Transmission Network Planning Model Applied to WECC's System Expansion in the United States

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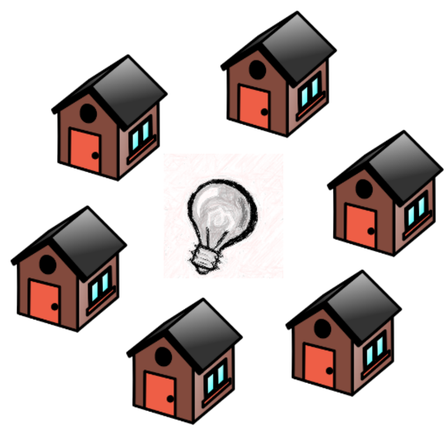
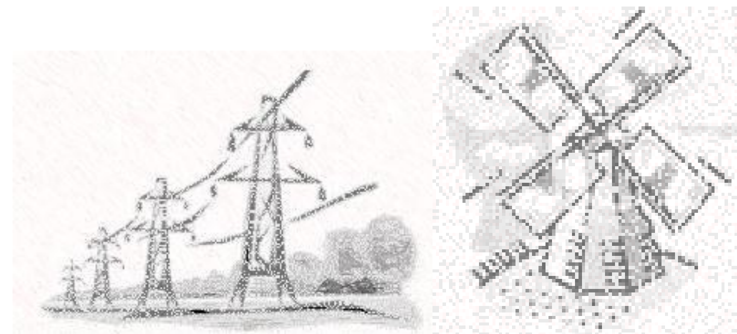
Electrical systems expansion

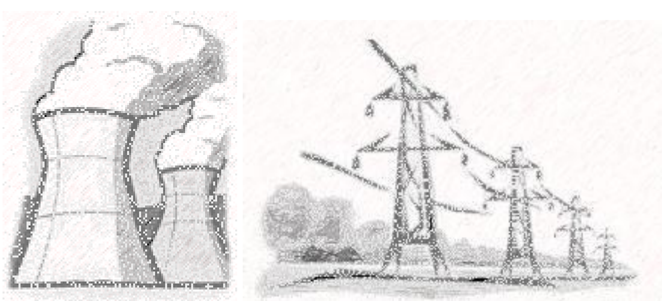
- The origin of the expansion problem of electrical systems resides on the need for new investments in generation and transmission systems required to face the demand growth and meet planning criteria



Electrical systems expansion

- Selecting the “best” of a group of alternatives is what characterizes the **combinatorial** nature of this problem





Electrical systems expansion

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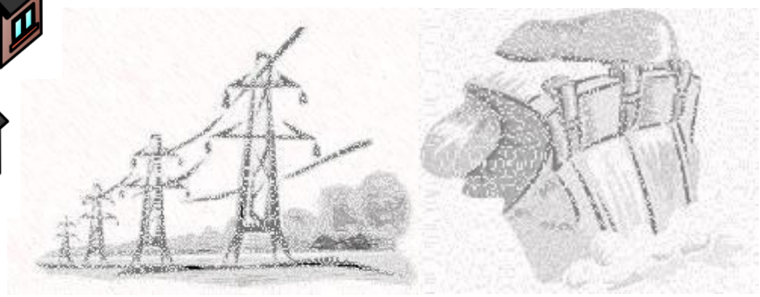
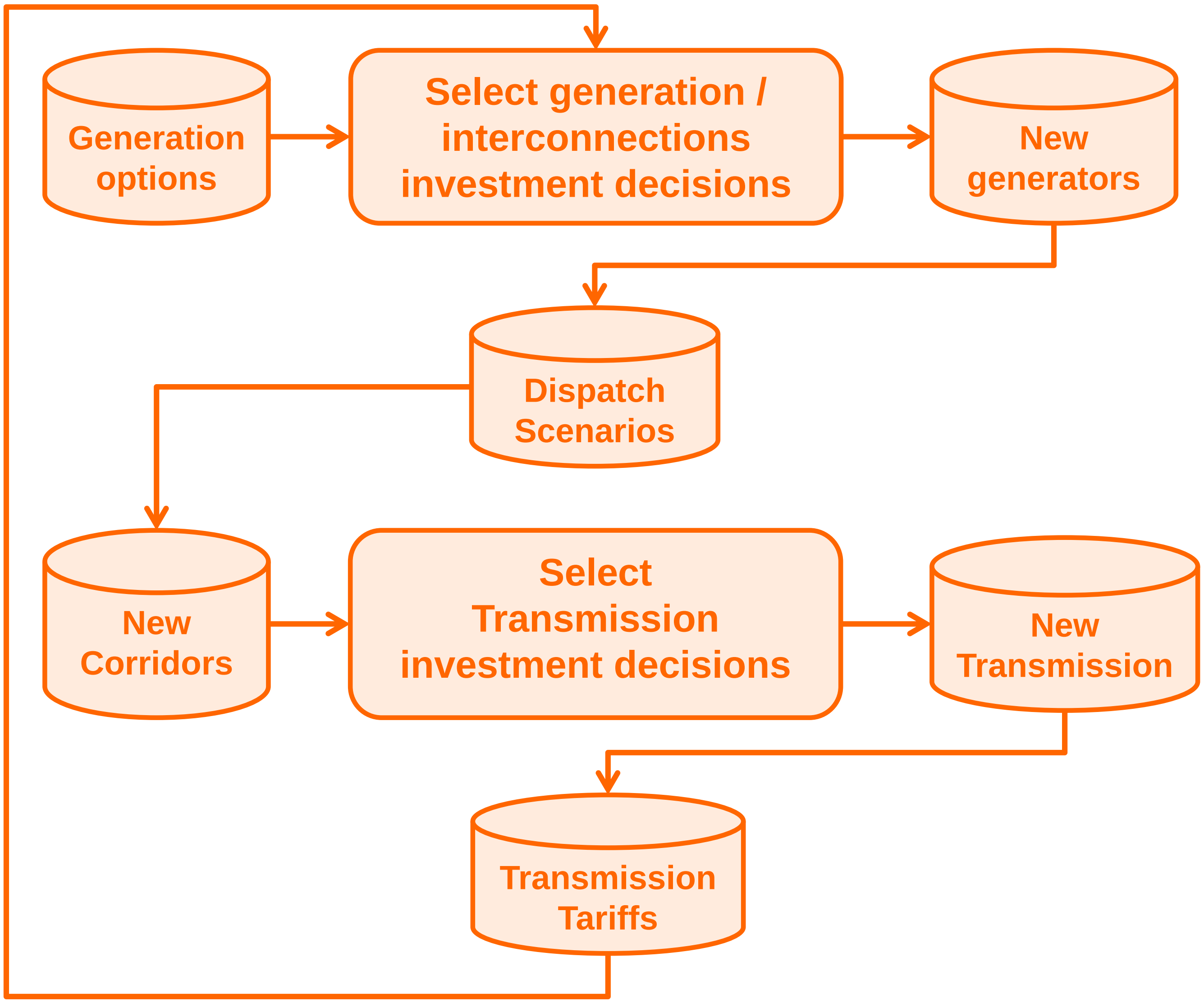


