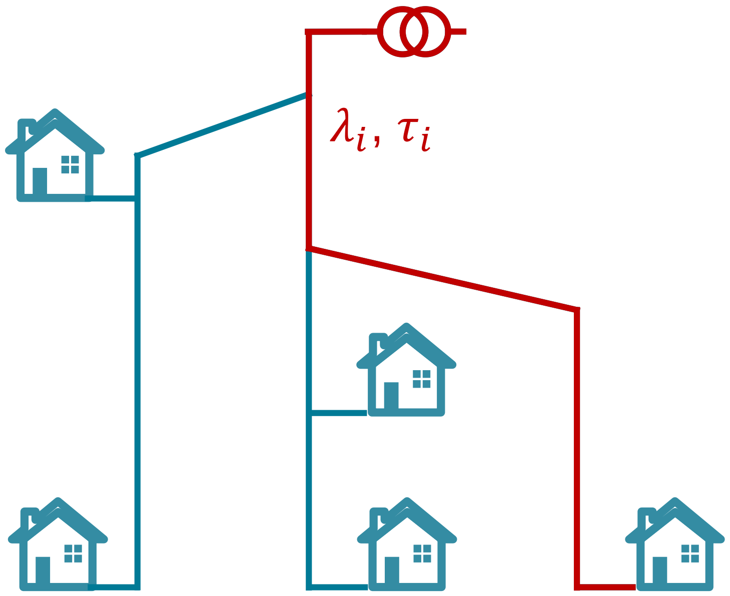
Reliability in Electricity Distribution

- Required function: Supply all power demands of all customers

- Modelling assumptions
  - Radial networks → Series configuration
  - Constant failure rates λ_i (1/year)
  - Constant repair times τ_i (hours)

$$\lambda_n = \sum_{i \in \mathbb{P}_{PCC,n}} \lambda_i$$

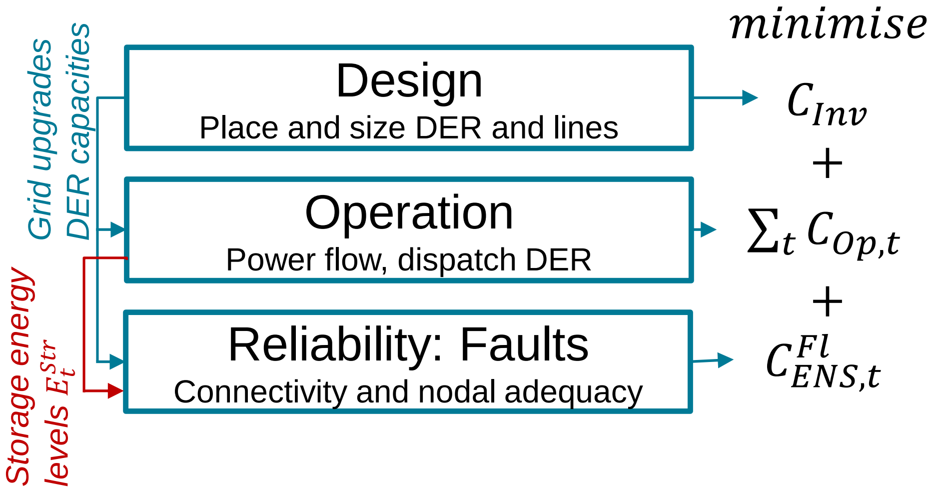
$$U_n = \sum_{i \in \mathbb{P}_{PCC,n}} \lambda_i \tau_i$$



- Reliability Indices (N_n: Number of customers at load point n)
  - $SAIFI = \frac{Number\ of\ customer\ interruptions}{Number\ of\ customers} = \frac{\sum_n \lambda_n N_n}{\sum_n N_n}$ (1/year)
  - $SAIDI = \frac{sum\ of\ customer\ interruption\ durations}{Number\ of\ customers} = \frac{\sum_n U_n N_n}{\sum_n N_n}$ (hours/year)
  - $EENS = \sum_n U_n \bar{P}_n^{Demand}$ (kWh/year)

