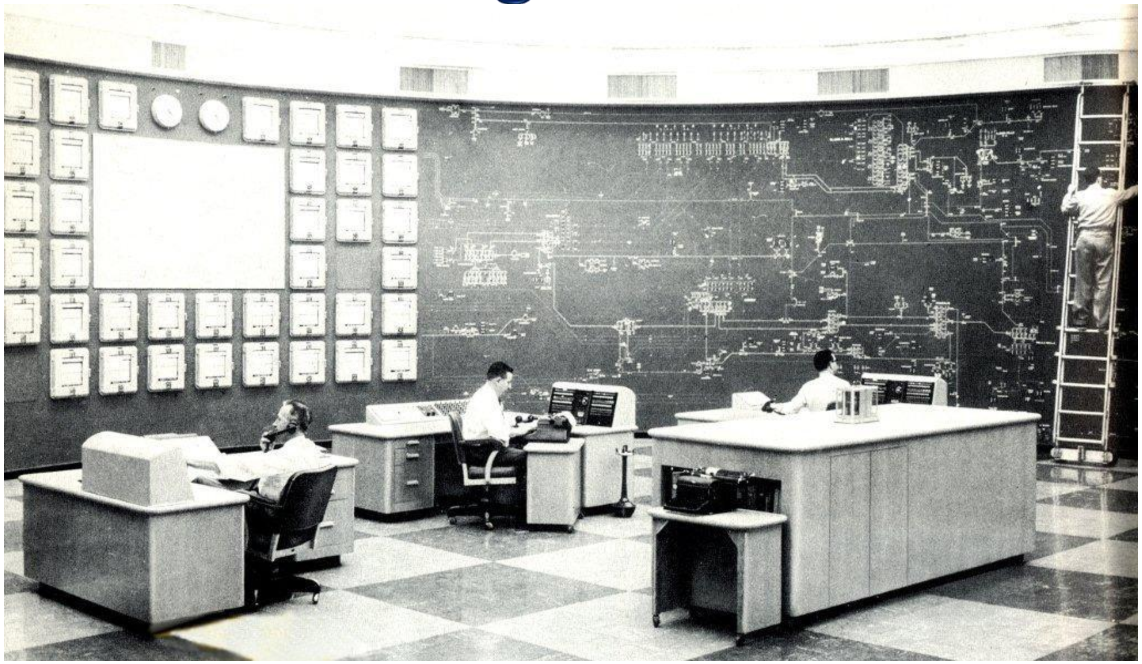
Generation + Transmission Investment: Decision Making under Uncertainty



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Outline

1. Introduction
2. Generic model: generation plus transmission expansion planning: (G+T)EP
3. TEP – Centralized framework
4. TEP – Market framework
5. GEP – Centralized framework
6. GIP – Market framework
7. RGI
8. Equilibria
9. Challenges

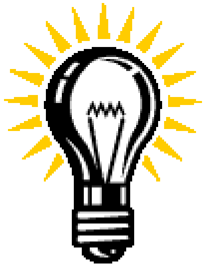
General framework
(G+T)EP

Generic model: (G+T)EP (decision-making)

- ✓ Model to generate best alternative G+T plans (stochastic MILP, stochastic MPEC)
- ✓ Plans: security checking
- ✓ Plans: stability checking
- ✓ Plans: updating
- ✓ Papers: REE

Model
(key ingredients)

- ✓ Uncertainty: stochastic modeling
- ✓ Market: complementarity modeling



Model (features)

- ✓ Static vs. dynamic (multi-stage) modeling
- ✓ Pseudo-dynamic: chronological modeling
- ✓ Uncertainty!
- ✓ Scenario modeling
  - ✓ Load
  - ✓ Fuel cost
  - ✓ Renewable sources
  - ✓ Rival behavior

Model: static (features)

- ✓ Perfect foresight (in target year)
- ✓ How many alternatives?
- ✓ Imperfect foresight (in target year)
- ✓ Many alternatives!

Perfect foresight (data & results)

- ✓ Data (for target year)
  - ✓ Demand (D)
  - ✓ Conventional generation units (CGU)
  - ✓ Renewable generation units (RGU)
  - ✓ Rival data
- ✓ Expansion alternatives
  - ✓ Candidate CGUs
  - ✓ Candidate RGUs
  - ✓ Candidate transmission lines (TL)

Perfect foresight (data and results)

- ✓ Results
  - ✓ Which RGUs to build
  - ✓ Which CGUs to build
  - ✓ Which TLs to build

Perfect foresight (expansion tool)

Perfect foresight

- D data
- RGU data
- CGU data
- Rival data

!!!: combinatorial explosion!

- TL alternatives !!!
- RGU alternatives !!!
- CGU data !!!

Expansion Tool

- TL to build
- RGU to build
- CGU to build

Perfect foresight (optimization algorithm)

Build alternative investment plans (IP)

Has to be done cleverly!

Evaluate alternative investment plans

Perfect foresight (how many IPs?)

Elements	Plans
2	4
3	8
4	16
***	***
10	1024
20	1,048,576
50	1.1259e+015

Perfect foresight (how many IPs?)

n elements

2^n altenatives

$$2^n = \sum_{i=0}^{n} \binom{n}{i} \text{ alternatives}$$

Perfect foresight (How many IPs?)

A	B	C
0	0	0
1	0	0
0	1	0
0	0	1
1	1	0
1	0	1
0	1	1
1	1	1

Imperfect foresight (scenarios)

Scenario	Profit/Cost	Probability
1	C_1	π_1
…	…	…
m	C_m	π_m

$$\sum_{i=1}^{m} \pi_i = 1$$

$$C = \sum_{i=1}^{m} \pi_i C_i$$

Imperfect foresight (expansion tool)

Imperfect foresight

- D data !!!
- RGU data !!!
- Rival data !!!
- CGU data !!!

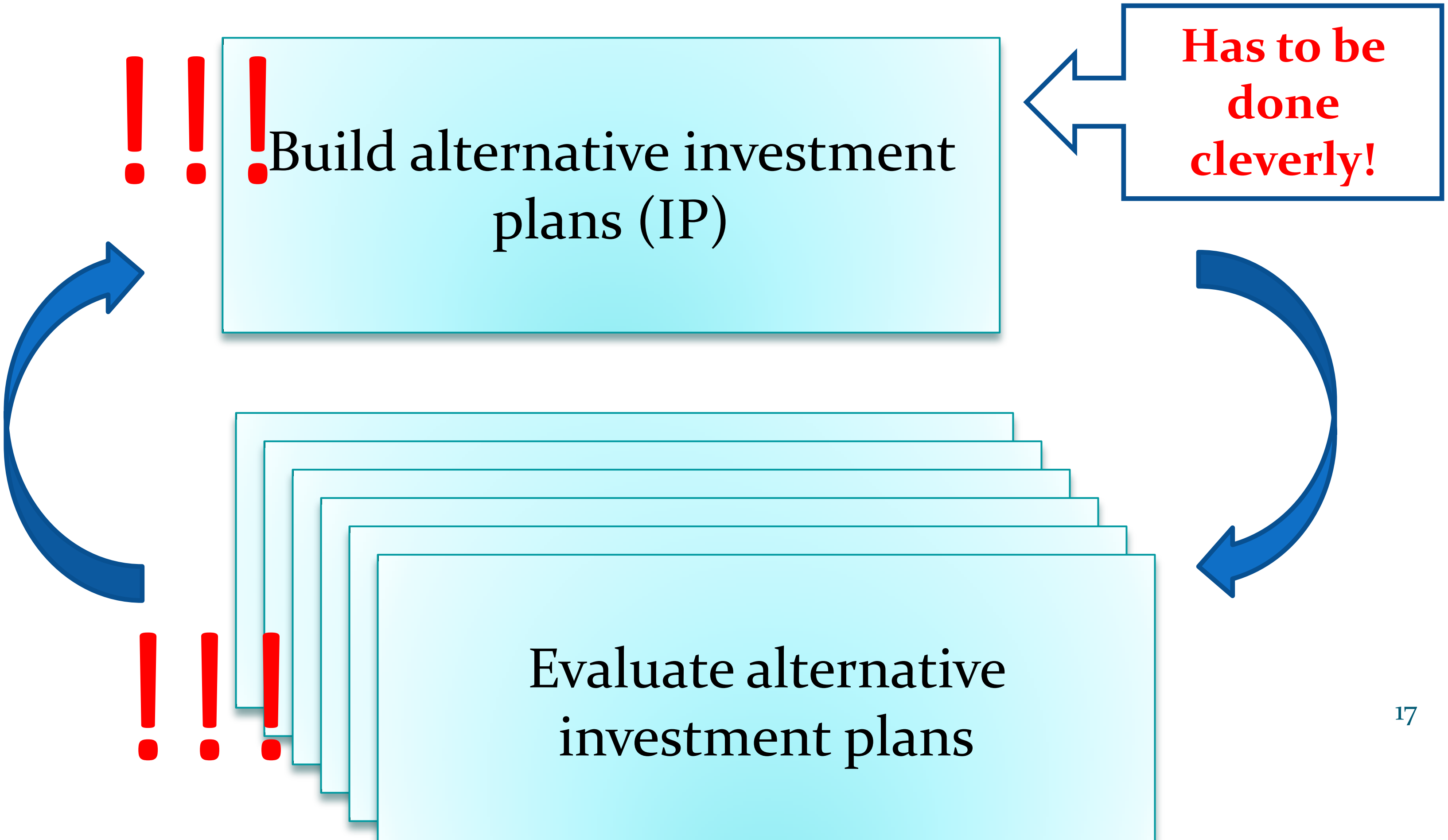
!!!: combinatorial explosion!