Usual approach: Hierarchical



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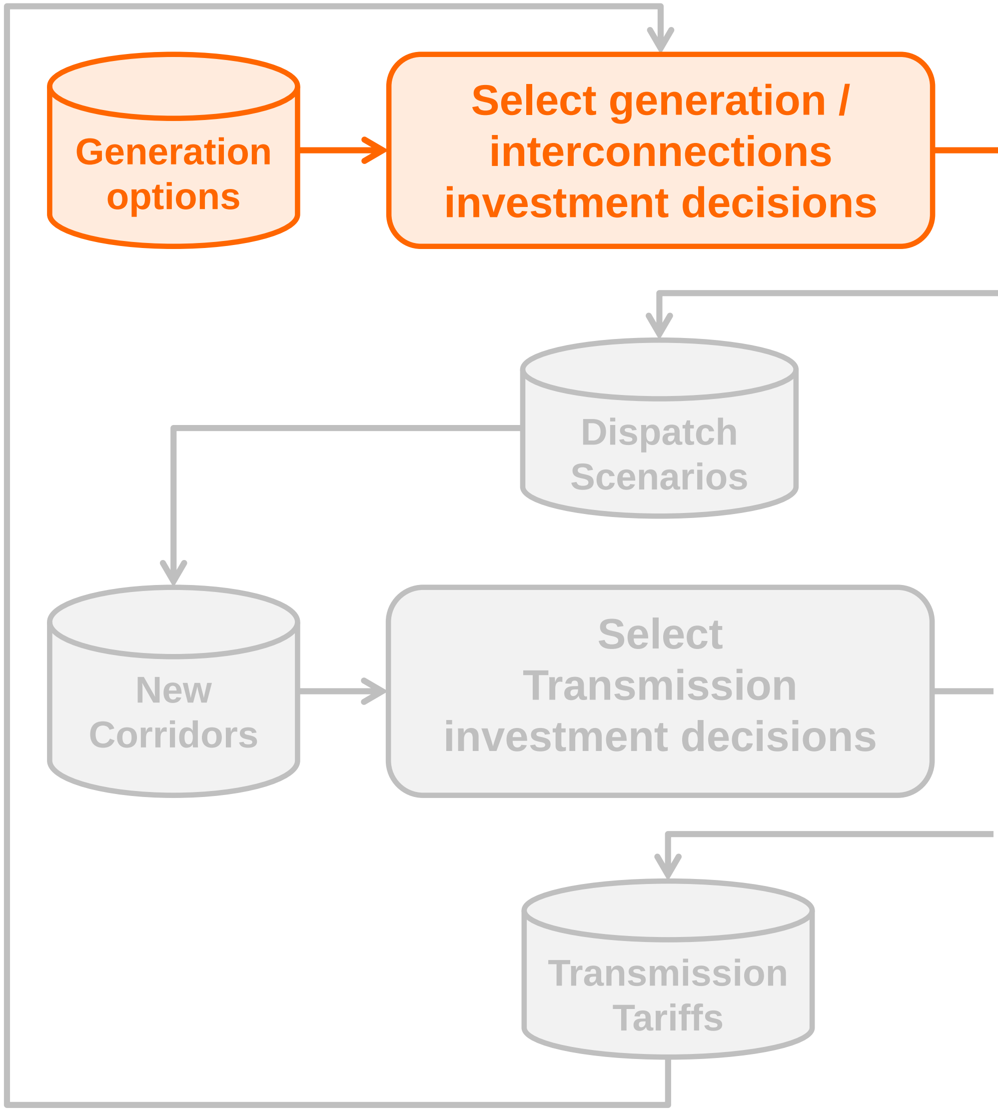
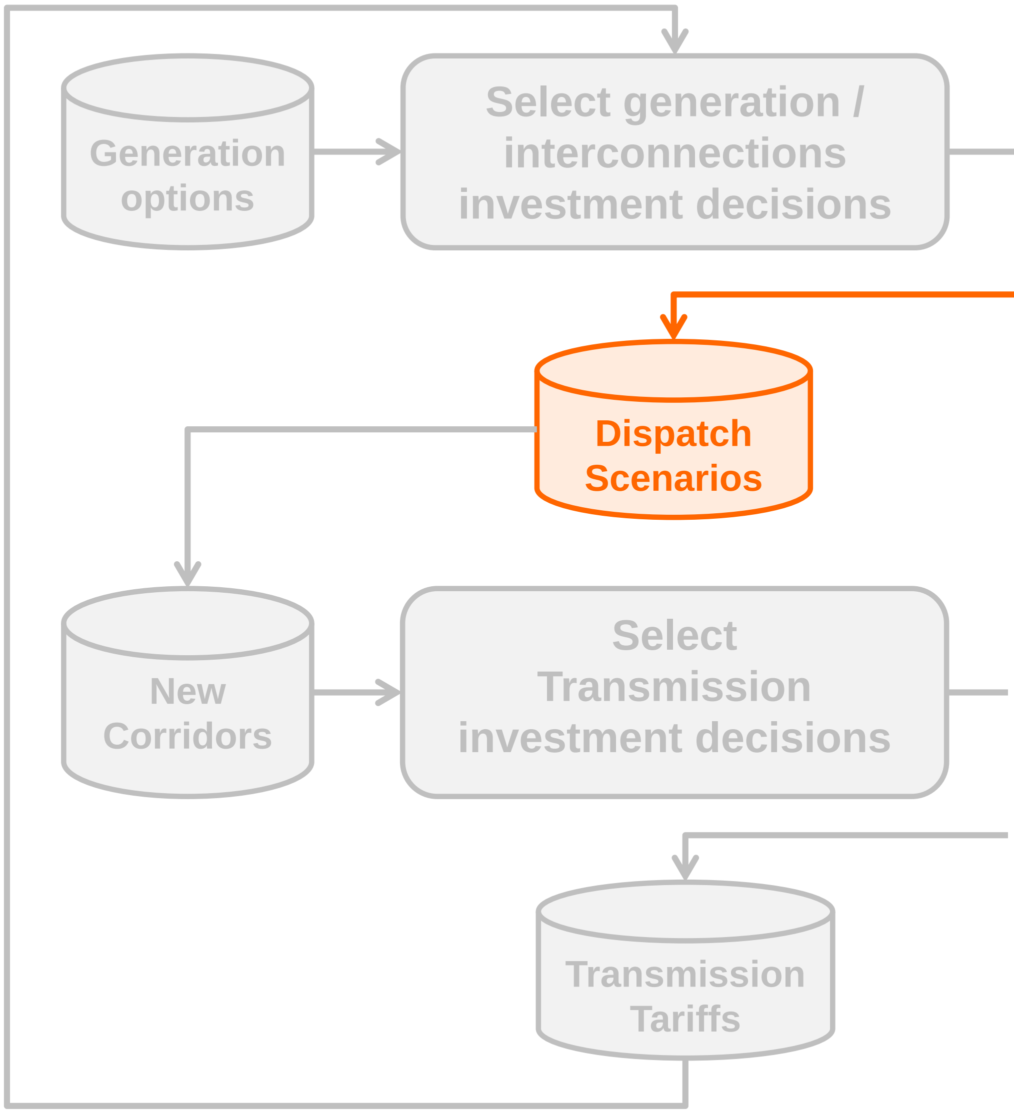


