From Blackouts to Flexibility: Socio-Economic Models for Next Generation Power Grids

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Motivation: A Power System Under Structural Stress

Energy transition & climate pressure

- Massive integration of decentralized renewables (wind, solar)
  - Greater intermittency and increased grid congestion risks.
- More frequent and intense extreme weather events
  - Higher probability of blackouts and cascading failures.

Limitations of existing approaches

- Predominantly technical optimization tools with limited socio-economic content:
  - VOLL (Value of Lost Load), consumer heterogeneity, contract-based flexibility, acceptability.
- Resilience models often focus on post-event restoration
  - Little emphasis on minimizing social welfare losses from load shedding.

Strategic challenge

- Need for an integrated framework linking:
  - Long-term design decisions (capacity, storage, contracts)
  - Operational responses under stress
  - Socio-economic trade-offs across consumer classes

Resilience and Flexibility: Key Challenges

Resilience

- Ability to anticipate, absorb, and recover from shocks without losing core functions.
- Blackouts, cascading failures, climate-related events.

Flexibility

- Required to integrate high shares of variable renewables.
- Supply-side: flexible generation units, ramping capabilities, storage, network topology.
- Demand-side: demand response, interruptibility contracts, Price-based mechanisms (dynamic pricing) vs contract-based mechanisms.

Joint challenge

- Design grids that are both *resilient* and *flexible*, accounting for socio-economic impacts.

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Blackouts and Cascading Failures

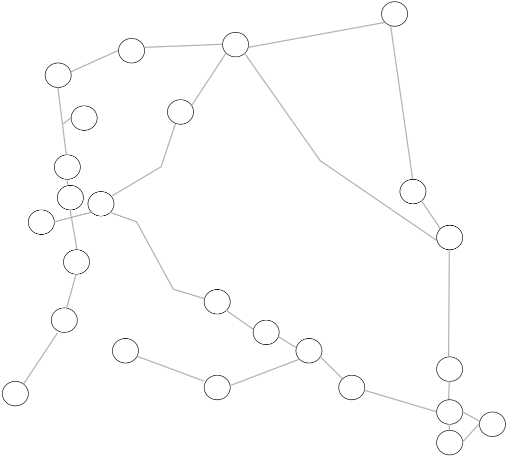

Figure: Initial Power grid.

Blackouts and Cascading Failures

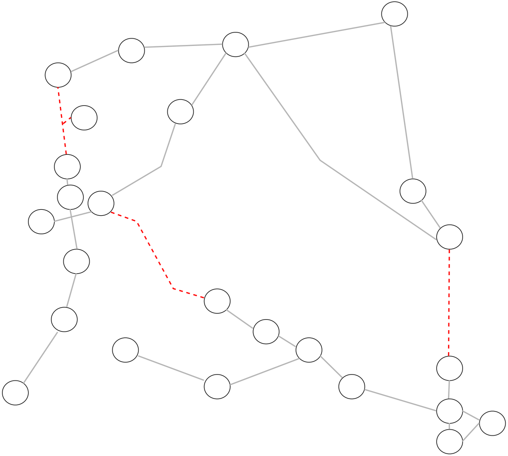

Figure: Trigger event on this Power grid.

Blackouts and Cascading Failures

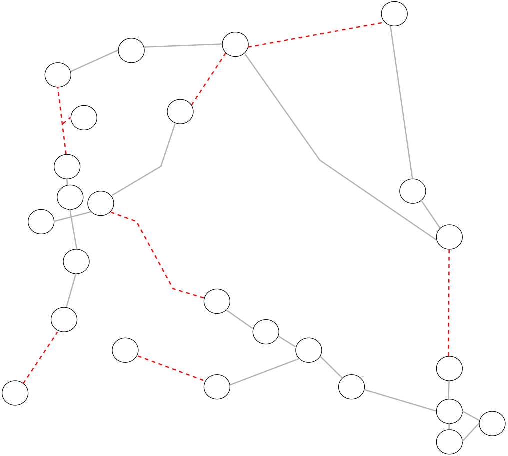

Figure: Cascade failure starting.

Blackouts and Cascading Failures

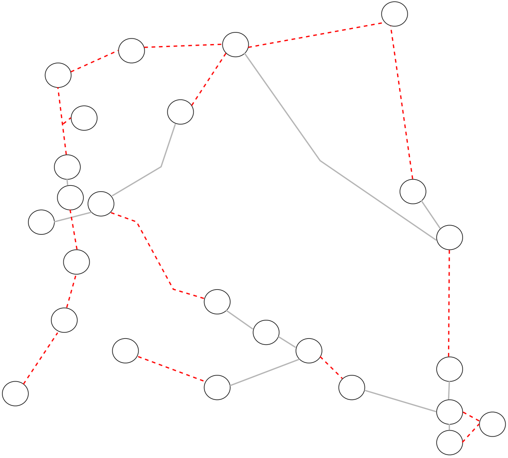

Figure: Cascade failure.

Blackouts and Cascading Failures

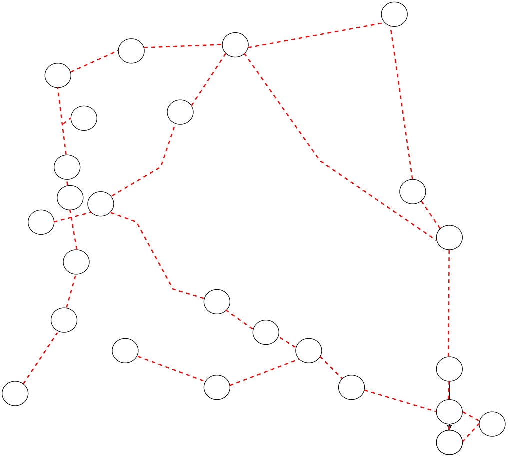

Figure: Blackout.

Blackouts and Cascading Failures

Blackout vs. blackout situation

- Blackout: actual large-scale interruption of service.
- Blackout situation: critical, unstable context where the grid risks tipping into a blackout.

Cascading failures

- Initial shock ⇒ overloads, frequency imbalances, component failures.
- Line or generator failure ⇒ new overloads on remaining components.
- Cascade propagation is one of the main challenges for modern grids.