[Billinton and Allan 2013]

Reliability: Internal faults

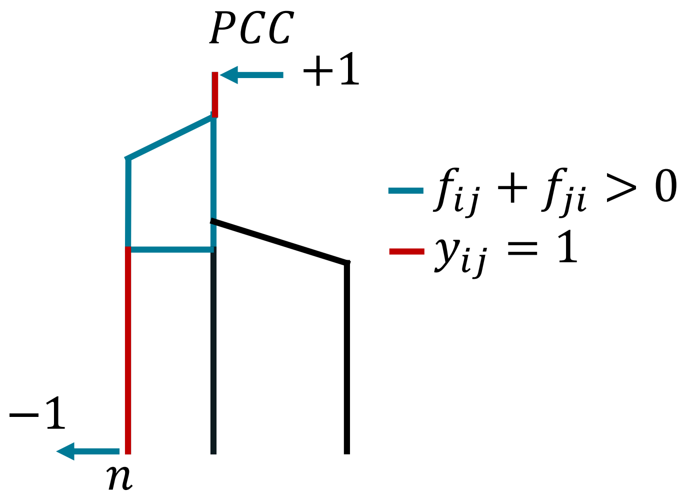


- Model unreliability of line segments $i \rightarrow j$ with flow on graph for node n

$$\min \sum_{i,j} y_{ij}^n \,,\ \ subject\ to$$

$$\sum_{j \in N(i)} f_{ij}^n - f_{ji}^n = \begin{cases} 1\ for\ PCC \\ -1\ for\ current\ node\ (i=n) \\ 0\ otherwise \end{cases}$$

- No contribution in case of multiple paths
  - Assuming single line failures $\quad y_{ij}^n \geq \left(f_{ij}^n + f_{ji}^n\right) - 0.6, y_{ij}^n \in \{0,1\}$

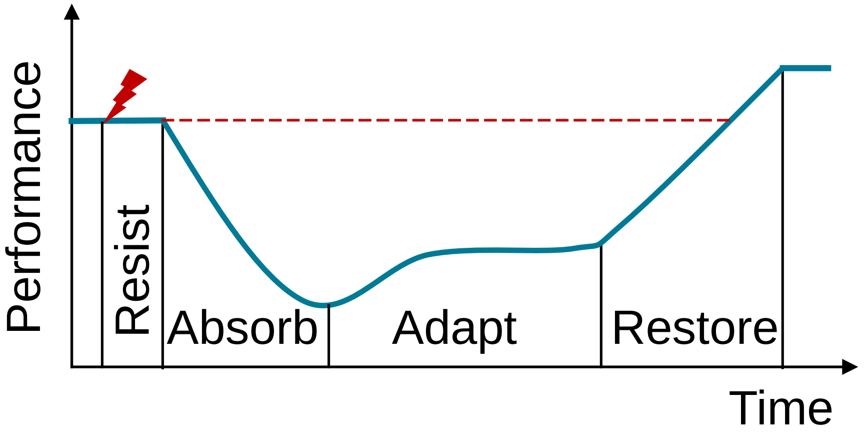


- Reliability indices: $SAIFI, SAIDI, EENS$

Resilience

Definition

- «Resilience is the ability of a system to *resist* the effects of a *disruptive force* and to *reduce performance deviations*» [Nan & Sansavini 2017]
- Absorptive, adaptive and restorative capability