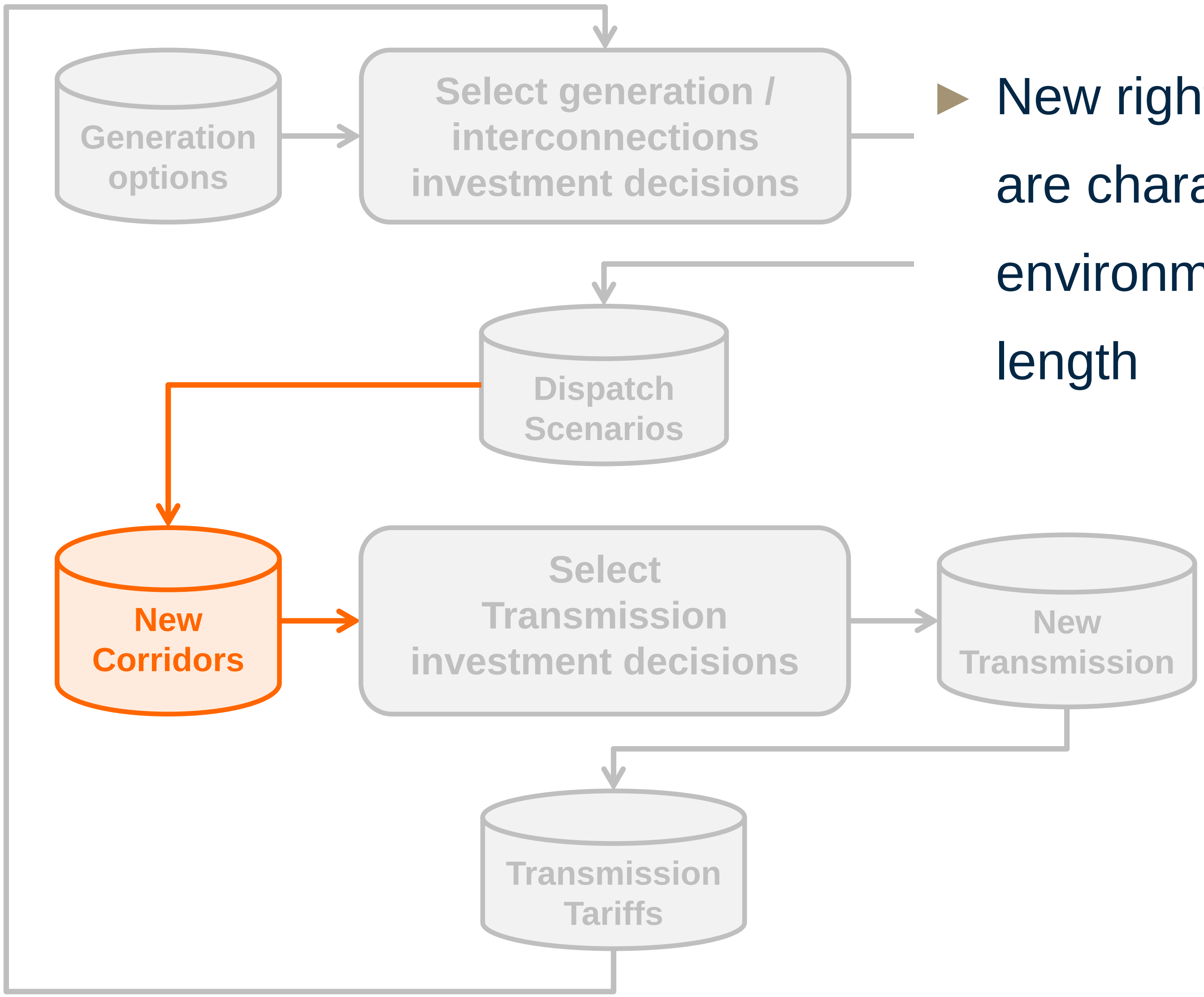
- First step: Decisions for generation are done beforehand, minimizing total cost of investment and operation along horizon study