Classical countermeasures

- Islanding, line switching, load shedding, redispatch, ...

Power Grid

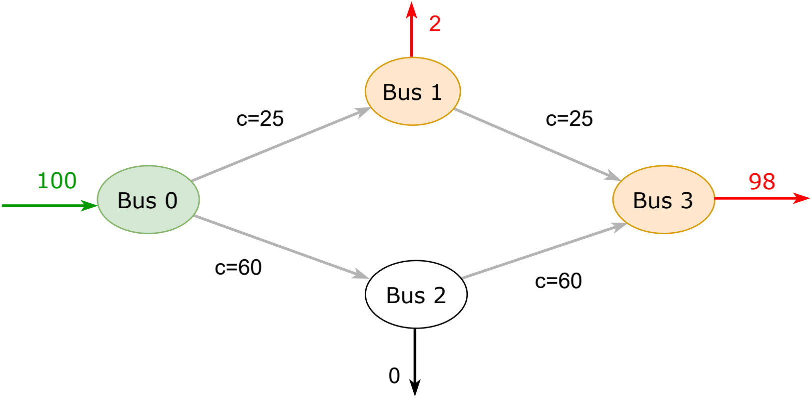

Figure: Initial grid.

Power Grid

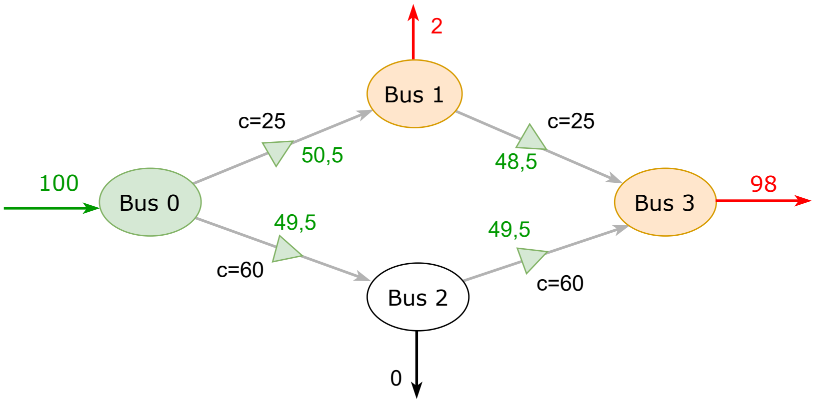

Figure: Flows computation.

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Power Grid

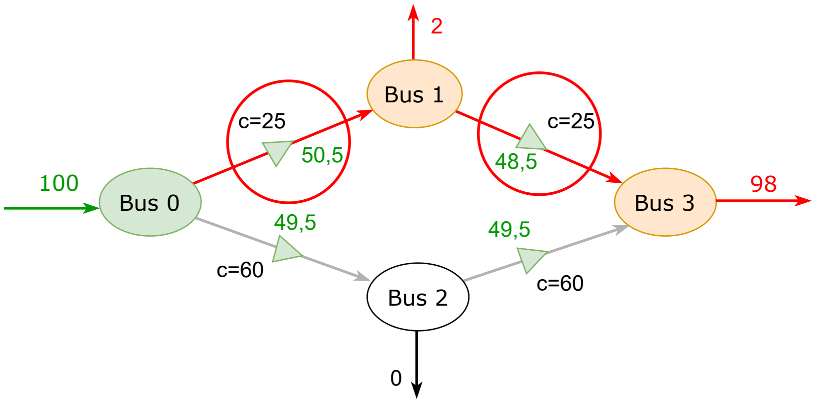

Figure: Some lines overloaded.

Power Grid

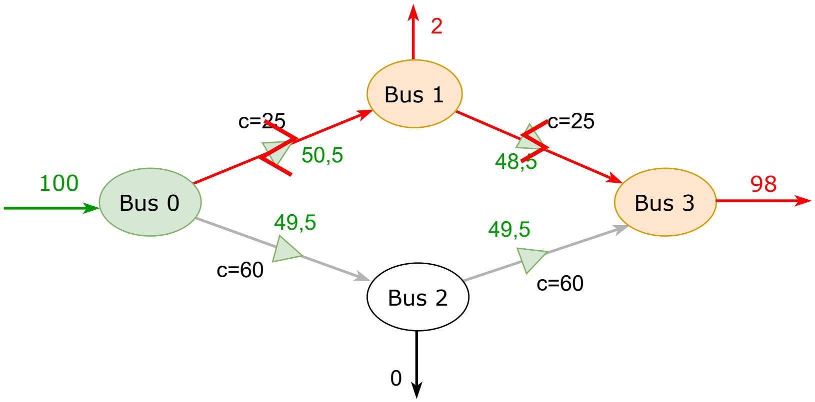

Figure: Lines overloaded are disconnected.

Power Grid

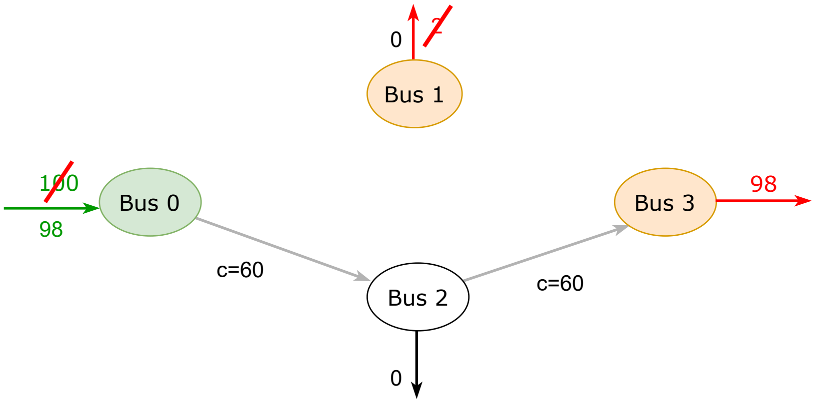

Figure: New grid.