Quantification

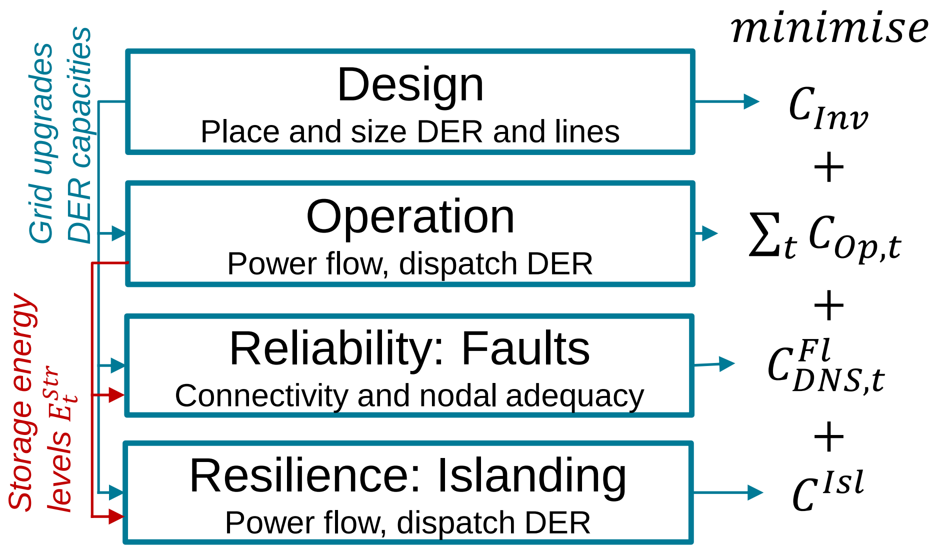
- Performance loss, e.g. Energy not supplied

In Distribution Grids

- Microgrid Islanding events

Resilience: Islanding events

- No power exchange at PCC $P_t^{PCC} = Q_t^{PCC} = 0$
- Unforeseen events with uncertain duration
  - Start 1 islanding scenario at every time step

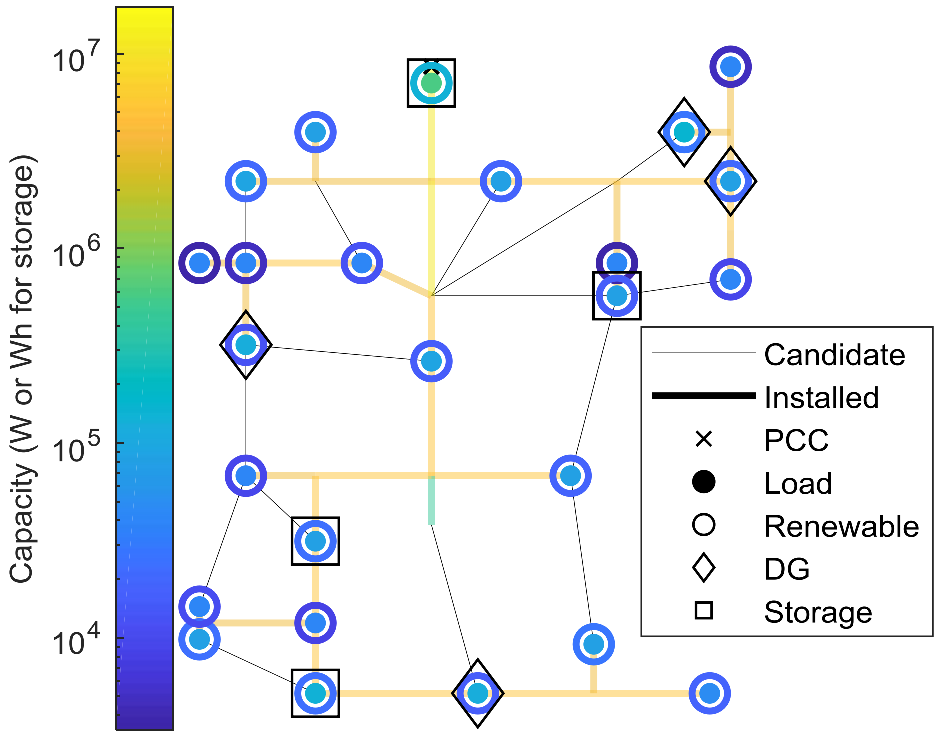


New decision variables

- Islanding investment y_{Inv}^{Isl}
- Demand not supplied for low-priority loads
  $0 \leq P_{NS,t}^{Dmd} \leq P_t^{Dmd} * y_{NS}^{Dmd}$