Usual approach: Hierarchical



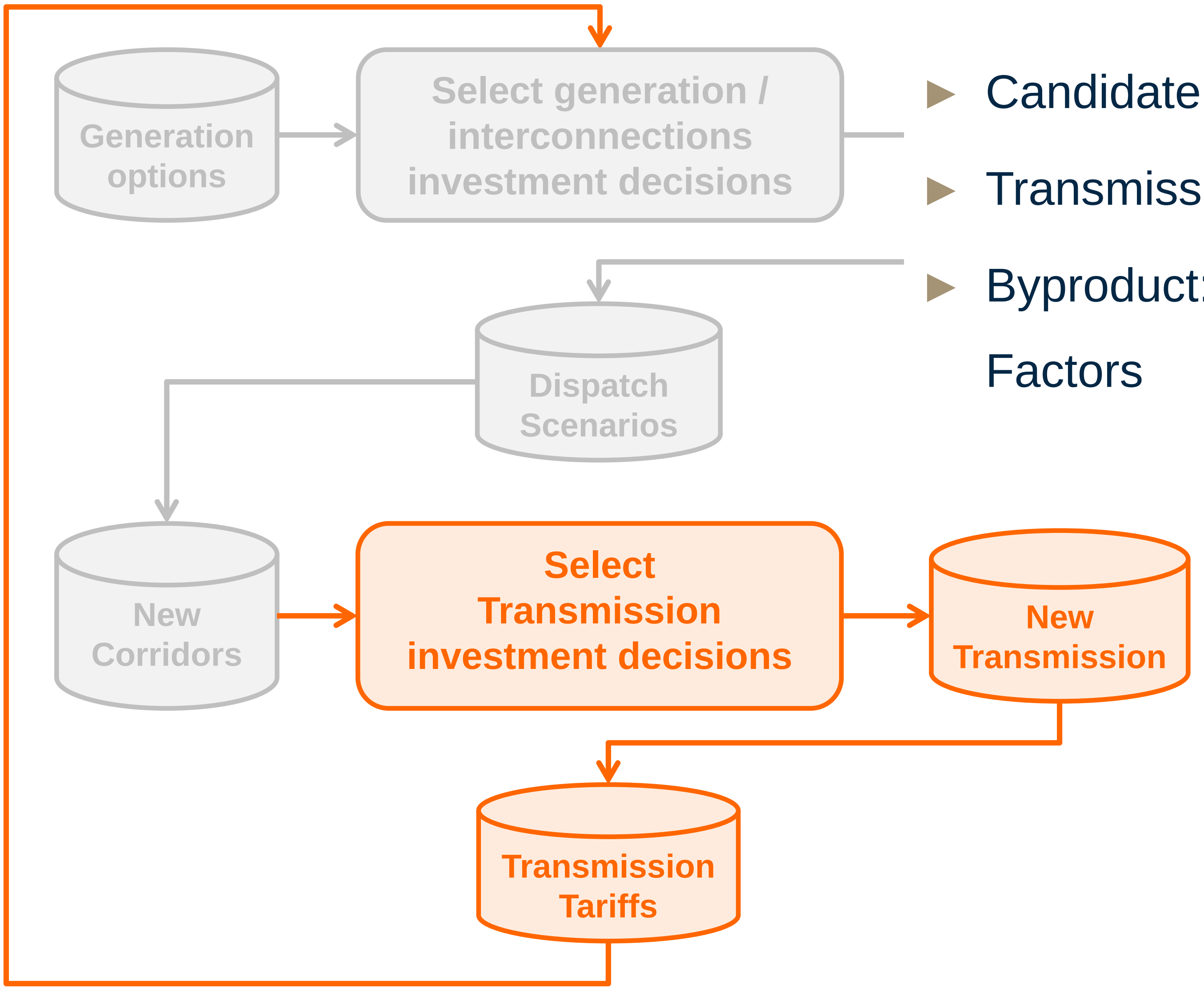
- Uncertainties are represented by likely dispatch scenarios obtained using production cost simulation tools