Power Grid

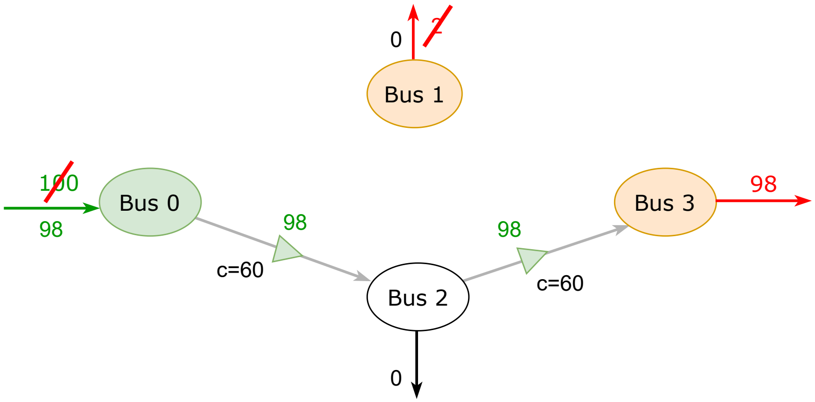

Figure: New flows computation.

Power Grid

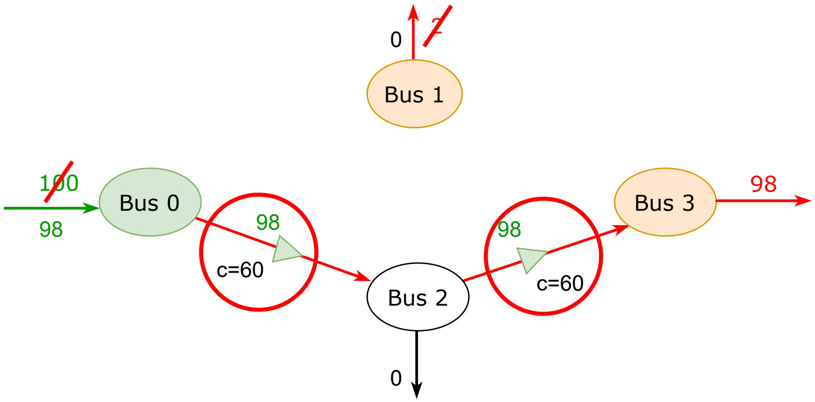

Figure: New lines overloaded.

Power Grid

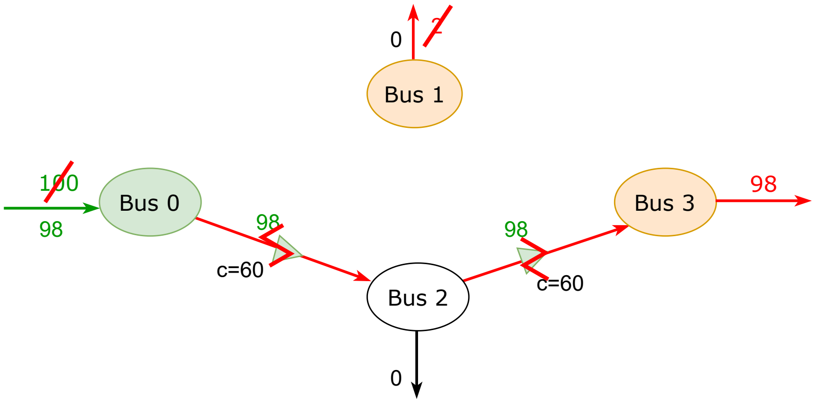

Figure: New lines disconnected.

Power Grid

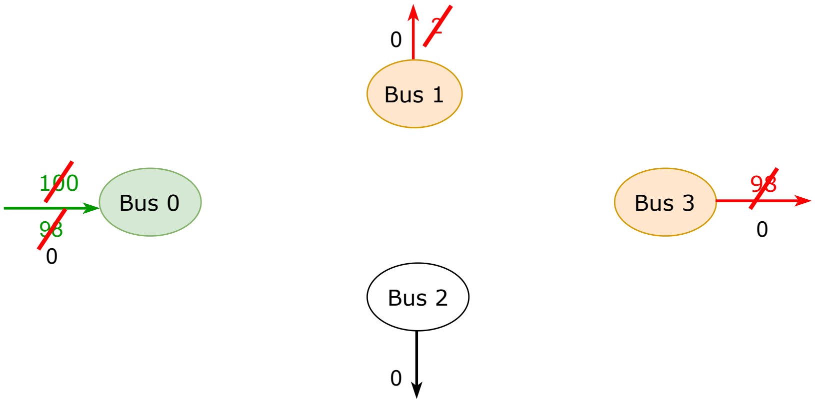

Figure: Final grid : Blackout.

Power Grid : with countermeasures

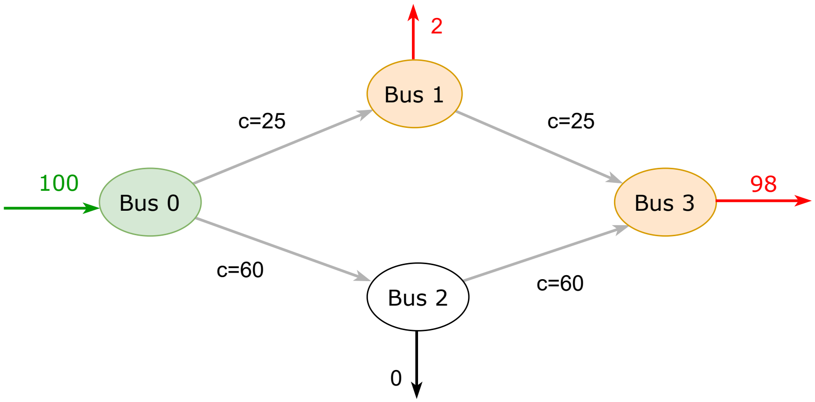

Figure: Initial grid.