- TL alternatives !!!
- RGU alternatives !!! !!!
- CGU alternatives !!!

Expansion Tool

- TL to build
- RGU to build
- CGU to build

Imperfect foresight (optimization algorithm)



Chronological model (pseudo-dynamic approach)

- ✓ Target year solution known
- ✓ Investment alternatives restricted to the "target" year solution
- ✓ Solve again "year by year"
- ✓ Solve again dynamically

References

✓ F. Soto, R. de Dios, A. J. Conejo, "Planning to Expand? Looking at mainland Spain to see the importance of well-planned transmission expansion". **IEEE Power and Energy Magazine**. Vol. 5, No. 5, pp. 64-70. September-October 2007.

TEP: centralized framework

TEP (centralized framework)

- ✓ Perfect foresight
- ✓ Imperfect foresight (scenarios)
- ✓ MILP formulation
- ✓ Solution: branch-and-cut (B&C) vs. decomposition
- ✓ Heuristics? No, thanks!
- ✓ Some papers: de la Torre

TEP (challenges)

- ✓ Large scale problem
- ✓ Mixed-integer problem
- ✓ Nonlinear problem
- ✓ Multiple objectives
- ✓ Uncertainty
- ✓ Data availability?
- ✓ Hard to solve!

TEP
(who is interested?)

- ✓ SO: System Operator
  - ✓ Get optimal plans
  - ✓ Plans: security checking
  - ✓ Plans: stability checking
  - ✓ Plans: updating

References

- ✓ N. Alguacil, A. L. Motto, A. J. Conejo, “Transmission Expansion Planning: A Mixed-Integer LP Approach”. **IEEE Transactions on Power Systems**. Vol. 18, No. 3, pp. 1070-1077. August 2003.
- ✓ S. de la Torre, A. J. Conejo, J. Contreras, “Transmission Expansion Planning in Electricity Markets”. **IEEE Transactions on Power Systems**. Vol. 23, No. 1, pp. 238-248. February 2008.

Optimization Problems constrained by other Optimization Problems (OPcOP)

OPcOP

Optimization Problem constrained by other Optimization Problems (OPcOP)

Objective function (minimize or maximize)

subject to:

- Constraints
- Constraining optimization problem 1
- ⋮
- Constraining optimization problem n

OPcOP

$$\text{Minimize}_{\{x\}\cup\{x^1,\dots,x^n\}\cup\{\lambda^1,\dots,\lambda^n,\mu^1,\dots,\mu^n\}}$$
$$f(x, x^1, \dots, x^n, \lambda^1, \dots, \lambda^n, \mu^1, \dots, \mu^n)$$

subject to:

$$h(x, x^1, \dots, x^n, \lambda^1, \dots, \lambda^n, \mu^1, \dots, \mu^n) = 0$$
$$g(x, x^1, \dots, x^n, \lambda^1, \dots, \lambda^n, \mu^1, \dots, \mu^n) \leq 0,$$

$$\begin{cases} \text{Minimize}_{x^1} \quad f^1(x, x^1, \dots, x^n) \\ \text{subject to:} \\ \quad h^1(x, x^1, \dots, x^n) = 0 \quad (\lambda^1) \\ \quad g^1(x, x^1, \dots, x^n) \leq 0 \quad (\mu^1), \end{cases}$$

$$\vdots$$

$$\begin{cases} \text{Minimize}_{x^i} \quad f^i(x, x^1, \dots, x^n) \\ \text{subject to:} \\ \quad h^i(x, x^1, \dots, x^n) = 0 \quad (\lambda^i) \\ \quad g^i(x, x^1, \dots, x^n) \leq 0 \quad (\mu^i), \end{cases}$$

$$\vdots$$

$$\begin{cases} \text{Minimize}_{x^n} \quad f^n(x, x^1, \dots, x^n) \\ \text{subject to:} \\ \quad h^n(x, x^1, \dots, x^n) = 0 \quad (\lambda^n) \\ \quad g^n(x, x^1, \dots, x^n) \leq 0 \quad (\mu^n). \end{cases}$$

MPEC

Mathematical Program with Equilibrium Constraints (MPEC)

Objective function (minimize or maximize)

Constraints

subject to:

KKT conditions of constraining problem 1

⋮

KKT conditions of constraining problem n

MPEC

$$\text{Minimize}_{\{x\}\cup\{x^1,\ldots,x^n\}\cup\{\lambda^1,\ldots,\lambda^n,\mu^1,\ldots,\mu^n\}}$$

$$f(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n)$$

subject to:

$$h(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n) = 0$$

$$g(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n) \leq 0,$$

$$\nabla_{x^i} f^i(x, x^1, \ldots, x^n) + {\lambda^i}^T \nabla_{x^i} h^i(x, x^1, \ldots, x^n) +$$

$$\quad {\mu^i}^T \nabla_{x^i} g^i(x, x^1, \ldots, x^n) = 0, \quad i = 1, \ldots, n$$

$$h^i(x, x^1, \ldots, x^n) = 0, \quad i = 1, \ldots, n$$

$$0 \leq \mu^i \perp -g^i(x, x^1, \ldots, x^n) \geq 0, \quad i = 1, \ldots, n.$$

TEP: market framework

TEP (who is interested?)

- ✓ TSO: Transmission System Operator (EU)
- ✓ RTO: Regional Transmission Operator (US)
- ✓ Transmission investors
  - ✓ Get optimal plans
  - ✓ Plans: security checking
  - ✓ Plans: stability checking
  - ✓ Plans: updating

TEP (market framework)

- Á la EU: TSO in charge and controlling (Transmission System Operator paradigm)
- Which objective function?
- Uncertainty: scenarios
- Single vs. multiple decision points
- Bilevel → Stochastic MPEC → MILP
- Solution: B&C vs. decomposition
- Some papers: Garcés

What?