Resilience quantification

- Same indicators as reliability: SAIFI, SAIDI, EENS



Reliability

Failure rate	0.14 per mile and year
Repair duration	4h

Resilience

Islanding events	2.4 per year
Islanding duration	2..8 h

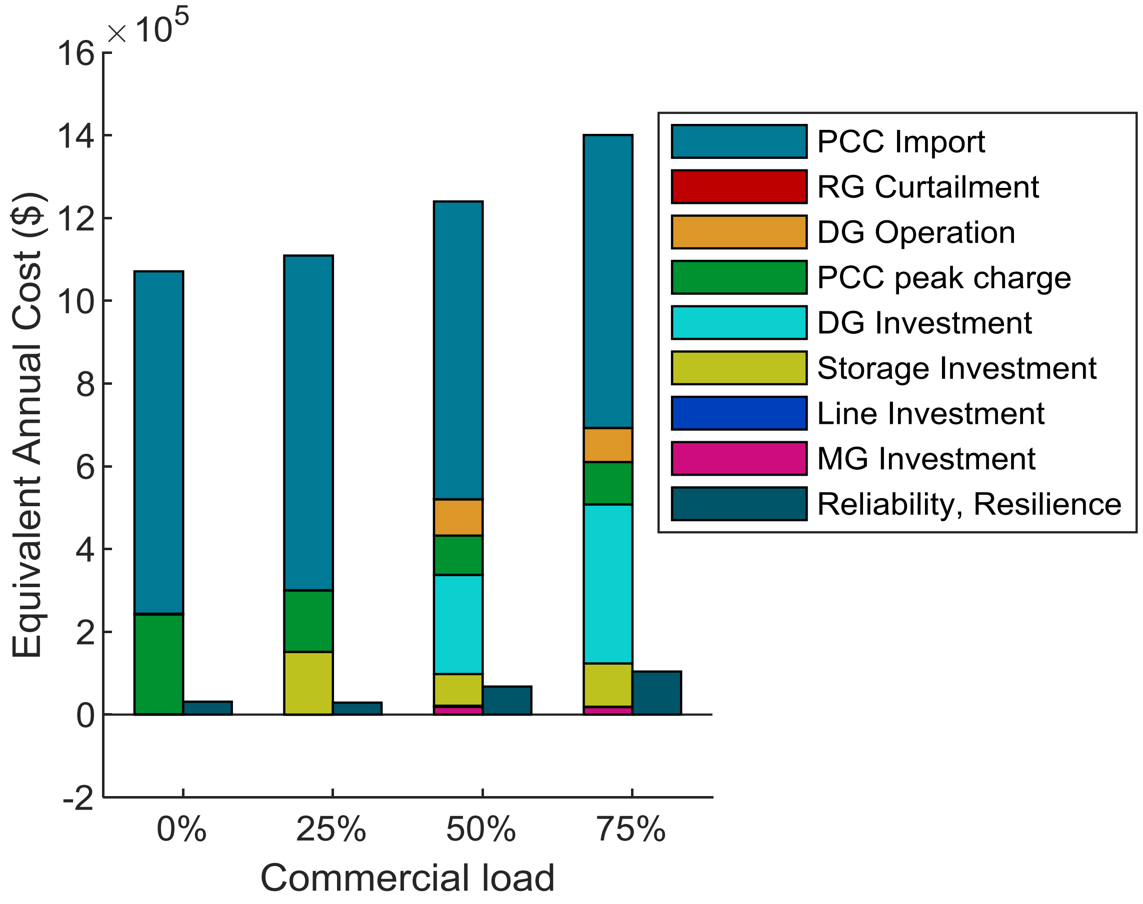
Cost

Residential ENS	3.3 $/kWh
Commercial ENS	370 $/kWh

Case Study: IEEE 37 bus system

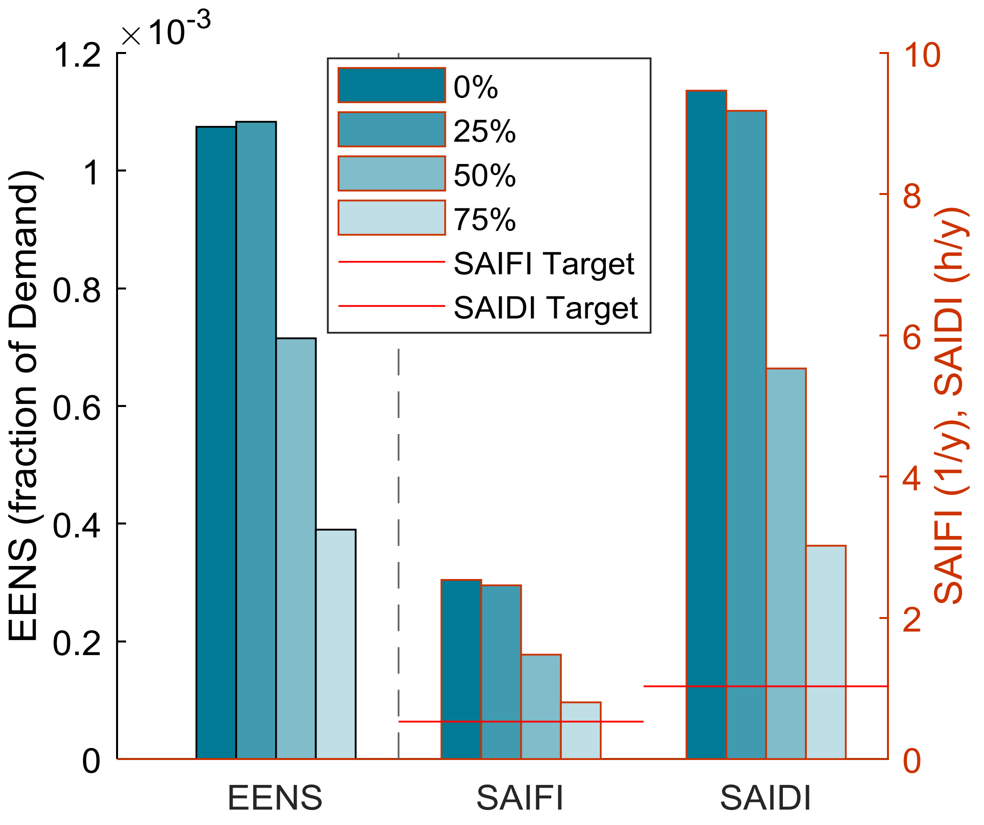
Results: Minimising Social Cost

- Microgrid and DER built for higher commercial load
- Shift from storage to DG
- DG mostly idle
- Low costs for reliability & resilience



Results: Reliability and Resilience

- Improvement with more DER and Microgrid
- Alternative approach: Predefine targets [CPUC 2017]
- EENS increase due to change in load shape