Power Grid : with countermeasures

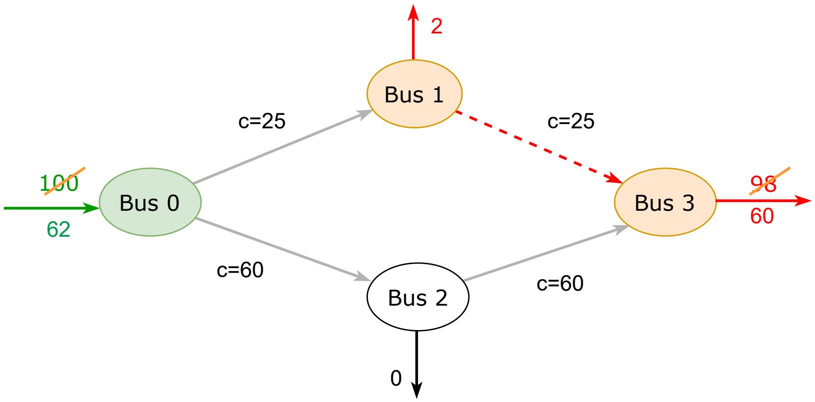

Figure: Countermeasures.

Power Grid : with countermeasures

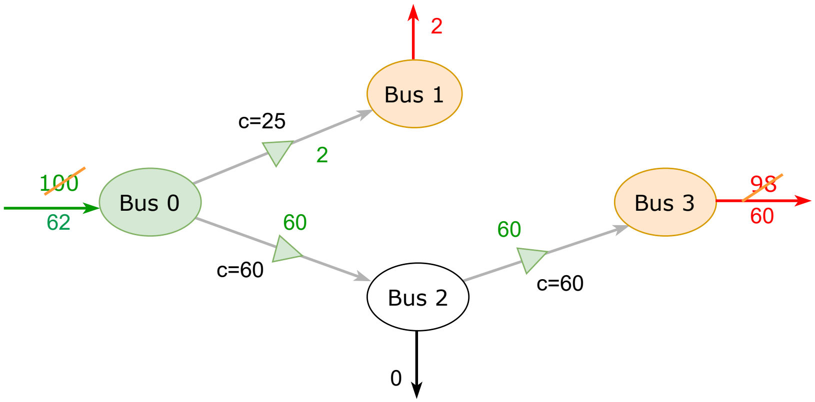

Figure: Flows computation with countermeasures.

Power Grid : with step of Network Design

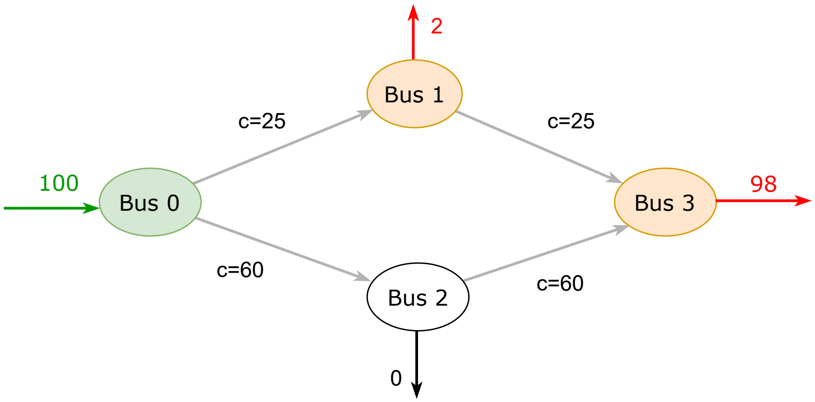

Figure: Initial grid.

Power Grid : with step of Network Design

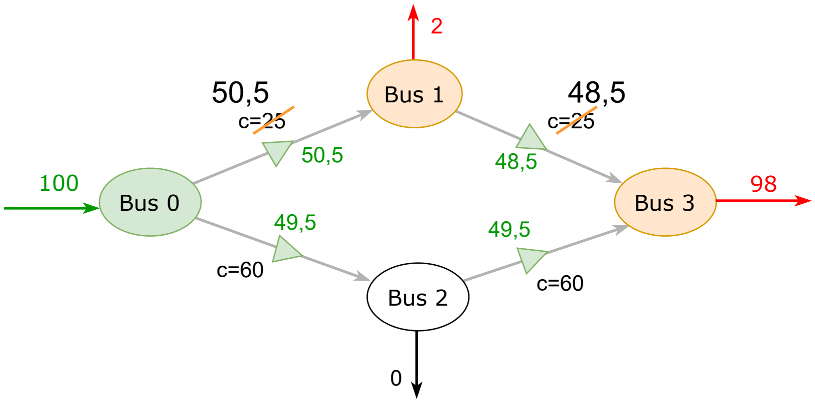

Figure: Flows after Network Design.

Overview of the Modeling Framework

Two phases

- **Design phase (Stage 1):**
  - Investment decisions in generation, line capacity, batteries, and contracts.
  - Subject to a budget constraint.
- **Response phase (Stage 2):**
  - After a shock scenario is realized.
  - Decisions: load shedding, line cutting, dispatch.

Objective

- Minimize a risk measure (CVaR) of the socio-economic cost across blackout scenarios.

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Network Representation and Assumptions

Grid representation

- Transmission network modeled as a directed graph $G = (V, E)$.
- $V_1 \subset V$: generators, $V_2 \subset V$: consumers.
- Line $(i, j) \in E$ has initial capacity c_{ij}^0 and potential capacity upgrades.

Power flow

- DC power flow approximation (with possible AC consistency checks).
- Decision to cut lines or keep them active in the response phase.

Uncertainty

- Scenario set Ξ: line outages, demand and production conditions.
- All uncertainty is revealed at the beginning of the response phase.

Stage 1: Design Decisions

Design variables

- q_i^+: additional generation capacity at bus i.
- c_{ij}^+: additional line capacity on arc (i, j).
- Battery capacity decisions at selected buses.
- Contract-based flexibility (interruptibility) at consumer nodes.

Budget constraint

- Total investment cost (generation, lines, batteries, contracts) cannot exceed a given budget B.

Goal

- Choose a design that performs well across all blackout scenarios when the recourse problem is solved optimally.

Stage 2: Response Decisions

Recourse variables (per scenario $\xi \in \Xi$)

- p_i^ξ: power served or produced at bus i.
- f_{ij}^ξ: power flow on line (i, j).
- $x_{ij}^\xi \in \{0, 1\}$: line status (active or cut).
- Load shedding by consumer type at each node.