Usual approach: Hierarchical



- New right-of-ways / corridors are characterized by: environmental factor and length

Usual approach: Hierarchical



- Candidate Circuits
- Transmission Expansion Plan
- Byproduct: Grid Capital Cost Factors

Transmission expansion problem

- Least cost transmission network reinforcements, taking into account:
  - Multiple stages (years), multiple scenarios (renewable resources, equipment availability, etc.), load blocks
  - Linearized power flow representation provides reasonable approximation of power flows, avoids lack of convergence problems
  - Additional constraints are automatic included in the model to get a tighter formulation
  - Environmental impacts of candidate circuits represented by factors that are used to guide the search
  - Etc.

Linearized power flow equations

- Bus power balance equation (Kirchhoff’s first law)
- Kirchhoff’s second law
- Circuit flow limit
- Flow sum constraints
- Bus angle difference constraints

Disjunctive formulation

- Second Kirchhoff's law for candidate circuits:

$$f_k = \gamma_k \, \boldsymbol{x_k}(\boldsymbol{\theta_i} - \boldsymbol{\theta_j})$$

- Non linearity due to product of bus angle and binary variable
- Disjunctive linear inequality replacing non linear equality:

$$-M(1 - x_k) \leq f_k - \gamma_k(\theta_i - \theta_j) \leq M(1 - x_k)$$

If $\boldsymbol{x_k} = \mathbf{1}$: $\quad 0 \leq f_k - \gamma_k(\theta_i - \theta_j) \leq 0$

$$f_k = \gamma_k(\theta_i - \theta_j)$$

Disjunctive formulation

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Transmission expansion planning problem

- Second Kirchhoff's law for candidate circuits:

$$f_k = \gamma_k \, \boldsymbol{x_k}(\boldsymbol{\theta_i} - \boldsymbol{\theta_j})$$

- Non linearity due to product of bus angle and binary variable
- Disjunctive linear inequality replacing non linear equality:

$$-M(1 - x_k) \leq f_k - \gamma_k(\theta_i - \theta_j) \leq M(1 - x_k)$$

- Finally, to ensure null power flow in non-constructed circuits, circuit flow limit constraint is modified to:

$$-\boldsymbol{x_k} \, \bar{f}_k \leq f_k \leq \bar{f}_k \, \boldsymbol{x_k}$$

Candidate Circuits

- Given the new corridors, the model calculates candidate parameters based on typical values and other information provided by the user
- Candidate circuits may be penalized by their environmental impact
- Transformer candidate cost per capacity; connection bays

New constraints: environmental impacts

- Environmental impact can be represented as:
  - Environment cost (penalty in the objective function)
  - Restricted candidate list (candidates with high-environmental index are neglected)
  - Environment constraints (used to limit the global impact caused when new transmission lines are built in a particular region / corridor):

$$\sum_{j \in \Gamma_e} w_j \, x_j - \alpha_e \leq \omega_e$$

w_j : environmental factor associated with construction of candidate *j*
w_e : maximum environmental impact
α_e : constraint's violation