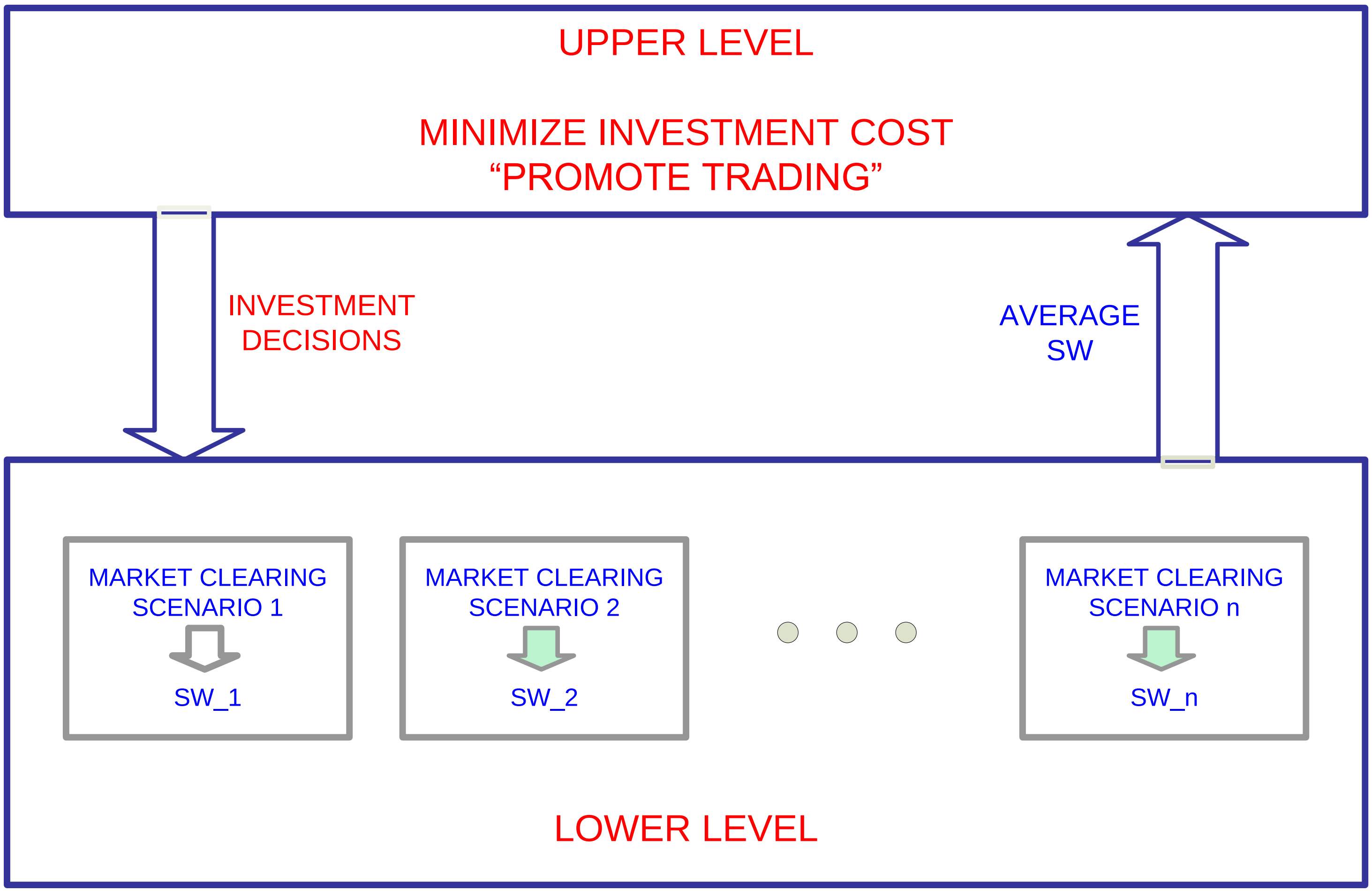
Transmission Expansion Planning (TEP) within a market environment:

- Pool based market
- Transmission: regulated monopoly
- Transmission System Operator (TSO) paradigm
- Minimum investment cost, minimum unserved energy and Maximum average social welfare (SW)

Outline

- Model paradigm
- Model structure
- MILP
- Example
- Final remarks

Model paradigm



Market scenarios

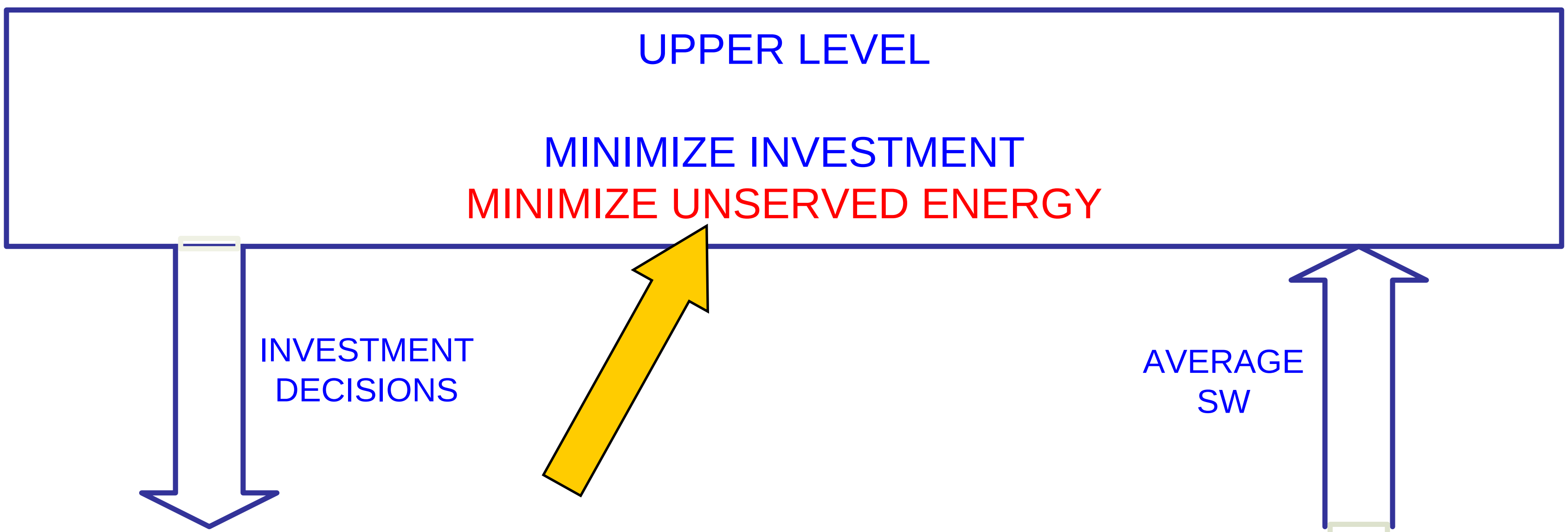
- Different load growth levels
- Load growth at different locations
- Line contingencies

Market scenarios

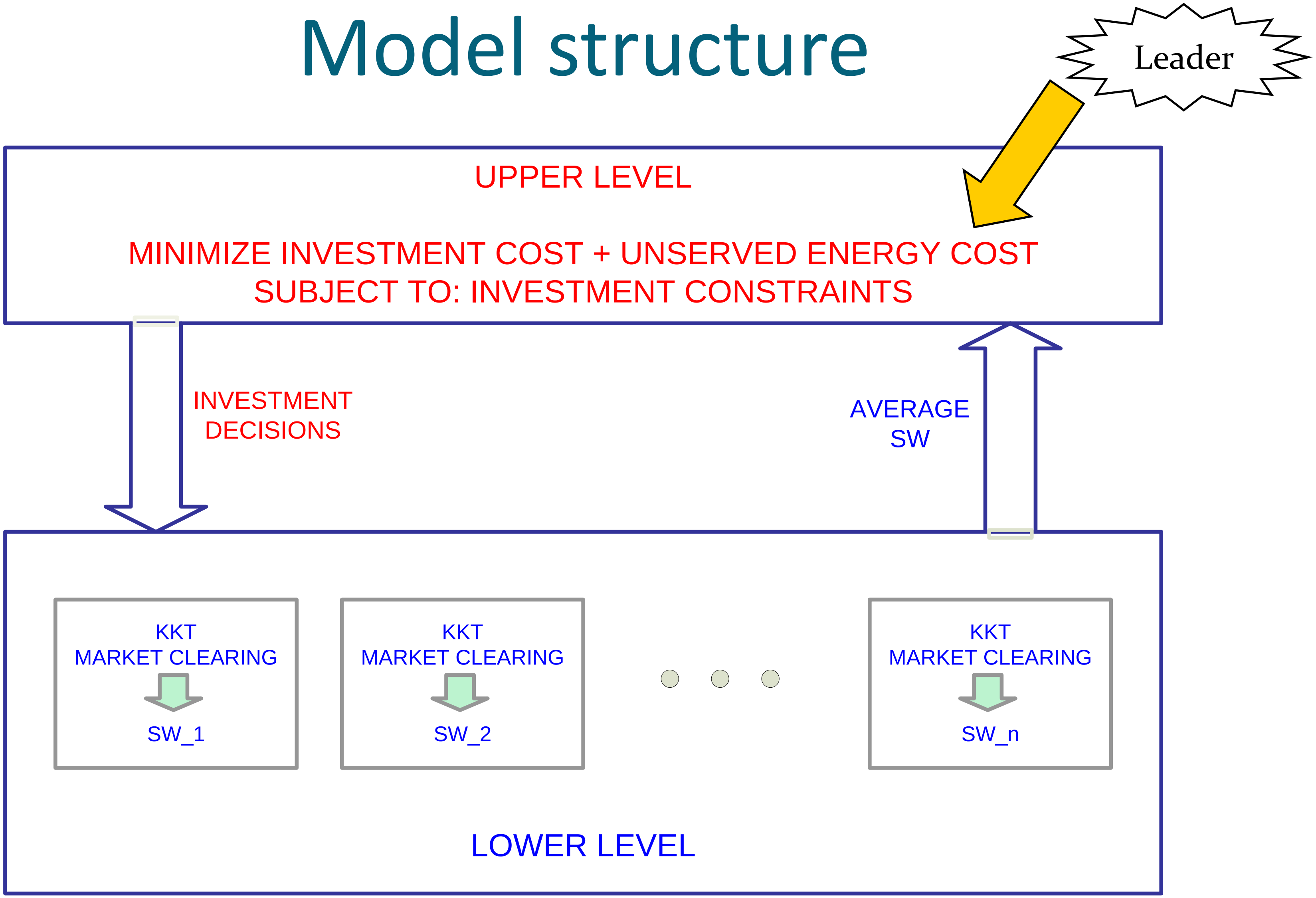
Scenarios!