Constraints

- Nodal power balance.
- Line capacity limits (with upgraded capacities when applicable).
- Connectivity and islanding constraints if lines are cut.

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Socio-Economic Cost and Welfare Loss

Load shedding vs demand response

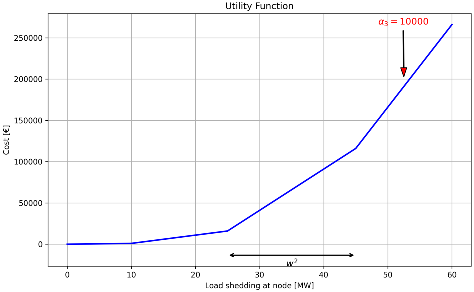
- Demand response: voluntary, incentivized, contract-based.
- Load shedding: involuntary, emergency measure imposed by the operator.

Cost functions

- For each node i and consumer category u, a cost function $\beta_i^{\xi,u}(x)$.
- Linear functions with different slopes α_u to reflect:
  - Households,
  - Industrial customers,
  - Critical services (hospitals, etc.).

Example of Utility / Cost Functions

- Class 0: Households with contracts : $\alpha_0 = 1$
- Class 1: Standard households : $\alpha_1 = 10$
- Class 2: Industries : $\alpha_2 = 50$
- Class 3: Hospitals, public services : $\alpha_3 = 100$



- Different **slopes** α_u **express different social priorities**.
- **Higher penalty** for shedding critical services than for **non-essential uses**.

Generic Two-Stage Optimization Model (Equation 3.1)

Design + Recourse Objective

$$\min_{(c^+,q^+)} (1-\lambda)\, \mathbb{E}_{\xi\in\Xi} \left[\sum_{i\in V_2} \sum_{u\in U} m_{iu}\, \beta_u(\bar{p}_i^{\xi}, p_i^{\xi}) \right] +$$

$$\lambda\, \mathrm{CVaR}_{\alpha,\xi\in\Xi} \left[\textstyle\sum_{i\in V_2} \sum_{u\in U} m_{iu}\, \beta_u(\bar{p}_i^{\xi}, p_i^{\xi}) \right].$$

Subject to

- $(c^+, q^+) \in Y$ (Design constraints, budget)
- $(x^{\xi}, f^{\xi}, p^{\xi}) \in X_{\xi}(\bar{x}^{\xi}, \bar{p}^{\xi}, c^0 + c^+, \bar{q}^{\xi} + q^+)$ (Recourse feasibility)

Interpretation

- First-stage decisions choose investments in generation, line capacity, batteries, and contracts.
- Second-stage optimizes flows, load shedding, and line status after each scenario ξ.
- Objective mixes expected social cost and tail risk (CVaR) of worst-case disruptions.

Toy Example: Setup

Motivation

- Validate modeling choices on a small test network.
- Understand qualitatively the impact of budget and costs.

Parameters (illustrative)

- c_{cont}: cost of contract-based curtailment.
- c_{prod}: cost of increasing generation capacity.
- c_{bat}: subsidy cost for batteries.
- c_{cap}: cost of increasing line capacity.

Objective function

$$(1-\lambda)\mathbb{E}_{\xi\in\Xi}\left[\sum_{i\in V_2}\sum_{u\in U}\alpha_i^{\xi,u}w_i^{\xi,u}\right]+\lambda\ \text{CVaR}_{\alpha,\xi\in\Xi}\left[\sum_{i\in V_2}\sum_{u\in U}\alpha_i^{\xi,u}w_i^{\xi,u}\right] \quad (1)$$

- $w_i^{\xi,u}$: load shed for customers of class u at node i under scenario ξ.
- $\alpha_i^{\xi,u}$: cost of load shedding 1 MW of power to customers of class u at node i under scenario ξ.
- $\sum_{u=0}^{3} w_i^{\xi,u} = \Delta_i^{\xi}$ where Δ_i^{ξ} is the total load shed on bus i under scenario ξ.

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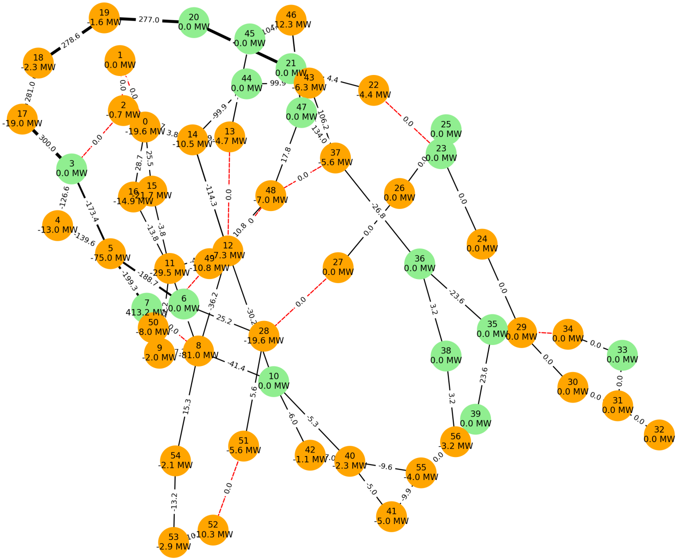
IEEE57 dataset with 10 different scenarios

- Network: IEEE 57-bus
- 10 scenarios with random line outages (5 to 15 line breaks per scenario)
- $c_{\text{cont}} = 4$: cost to give the right to reduce 1 MW of potential power from "contract" customers.
- $c_{\text{prod}} = 1$: cost to increase production capacities; it is assumed that increasing a power plant's capacity by 1 MW requires an investment of 1 million euros.
- $c_{\text{bat}} = 5$: subsidy cost to install 1 MW of potential battery power.
- $c_{\text{cap}} = 4$: cost to increase line capacities by 1 kA/km.
- kpMAX $= 300$: maximum allowable capacity on network lines.

Réseau électrique - Scénario 5



- Green nodes represent generator buses and the Orange nodes represent consumer buses.
- The red lines correspond to the lines that are cut in scenario 5.
- Each node is annotated with the generated or consumed power, and each edge displays the corresponding flow.
- The lines that would be cut in reaction to the catastrophic event are shown in blue.