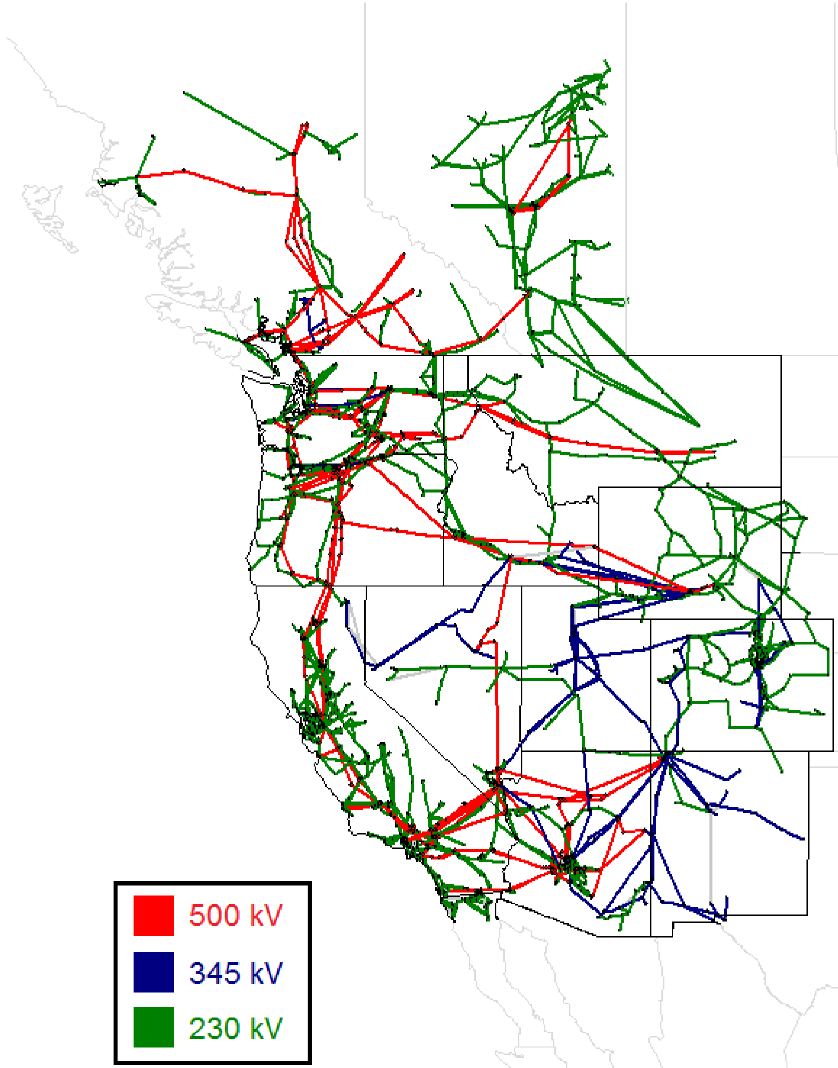
Objective function reformulation

- The objective function takes into account investment costs and penalties associated with violations of operational and environmental constraints (load supply, overloads, additional constraints etc.)

$$Min \sum_{j=1}^{J} c_j x_j + \delta \sum_{i \in \mathbb{Q}}^{I} \alpha_i$$

c_j : **investment cost of candidate *j***
x_j : **investment decision of candidate *j***
δ : **penalty violation**
α_i : **constraint's violation**
$\mathbb{Q}$: **set of penalized constraints**

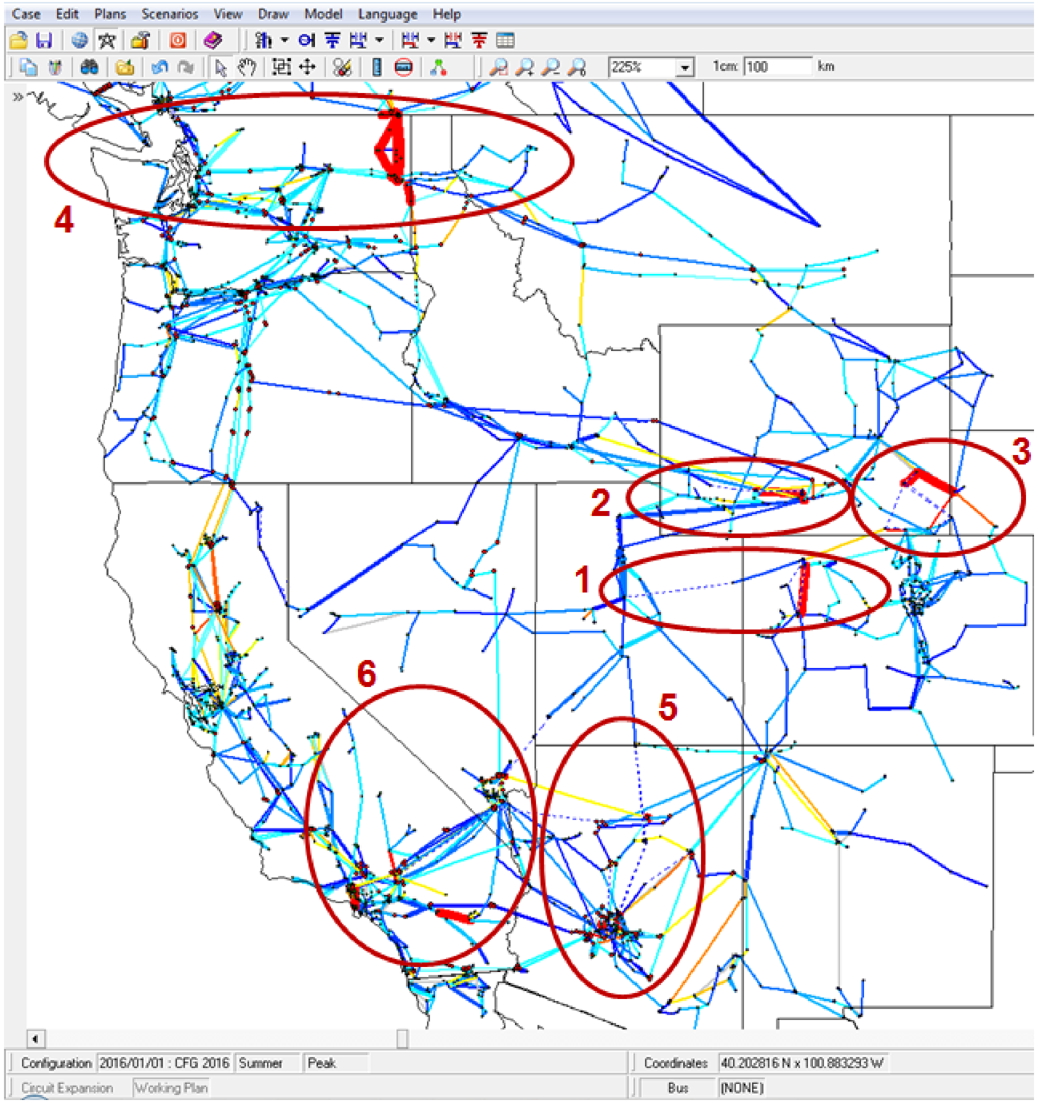
Case Study – US Western System (2016)