!!!

Proxy for “promoting trade”



Model structure



Model structure (bi-level)

Minimize Investment cost + Unserved energy cost

subject to:

Investment constraints

- ✓ Maximize social welfare for scenario 1

  • • •

- ✓ Maximize social welfare for scenario n

Model structure

Decision variables (bilevel model):

- Investment decisions

  (upper level)

- Productions and consumptions per scenario

  (lower level)

Model structure

Bilevel model coupling:

- Social welfare per scenario

Single-level

1

2

- ✓ KKT market clearing scenario 1
- ✓ …
- ✓ KKT market clearing scenario n

⟷

- ✓ Primal constraints (PC), dual constraints (DC), strong duality equality(SDE): scenario 1
- ✓ …
- ✓ Primal constraints, dual constraints, strong duality: scenario n

Better

Model structure (MPEC)

Minimize Investment cost + Unserved energy cost

subject to:

- ✓ Investment constraints
- ✓ PC+DC+SDE market clearing scenario 1

…

- ✓ PC+DC+SDE market clearing scenario n

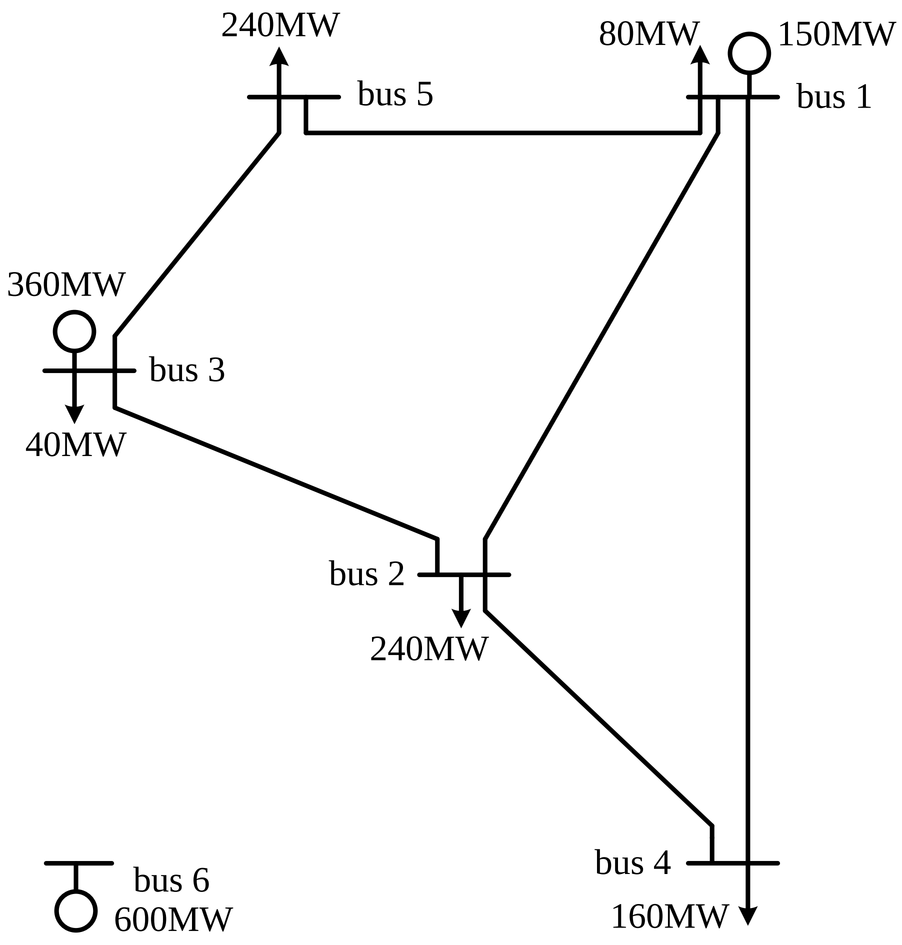
Linearization

Mixed-Integer NONLINEAR mathematical programming problem

Mixed-Integer LINEAR mathematical programming problem:

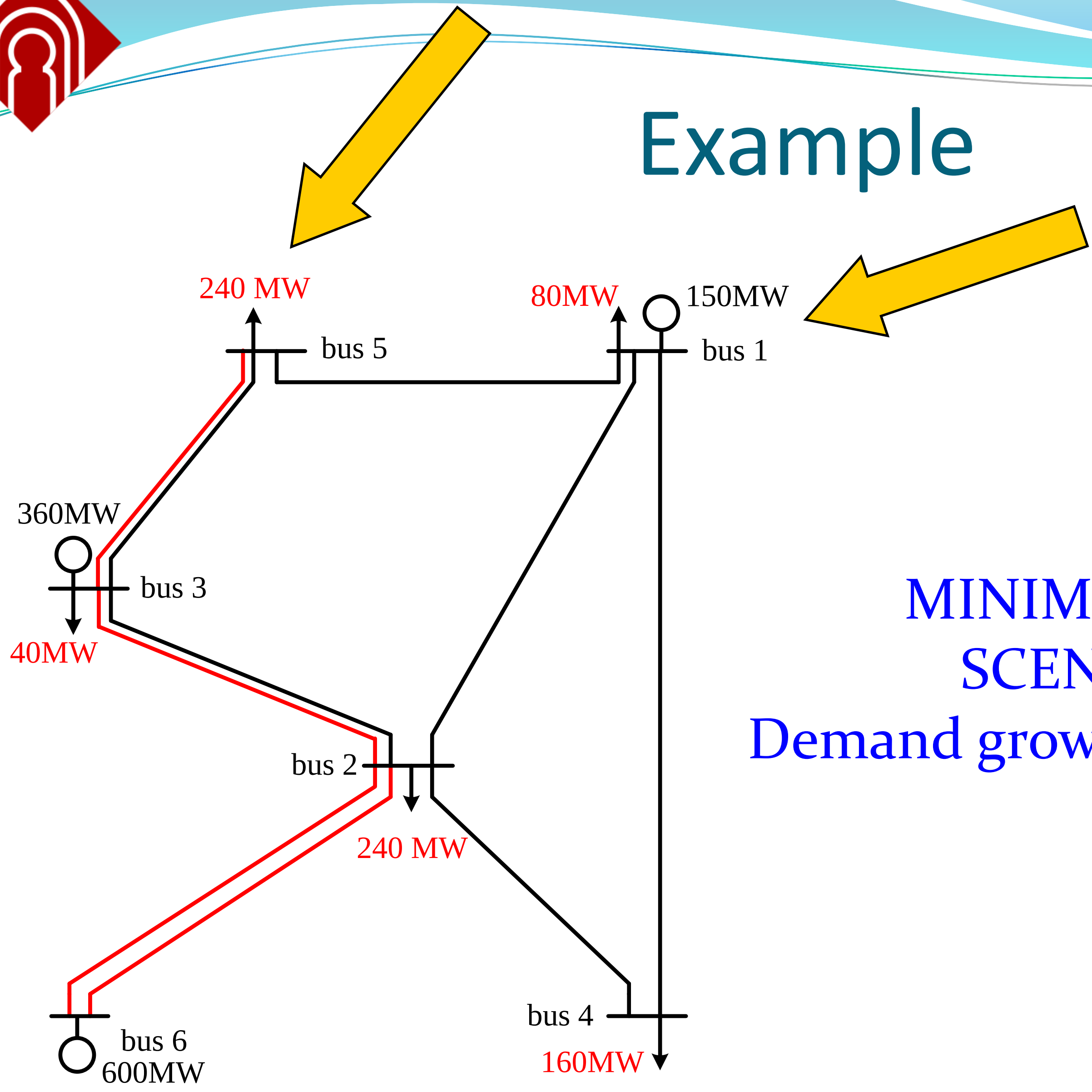
- Tractable
- Sufficiently well-conditioned