DER Flexibility

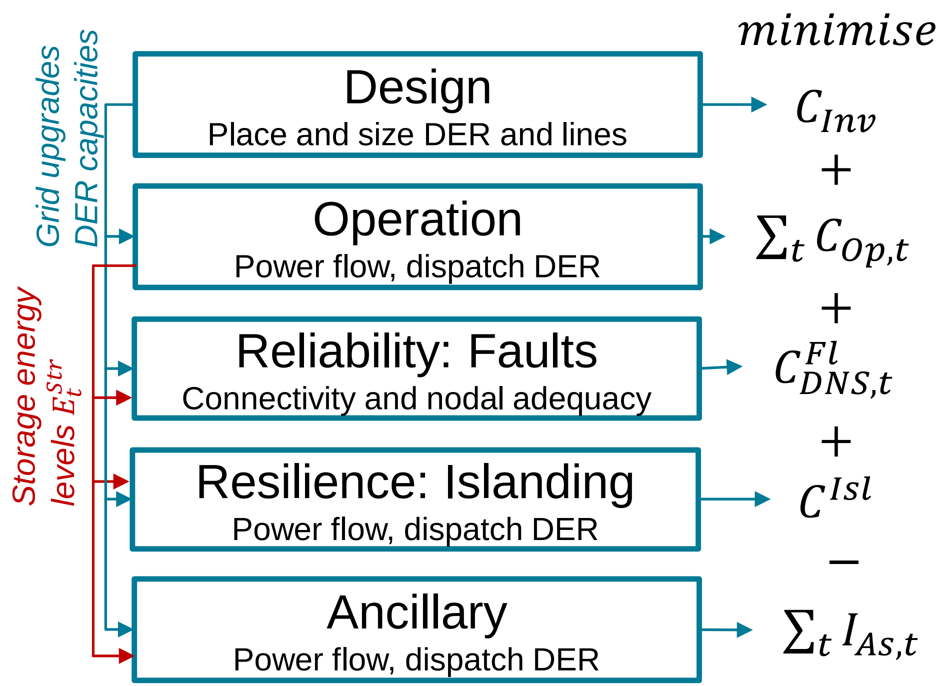
Additional income opportunities

Ancillary services

- Offering capacity to ramp up or down
- Remuneration
  - Capacity payment
  - Energy payment

Modelling

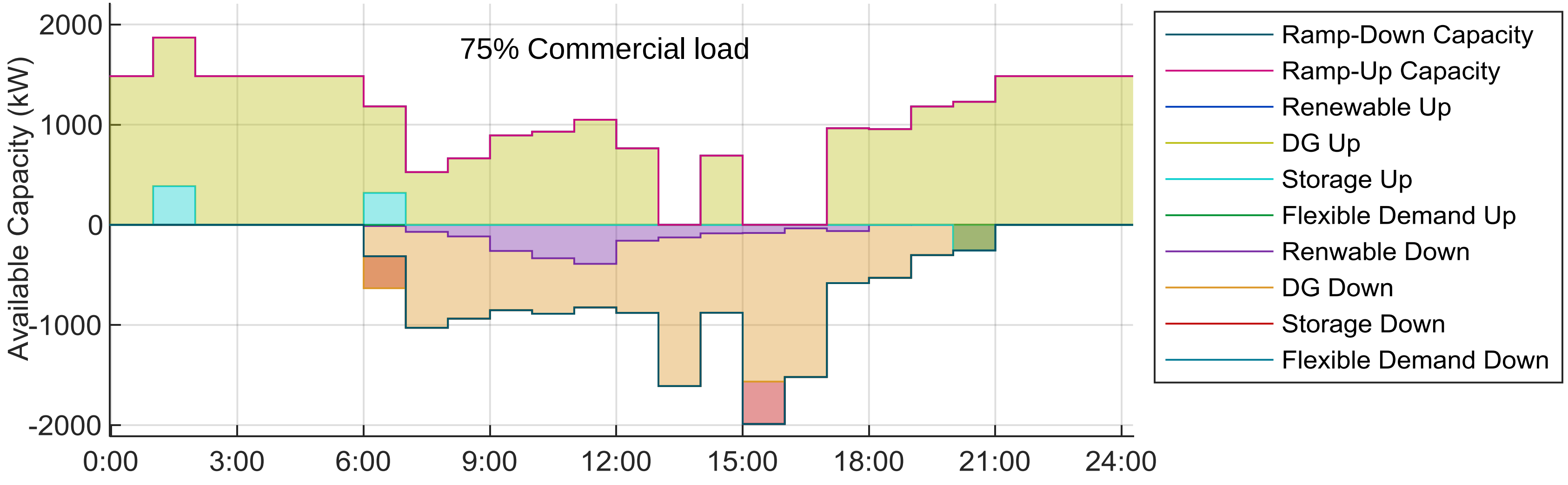
- Maximum ramp-up scenario → $P_t^{PCC,Up}$
- Maximum ramp-down scenario → $P_t^{PCC,Dn}$
- Income $I_{As,t} \propto \left(P_t^{PCC,Up} - P_t^{PCC}\right) + \left(P_t^{PCC} - P_t^{PCC,Dn}\right)$