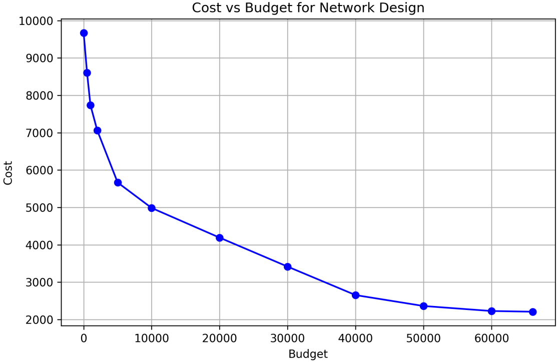
We observe that no line was actually cut. More generally, in our model, no line is ever cut. Instead, the model prefers to reduce the load at a bus or decrease a generator's output when a flow approaches the line's capacity, in order to keep every line in the network active and thus better distribute the power flows.

Budget	Budg_cont	Budg_bat	Budg_cap	Budg_prod	Coût
0	0	0	0	0	9674
500	397	102	0	0	8605
1000	450	549	0	0	7737
2000	–	563	986	0	7064
5000	–	–	3986	0	5668
10000	–	–	8986	0	4987
20000	–	–	18986	0	4193
30000	–	–	28986	0	3418
40000	–	–	38986	0	2656
50000	–	–	48986	0	2364
60000	–	–	58986	0	2230

Table: Budget allocation and costs for different scenarios

1. Allocated first to contracts
2. Then to batteries
3. Only afterwards to increasing line capacity
4. In this example, there is no need to expand the generation capacity in the production areas

Objective function as a function of the initial global budget



The cost decreases sharply at first, but beyond 30000 euros each additional euro invested only marginally reduces the objective function.

Most vulnerables

Bus	% load shedding	shedding/initial demand
25	29	25
18	14	12
2	11	9
7	10	7
17	10	6

Table: Identification of the most vulnerable buses

Line	% cut
(8,10)	81
(0,1)	56
(0,2)	55
(5,8)	43

Table: Identification of the most vulnerable lines

Policy Insights and Interpretation

Key insights

- At realistic budget levels, *contracts and distributed batteries* can be more cost-effective than major line reinforcements.
- Designing for resilience requires explicit modeling of social welfare and consumer heterogeneity.
- Vulnerability analysis highlights critical buses and lines for targeted interventions.

For Transmission System Operator (TSO) and policymakers

- Use Mixed-Integer Linear Programming (MILP)-based design tools to explore trade-offs between:
  - technical robustness,
  - social welfare protection,
  - investment costs.

Conclusion

We propose a two-stage MILP framework for power grid design under blackout risk.

- The model couples:
  - technical constraints,
  - socio-economic cost of load shedding,
  - flexibility levers (contracts, batteries, line upgrades),
  - and a CVaR risk measure.
- Numerical experiments (toy example, IEEE 57) illustrate:
  - the importance of targeted flexibility,
  - nontrivial budget allocation patterns,
  - and the potential for informed, welfare-aware grid design.

Thank you for your attention!

EFC 2011

Type of model

Two-stage stochastic program :

1. First-stage variables : decisions on budget allocation.
2. Second-stage variables are conditioned on the first stage.

This problem is not easy :

1. Limit in instance sizes for commercial solvers :
   1. 30 nodes and 100 scenarios.
   2. 57 nodes and 10 scenarios.
   3. 118 nodes and 3 scenarios.
2. Problem of increasing capacity decisions : already difficult.

Contraints

Interruptibility Contract: This contract offers the customer a reduced electricity bill of 100 € per year in exchange for prioritized disconnection during exceptional network events. The cost for the electricity provider is therefore 100 € per contract per year. Considering that the network investments are assumed to be valid over the next 20 years, the total contract cost per customer is computed as:

$$c^{cont} = 100 \text{ €} \times 20 = 2000 \text{ €}.$$

Battery Storage: A battery with a storage capacity of 15 kWh has an installation cost of 15000 € for an end consumer. To encourage adoption, the state would provide a subsidy of 5000 € per installation. Thus, the effective cost per battery is

$$c^{bat} = 5000 \text{ €}.$$

A 15 kWh battery can theoretically supply 15 kW for 1 hour, or 7.5 kW for 2 hours. However, the maximum output is limited by the inverter. Typical domestic batteries have a continuous output power of

$$P^{bat} = 5 \text{ kW} = 0.005 \text{ MW}.$$

Acceptability of Countermeasure Installations: Not all consumers are willing to adopt the proposed countermeasures. Therefore, the proportions of potential load shedding on these consumer groups per node are limited as follows:

$$y_i \leq -0.15 p_i^{\xi}, z_i \leq -0.15 p_i^{\xi}.$$

Additional Costs for Network Design:

- **Increase in production capacity:** Expanding a power plant by 1 MW requires an investment of $c^{prod} = 1.000.000$ €.
- **Increase in line capacity:** The current network lines have a maximum capacity

  $$S_{\max} = I_{\max} \cdot V_{\text{nom}} \cdot \sqrt{3} = 50 \text{ kA} \times 115 \text{ kV} \times \sqrt{3} \approx 9959 \text{ MVA}.$$

  No line can exceed a maximum capacity of $k^{+}_{max} = 12000$ MVA. The cost to increase line capacities by 1 MVA per km is $c^{cap} = 5.000.000$ €.

Risk Measure: CVaR of Societal Cost

CVaR objective

- Let C^{ξ} be the total socio-economic cost in scenario ξ.
- We minimize $\mathrm{CVaR}_{\alpha}(C)$ over the design and response decisions.

MILP formulation (Rockafellar–Uryasev)

- Introduce auxiliary variables η and $\zeta_{\xi} \geq 0$:

$$\min_{\eta, \{\zeta_{\xi}\}} \; \eta + \frac{1}{(1-\alpha)|\Xi|} \sum_{\xi \in \Xi} \zeta_{\xi}$$

subject to

$$\zeta_{\xi} \geq C^{\xi} - \eta, \quad \forall \xi \in \Xi.$$

- This keeps the overall problem linear and compatible with MILP.