Example



Classical GARVER Network

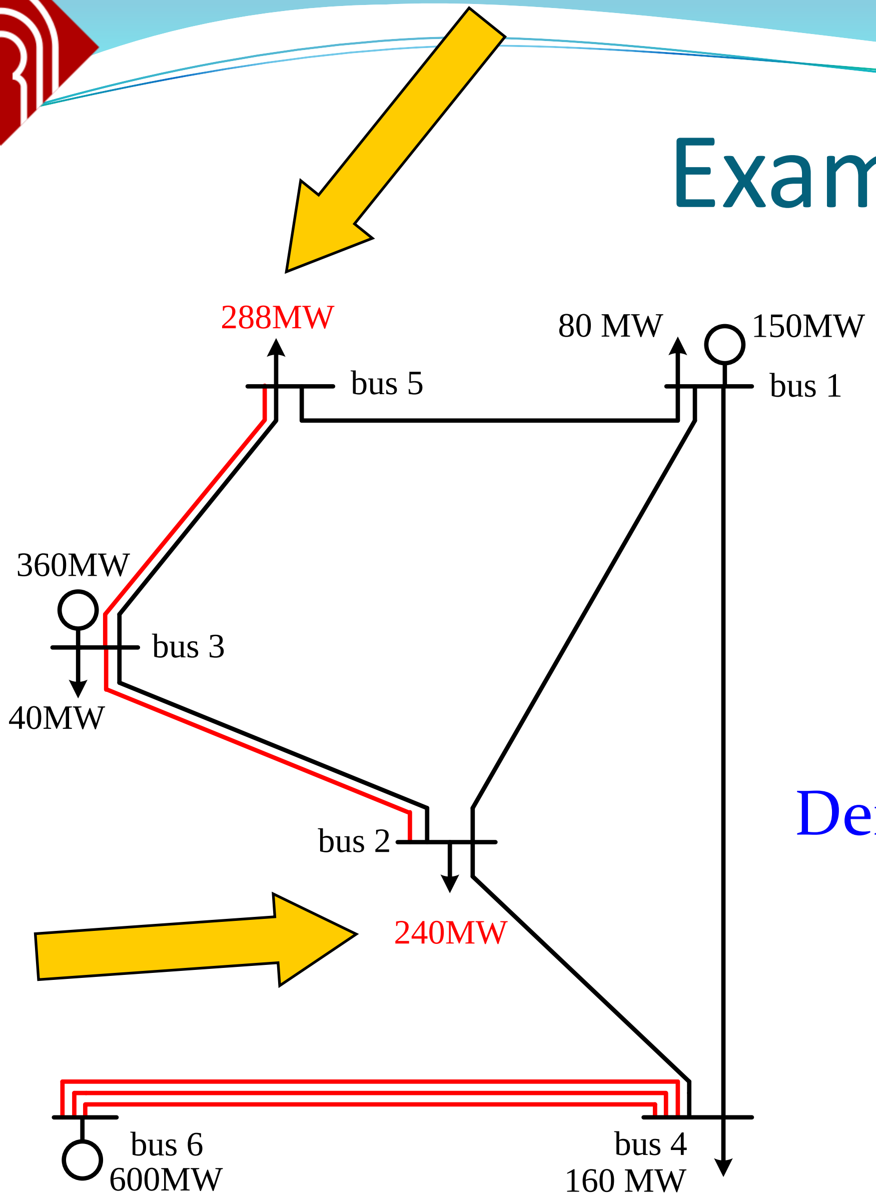
Example



MINIMUM COST SCENARIO 1:

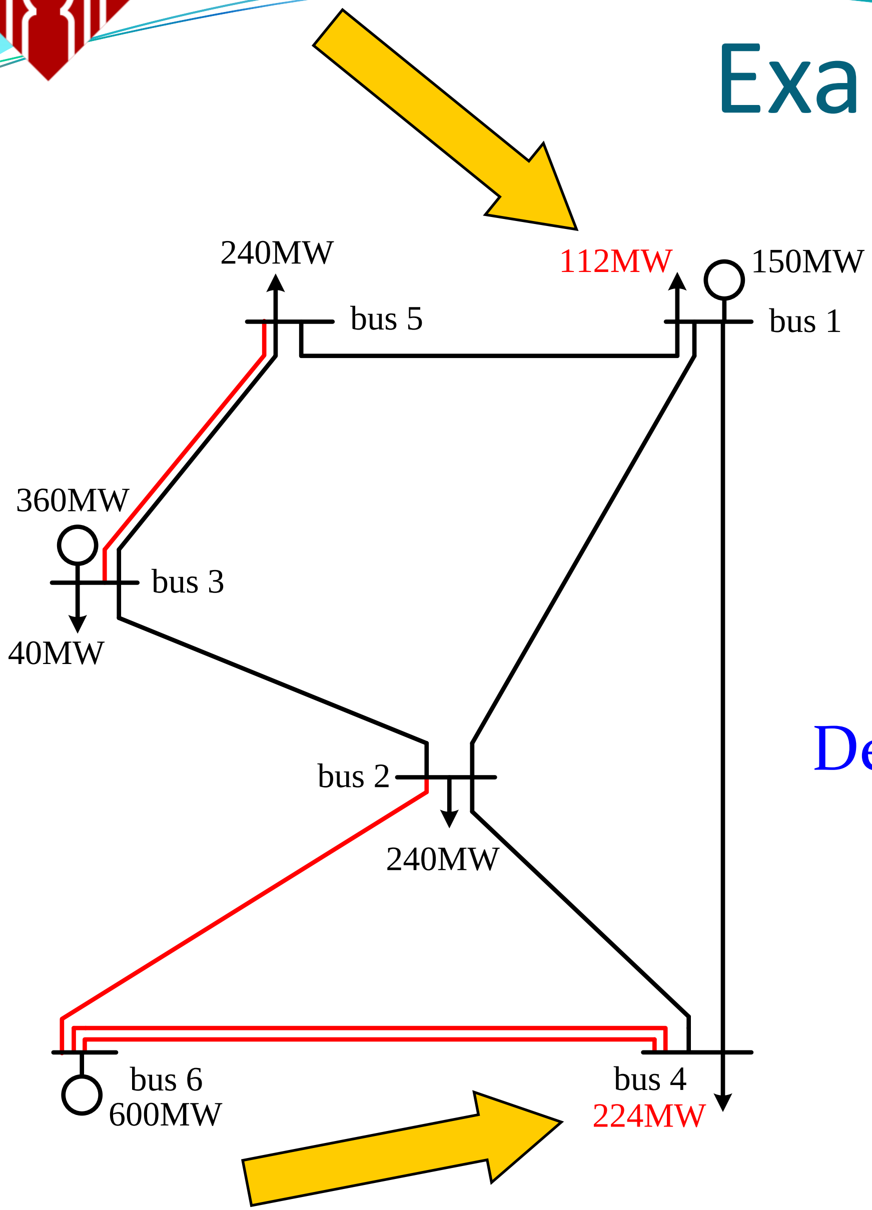
Demand growth at buses 1 to 5

Example



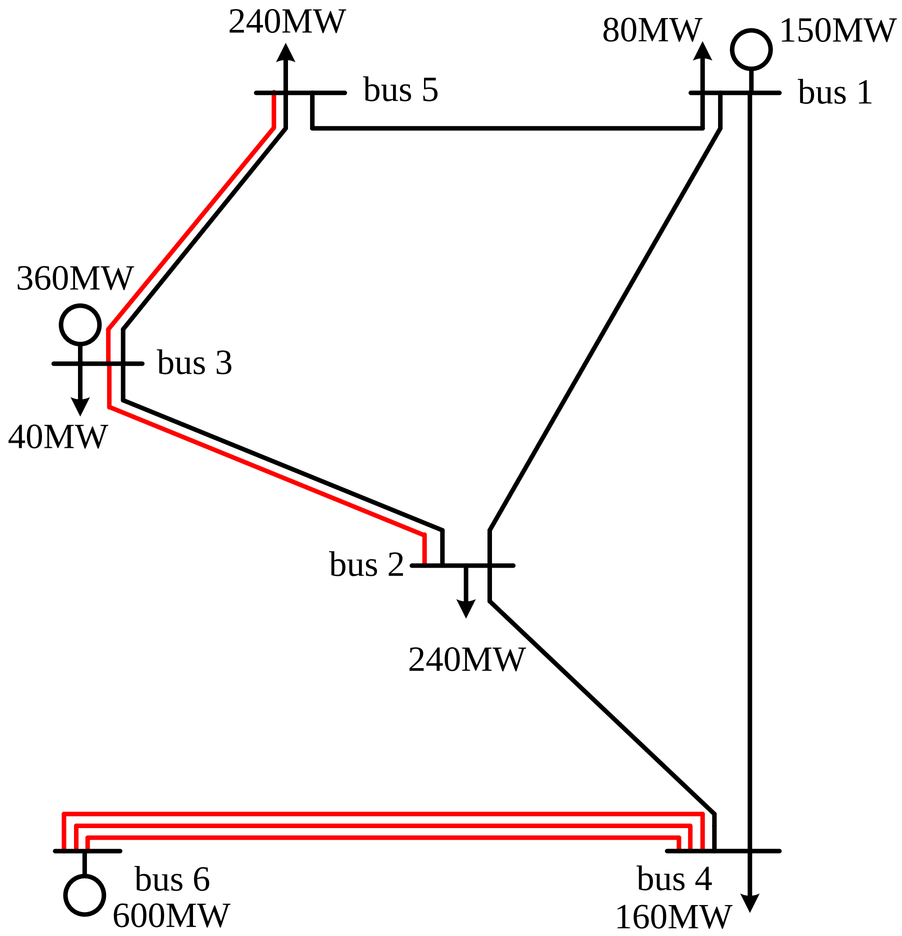
MINIMUM COST
SCENARIO 2
Demand growth mostly at buses 2 & 5

Example



MINIMUM COST
SCENARIO 3
Demand growth mostly at buses 1 & 4

Example



BILEVEL MODEL:
MAXIMUM
AVERAGE (3 scenarios)
SOCIAL WELFARE

Example

Approach	Investment Plan	Total investment cost (M€)	Social welfare (M€)	Average social welfare (M€)
Bilevel	3-5 , 2-3 4-6 (3)	25.10	--	292.71
Cost Min. Scenario 1	3-5 , 2-3 2-6 (2)	19.31	275.60	- 2,613.02
Cost Min. Scenario 2	3-5 , 2-3 4-6 (3)	25.10	291.50	292.71
Cost Min. Scenario 3	3-5 , 2-6 4-6 (2)	21.24	286.62	- 423.57

Example

Line contingencies:

- One contingency at a time in one scenario
- Low probability scenario

Example

Contingency	Investment plan	Total investment cost (M€)	Average social welfare (M€)
1 – 2	2-3 , 3-5, 4-6 (3)	25.10	292.71
1 – 5	1-5 , 2-3 , 3-5 4-6 (3)	28.96	292.72
2 – 4	2-3 , 3-5 4-6 (3)	25.10	292.71
3 – 5	2-3 3-5 (2) 4-6 (3)	28.96	292.70

References

✓ L. Garcés, A. J. Conejo, R. García-Bertrand, R. Romero, "A Bi-level Approach to Transmission Expansion Planning within a Market Environment". **IEEE Transactions on Power Systems**. Vol. 24, No. 3, pp. 1513-1522, August 2009.

GEP: centralized framework

GEP (centralized framework)

- ✓ Anyone interested (besides EdF)?
- ✓ Worst scenario analysis
- ✓ Multi-scenario analysis
- ✓ MILP formulation
- ✓ Solution: B&C vs. decomposition
- ✓ Some papers: Smeers & Murphy

References

✓ F. H. Murphy, and Y. Smeers, "Generation capacity expansion in imperfectly competitive restructured electricity markets," ***Operations Research***, vol. 53, no. 4, pp. 646-661, 2005.

GIP: market framework

GI
(who is interested?)

- ✓ Oligopolistic generation investors
- ✓ Generation investors
- ✓ Regulators

GI
(market framework)

- ✓ Competitive agent
- ✓ Oligopolistic agent
- ✓ Renewable producer
- ✓ Uncertainty: multi-scenario!
- ✓ Bilevel → Stochastic MPEC → MILP
- ✓ Solution: B&C vs. decomposition
- ✓ Papers: Kazempour

Background and Aim

Strategic power producer

- Comparatively large number of generating units
- Units distributed throughout the power network

Background and Aim

Pool-based electricity market

- Cleared once a day, one day ahead and on a hourly basis
- DC representation of the network including first and second Kirchhoff laws
- Hourly Locational Marginal Prices (LMPs)