Ancillary service results

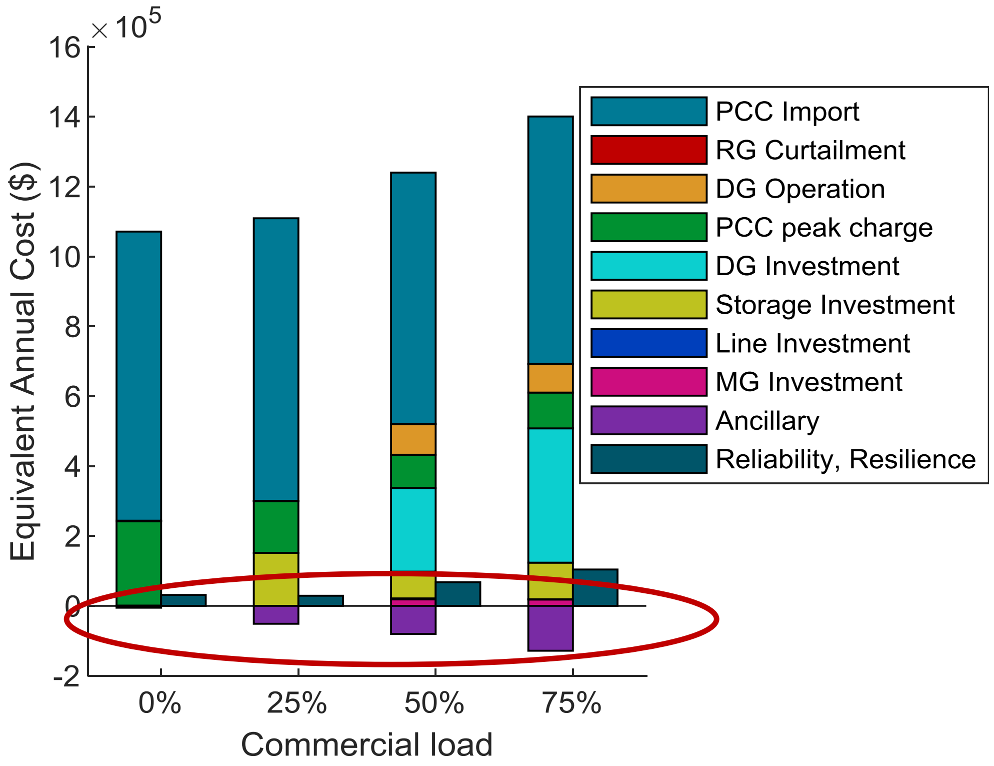
- DER can provide substantial flexible capacity
  - Up to 85% of peak load

- Increased use of Distributed Generator



Additional income

- Up to 15% of operating cost reduction
- Optimal DER capacities do not change
- Current ancillary services do not justify DER investments



Conclusions

▪ Smart grids or Microgrids?	▪ Depends on demand, costs and resilience goals
▪ Incentives and drivers	▪ Reliability and resilience goals ▪ Ancillary services
▪ Preferred future solutions	▪ Both DER and microgrids

References

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Image sources

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