Limitations and Future Research

Current limitations

- DC power flow approximation; limited AC modeling.
- Simplified uncertainty structure (full information revealed at once).
- No explicit modeling of customer behavior or acceptability.

Future extensions

- Integrate more detailed AC constraints and generator coherency.
- Refine scenario generation (location of outages, correlated risks).
- Incorporate fairness constraints and behavioral responses.
- Consider network aging and technology-specific cost structures.

Context

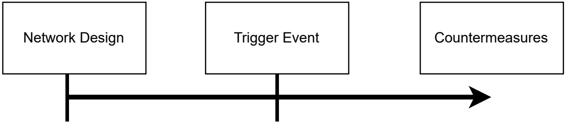
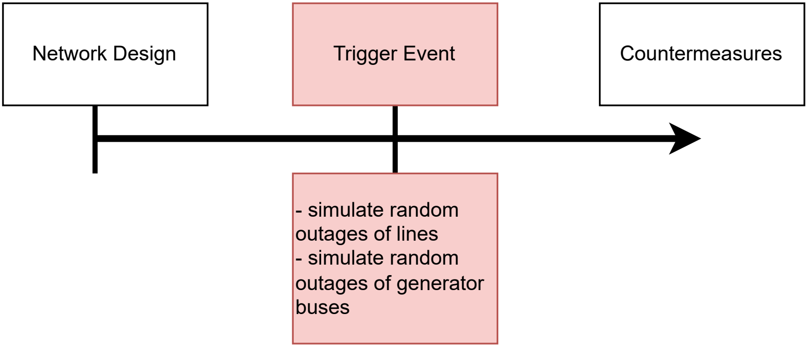


Figure: Process.

Several questions arise:

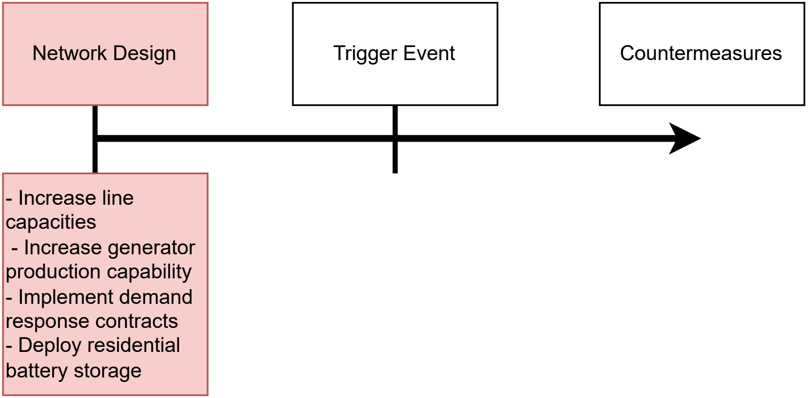
- What are the triggering elements of a cascade?
- How to measure and minimize the risk and socio-economic consequences of a blackout (see WP3)?
- Which downstream countermeasures can we use to prevent cascading failures?
- Which design variables of the network can be leveraged to strengthen resilience?
- How to consider the integration of renewable energies ?

Modeling assumptions — Trigger events

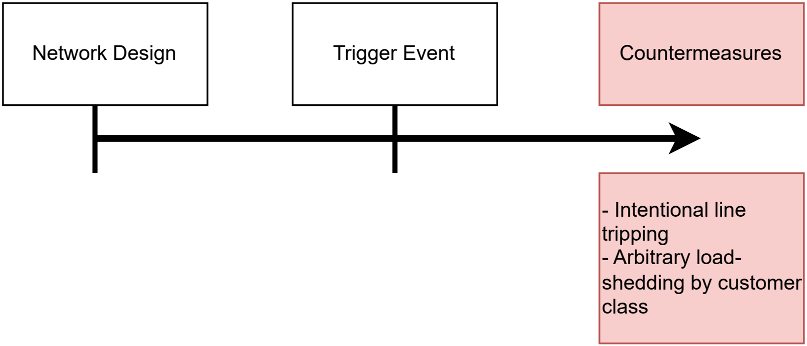


- How do we produce a list of the most likely scenarios ?

Modeling assumptions — Design levers



Modeling assumptions — Countermeasures

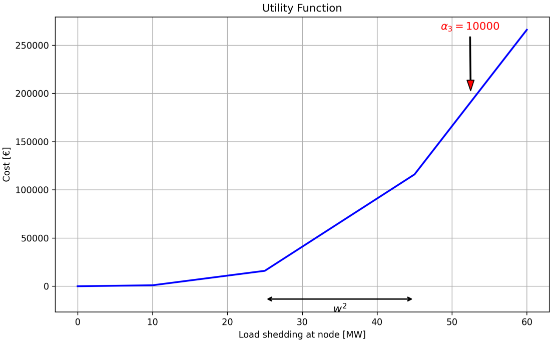


Intentional line tripping : binary decision variables — major source of complexity)

Client categories

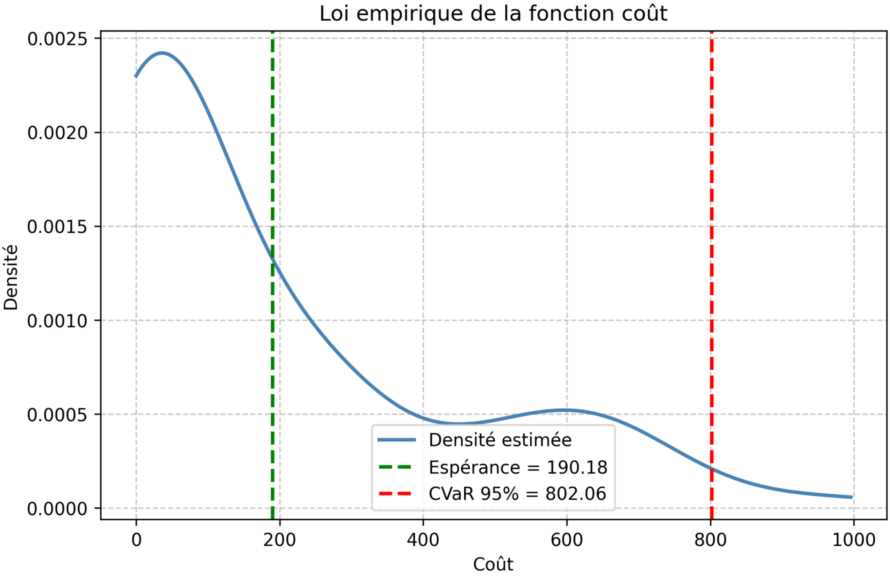
- Class 0: Households with contracts : $\alpha_0 = 1$
- Class 1: Standard households : $\alpha_1 = 10$
- Class 2: Industries : $\alpha_2 = 50$
- Class 3: Hospitals, public services : $\alpha_3 = 100$