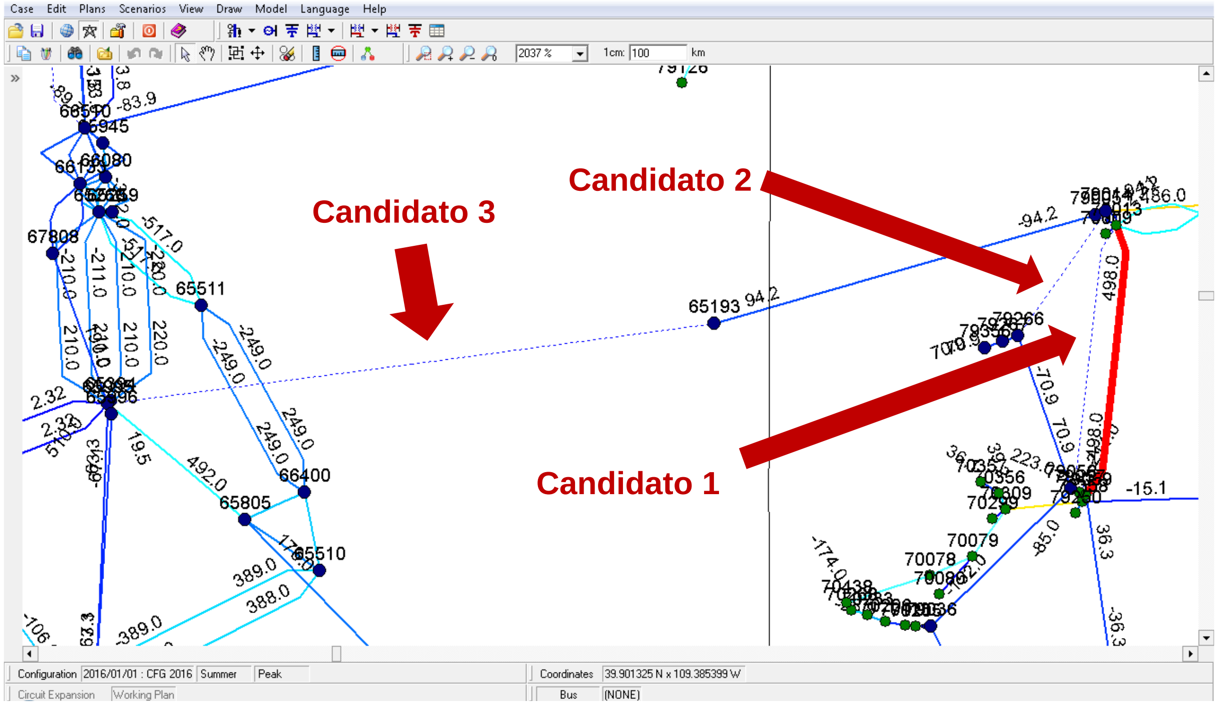
source: WECC (http://www.wecc.biz)

- In the US, Western Interconnection includes:
  - All 14 Western states, Alberta and British Columbia in Canada and Northern Baja California in Mexico
  - More than 20,000 circuits connecting over 15,000 buses
  - Loads are projected to increase 1.2% per year until 2020
  - There are over 33,000 MW of renewable generation capacity to be added until 2020
  - At least 44 transmission projects should be constructed before 2020

Case Study – 66 Overloaded Circuits



Case Study – Region 1



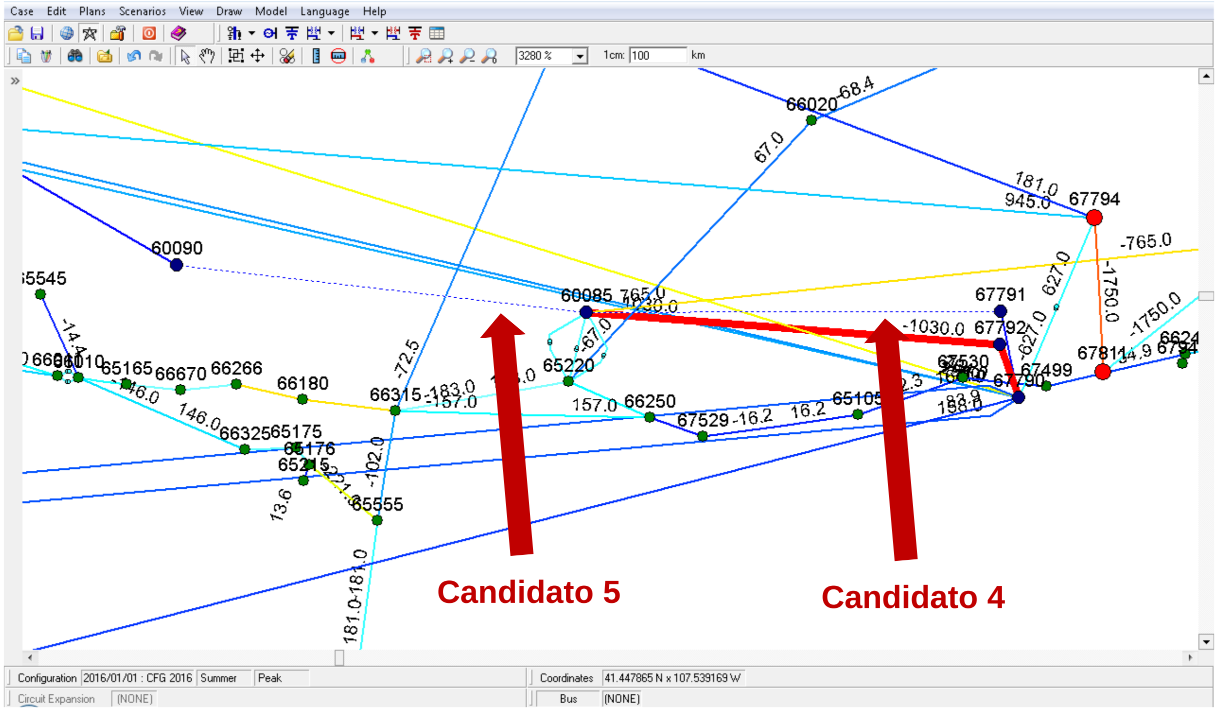
- Highlighted line in red (230 kV, 478 MW, 104 km) has an overload of 5%
- Three candidate circuits were proposed:

  (i) Duplication of the 230 kV overloaded line; investment of $ 39 million

  (ii) Construction of a new 345 kV line; 598 MW; 67 km; investment of $ 19 million

  (iii) Construction of a new 345 kV line; 725 MW; 273 km; investment of $ 78 million

Case Study – Region 2



- Highlighted line in red (345 kV, 985 MW, 298 km) has an overload of 8%
- To solve the overload two candidates were proposed:

  (i) Duplication of the 345 kV overloaded line; investment of $ 87 million

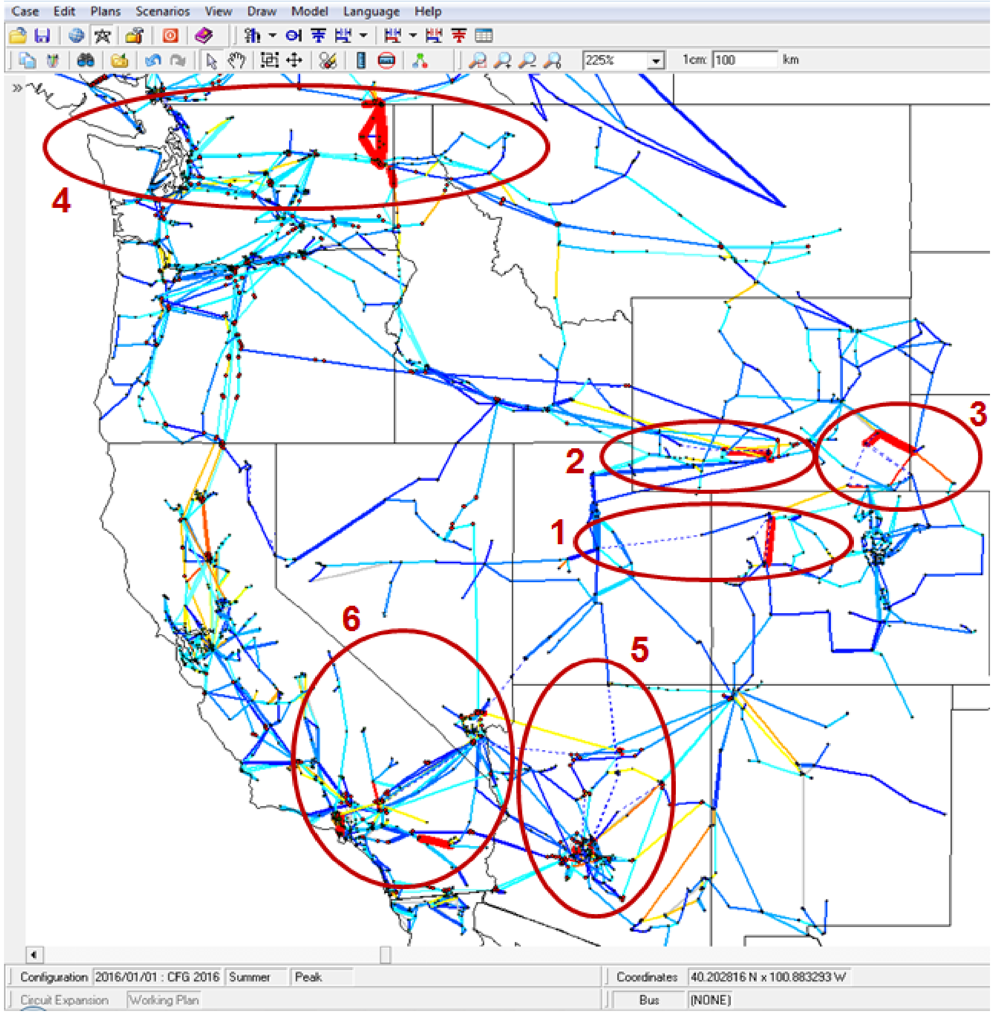
  (ii) Construction of a new 345 kV line; 956 MW; 177 km; investment of $ 76 million

Case Study – US Western System (2016)

- Overloaded circuits: 66
- 143 candidate circuits
- The optimal solution was obtained in approximately 4 minutes (Intel Quad-Core 2.4 GHz, 64-bit, 8 GB of RAM)
- The optimal transmission expansion plan has 8 lines and 11 transformers
- Total investment of $ 417 million

Importance of the Expansion Planning Model

- Overloads cannot be locally analyzed in meshed high voltage networks



Conclusions

- The expansion planning problem with the WECC system is a complex task because it involves:
  - Large transmission system (approx. 15,000 buses and 20,000 circuits)
  - Interactions with a large number of *stakeholders*
  - Creation of new corridors and candidate circuits
  - Environmental aspects must be considered
  - Generation and transmission decisions are coupled by transmission signs (transmission tariffs)

Conclusions

- It was shown that the WECC transmission expansion problem can be effectively solved by optimization models based on Mixed Integer Programming (MIP)

- The experience acquired with the WECC system will be useful for the solution of other studies of transmission expansion

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THANKS!

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