Objective function - utility function



$$\text{utility function}: \sum_{i \in V_2} \sum_{u \in U} \alpha_i^u w_i^u \tag{2}$$

Objective function - empirical law



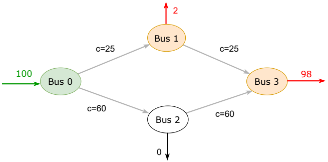
Optimization Model - Inputs

Objective Function

$$(1-\lambda)\mathbb{E}_{\xi\in\Xi}\left[\sum_{i\in V_2}\sum_{u\in U}\alpha_i^{\xi,u}w_i^{\xi,u}\right]$$

$$+\lambda\ \mathrm{CVaR}_{\alpha,\xi\in\Xi}\left[\sum_{i\in V_2}\sum_{u\in U}\alpha_i^{\xi,u}w_i^{\xi,u}\right]$$

Initial Network : c_{ij}, b_{ij}, p_i



Power Flow Equations

$$f_{ij} = b_{ij}(\theta_i - \theta_j)$$

$$\sum_{j:(i,j)\in E} f_{ij} - \sum_{j:(j,i)\in E} f_{ji} = p_i$$

Budget Constraint : B

Optimization Model - Permitted Actions

- Disconnecting lines : $x_{ij} = 0 \Rightarrow (f_{ij} - b_{ij}(\theta_i - \theta_j))x_{ij} = 0$.
- Increase or decrease power at each bus : g_i^+, g_i^-, $\Delta_i \Rightarrow$

$$\sum_{j:(i,j)\in E} f_{ij} - \sum_{j:(j,i)\in E} f_{ji} = p_i + g_i^+ - g_i^- \quad \text{on generator buses}$$

$$\sum_{j:(i,j)\in E} f_{ij} - \sum_{j:(j,i)\in E} f_{ji} = p_i + \Delta_i + g_i^+ \quad \text{on load buses}$$

- Increase line capacities : $k_{ij}^+ \Rightarrow f_{ij} \leq k_{ij} + k_{ij}^+$.
- Increase generator capacities : $q_i^+ \Rightarrow p_i + g_i^+ \leq P_i^{\max} + q_i^+$.
- Install batteries at private residences : $y_i \leq -0.15 p_i \Rightarrow g_i^+ \leq y_i$
- Engage customers through contracts : $z_i \leq -0.15 p_i \Rightarrow w_i^0 - z_i \leq 0$

Optimization Model - Constraints

- Respect the budget :

$$\sum_{(i,j)} c_{ij}^{\text{cap}} k_{ij}^{+} + \sum_{i} c_{i}^{\text{prod}} q_{i}^{+} + \sum_{i} c^{\text{bat}} y_i + \sum_{i} c_{i}^{\text{cont}} z_i \leq B$$

- Staying within line capacities to prevent blackouts :

$$f_{ij} \leq k_{ij} + k_{ij}^{+}$$

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Optimization problem - in some words

Goal: Minimize the socio-economic risk subject to:

1. The design budget is not exceeded.
2. For each scenario and resulting subnetworks:
    1. Flows respect physical equations.
    2. Line capacities are respected.
    3. Load shedding or power generation are limited.
    4. Load losses by customer category are limited : $\sum_{u=0}^{3} w_i^{\xi,u} = \Delta_i^{\xi}$

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Optimization Model - equations

$$\min \quad (1-\lambda)\mathbb{E}_\xi\left[\sum_{i,u} \beta_i^{\xi,u}(w_i^{\xi,u})\right] + \lambda \ \text{CVaR}_{\alpha,\xi}\left[\sum_{i,u} \beta_i^{\xi,u}(w_i^{\xi,u})\right]$$

$$\text{s.t.} \quad \sum_{(i,j)} c_{ij}^{\text{cap}} k_{ij}^{+} + \sum_i c_i^{\text{prod}} q_i^{+} + \sum_i c^{\text{bat}} y_i + \sum_i c_i^{\text{cont}} z_i \leq B,$$

$$\sum_{j:(i,j)\in E} f_{ij}^{\xi} - \sum_{j:(j,i)\in E} f_{ji}^{\xi} - g_i^{+,\xi} + g_i^{-,\xi} = p_i^{\xi} \quad \text{on generator buses,}$$

$$\sum_{j:(i,j)\in E} f_{ij}^{\xi} - \sum_{j:(j,i)\in E} f_{ji}^{\xi} - \Delta_i^{\xi} - g_i^{+,\xi} = p_i^{\xi} \quad \text{on load buses,}$$

$$(f_{ij}^{\xi} - b_{ij}(\theta_i^{\xi} - \theta_j^{\xi}))x_{ij}^{\xi} = 0, \quad f_{ij}^{\xi} - \epsilon_{ij}^{\xi} k_{ij}^{+} \leq \epsilon_{ij}^{\xi} k_{ij},$$

$$g_i^{+,\xi} - q_i^{+} \leq P_i^{\max} - p_i^{\xi}, \quad \Delta_i^{\xi} \leq -p_i^{\xi},$$

$$w_i^{\xi,0} - z_i \leq 0, \quad \sum_{u=0}^{3} w_i^{\xi,u} - \Delta_i^{\xi} = 0, \quad y_i, z_i \leq -0.15 p_i^{\xi}$$

Next steps / Open items

- Finalize model formalization and implement scalable solvers.
- Validate with realistic network datasets.
- Work with WP2/WP3 to obtain reliable cost & scenario inputs.
- Consider different assumptions regarding the integration of renewable energies as inputs to our model.

Thank you

Questions?

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