Background and Aim

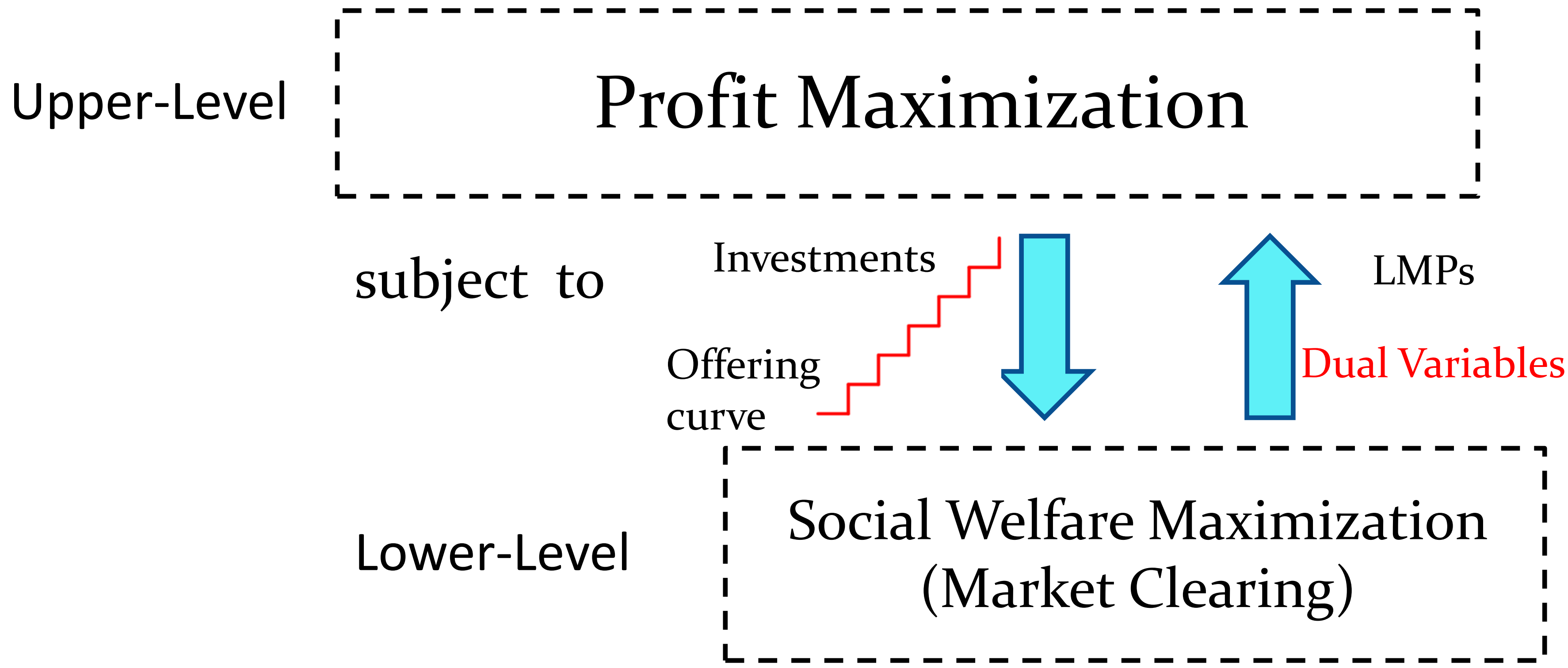
Strategic power producer

Best investment options and
Best offering strategy to
maximize profit

Pool-based electricity market

Approach

Bilevel model:



Approach

MPEC:

Upper-Level

Profit Maximization

subject to

Investments

Offering curve

LMPs

KKT Conditions

Features

1) Strategic investment and offering for a producer in a pool with endogenous formation of LMPs.
2) Uncertainty of demand bids, rival production offers and rival investments.
3) MPEC approach under multi-period, network-constrained pool clearing.
4) MPEC transformed into an equivalent MILP.

Deterministic Model

Upper-Level → Profit Maximization:

Minimize

Costs - Revenues

subject to:

Investment options

Price = Balance dual variable

Deterministic Model

Lower-Level → Market Clearing

Powers and prices ∈

Maximize Social Welfare

subject to:

Power Balance

Deterministic Model

Lower-Level → Market Clearing

subject to:

Production / Demand Power Limits

Transmission Capacity Limits

Angle Limits

Deterministic Model

Linearizations

The MPEC includes the following non-linearities:

1) The complementarity conditions ($0 \leq a \perp b \geq 0$).

2) The term $\lambda_{tn} P_{tib}^{S}$ in the objective function.

Deterministic Model

Linearizations → Complementarity Conditions

Fortuny-Amat transformation

$$0 \le a \perp b \ge 0$$

$$\Downarrow$$

$$a \ge 0$$

$$b \ge 0$$

$$a \le uM$$

$$b \le (1-u)M$$

$$u \in \{0,1\}$$

M Large enough constant (but not too large)

Deterministic Model

Linearizations → $\lambda_{tn} P^S_{tib}$

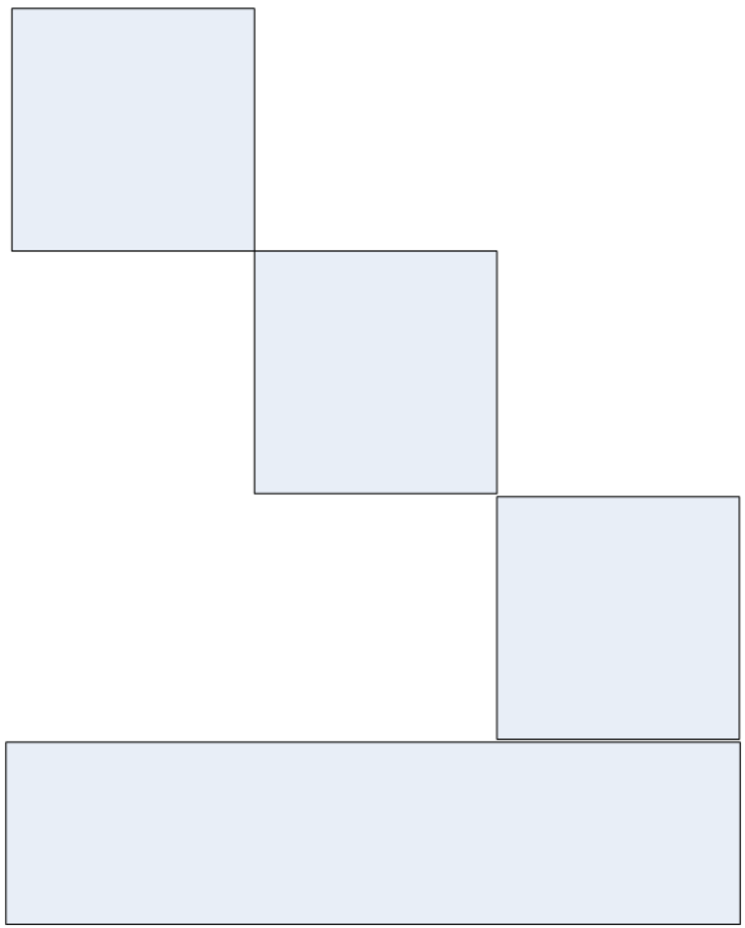
- Problem-dependent procedures

Stochastic Model

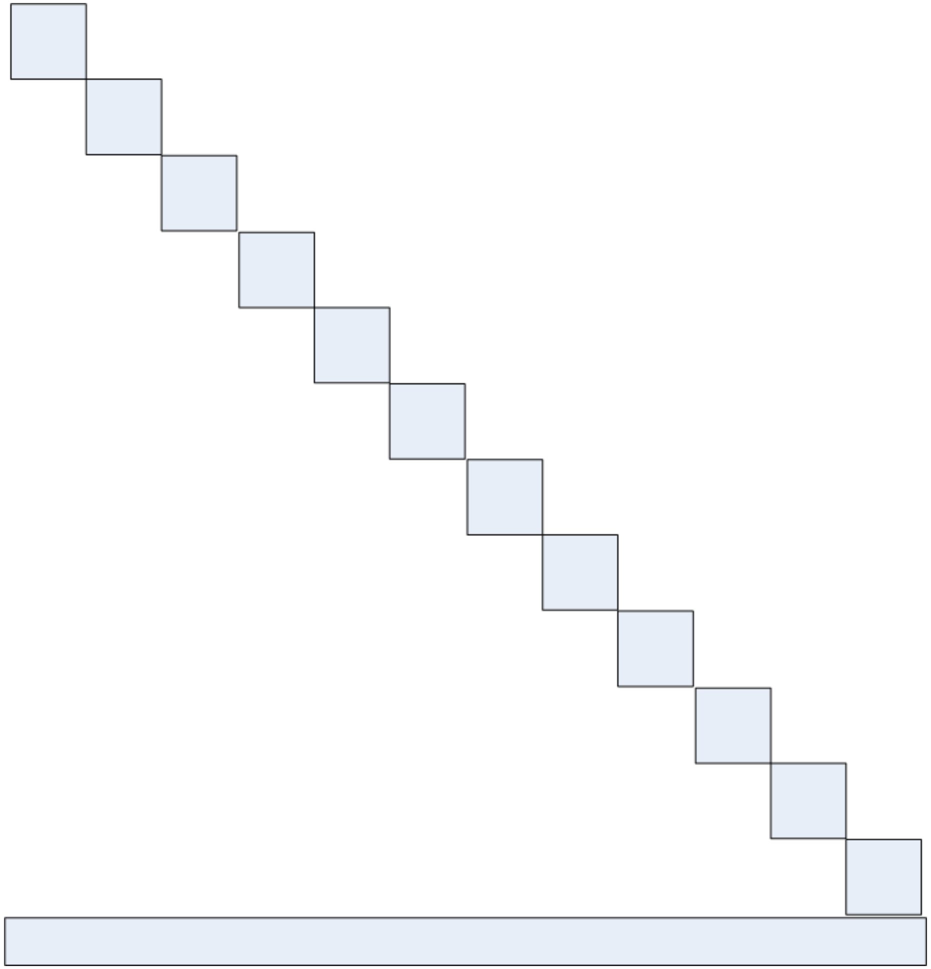
Uncertainty incorporated by using a set of scenarios modeling different realizations of:

- Consumers' bids
- Rival producers' offers
- Future demands
- Rival investments

Stochastic Model. Math Structure
(B&C vs. decomposition)



Stochastic Model. Math Structure
(B&C vs. decomposition)

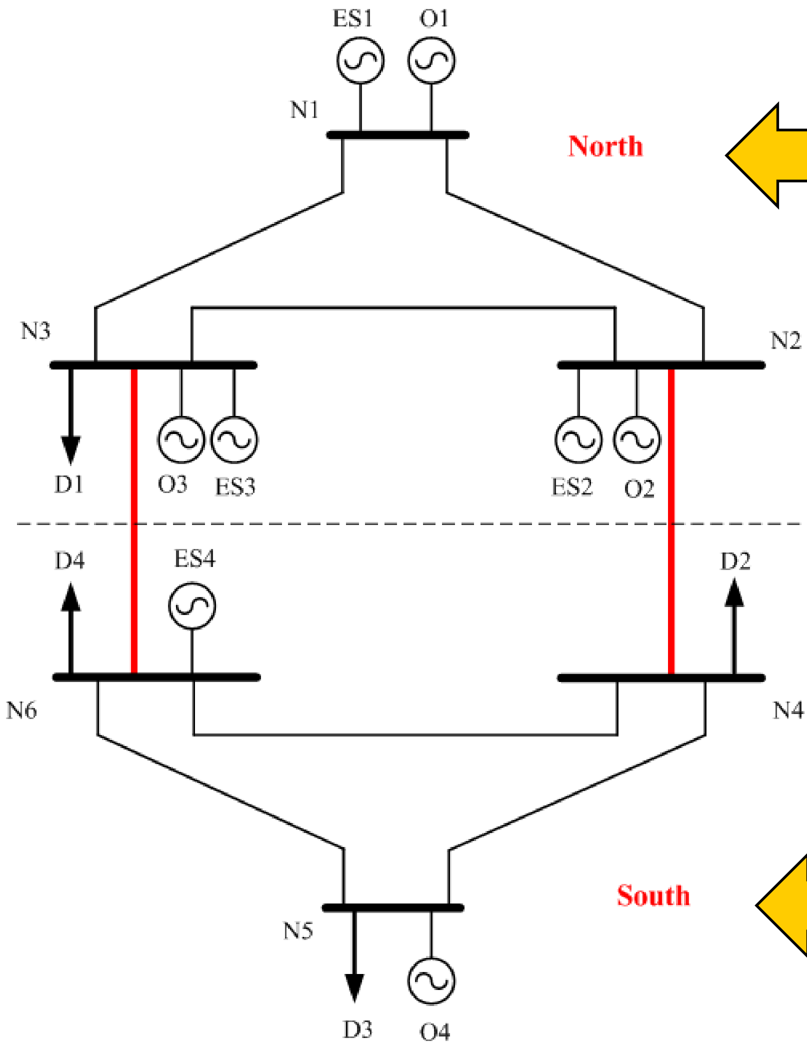


Stochastic Model. Math Structure

1. Direct solution: CPLEX, XPRESS

2. Decomposition procedures (Lagrangian Relaxation)

Example



Generation prevails

North-south interconnected tie-lines

Demand prevails

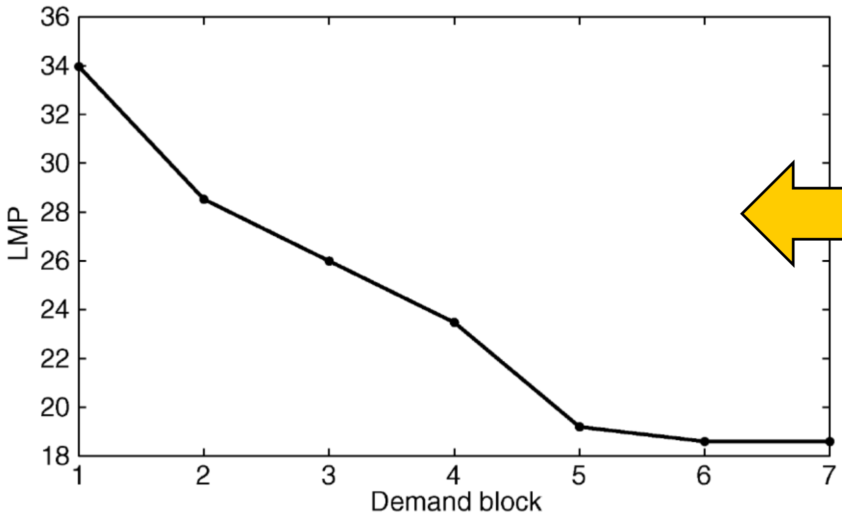
Investment options

option	Base technology	Peak technology
Investment Cost (€/MW)	75000	15000
Capacity (MW)	0, 500, 750, 1000	0, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000
Cost: block 1 (€/MWh)	6.01	6.31
Cost: block 2 (€/MWh)	14.72	15.20

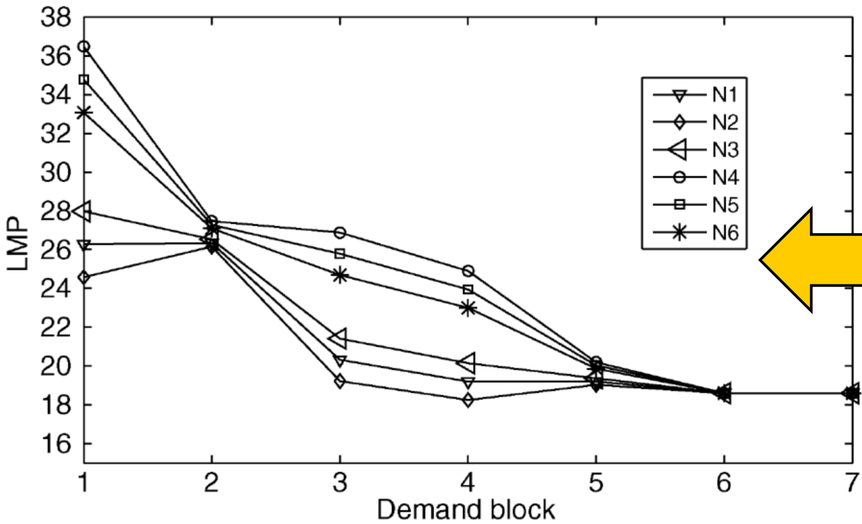
Investment results

Capacity of tie-lines	Uncongested	450 MW	150 MW
Base technology (MW)	500 (north)	500 (south)	500 (south)
Peak technology (MW)	200 (south)	200 (south)	600 (south)
Total investment (MW)	700	700	1100
Investment profit (M€)	45.55	45.55	47.64

LMPs



Cases: uncongested and 450 MW



Congested case (150 MW)

LMPs in the south area are higher!

Stochastic case

Uncertainties:

- Rival investment
- Rival offering

Number of scenarios	One	4	12
Base technology (MW)	500 (south)	-	500 (north)
Peak technology (MW)	200 (south)	350 (north) 350 (south)	200 (south)
Total investment (MW)	700	700	700
Investment profit (M€)	45.55	32.25	31.38

IEEE one-area RTS

Number of scenarios	One	4	12 (reduced version)
Base technology (MW)	-	-	-
Peak technology (MW)	750 (bus 15)	550 (bus 11)	450 (bus 23)
Total investment (MW)	750	550	450
Investment profit (M€)	82.97	65.66	61.95
Optimality gap (%)	0.10	1.00	1.75
CPU time	12.14 (s)	3.95 (hours)	3.76 (hours)

The resulting model, although computationally expensive, is tractable!

Conclusions

- Procedure to derive investments and strategic offers for a power producer in a network constrained pool market.
  - LMPs are endogenously generated.
  - Uncertainty is taken into account.
  - Resulting MILP problem.
- Strategic behavior results in higher profit and lower production.
- Network congestion can be used to further increase profit.

References

- ✓ S. J. Kazempour, A. J. Conejo, C. Ruiz, "Strategic Generation Investment using a Complementarity Approach". **IEEE Transactions on Power Systems**. In press, 2010.

Renewable Generation Investment (RGI)

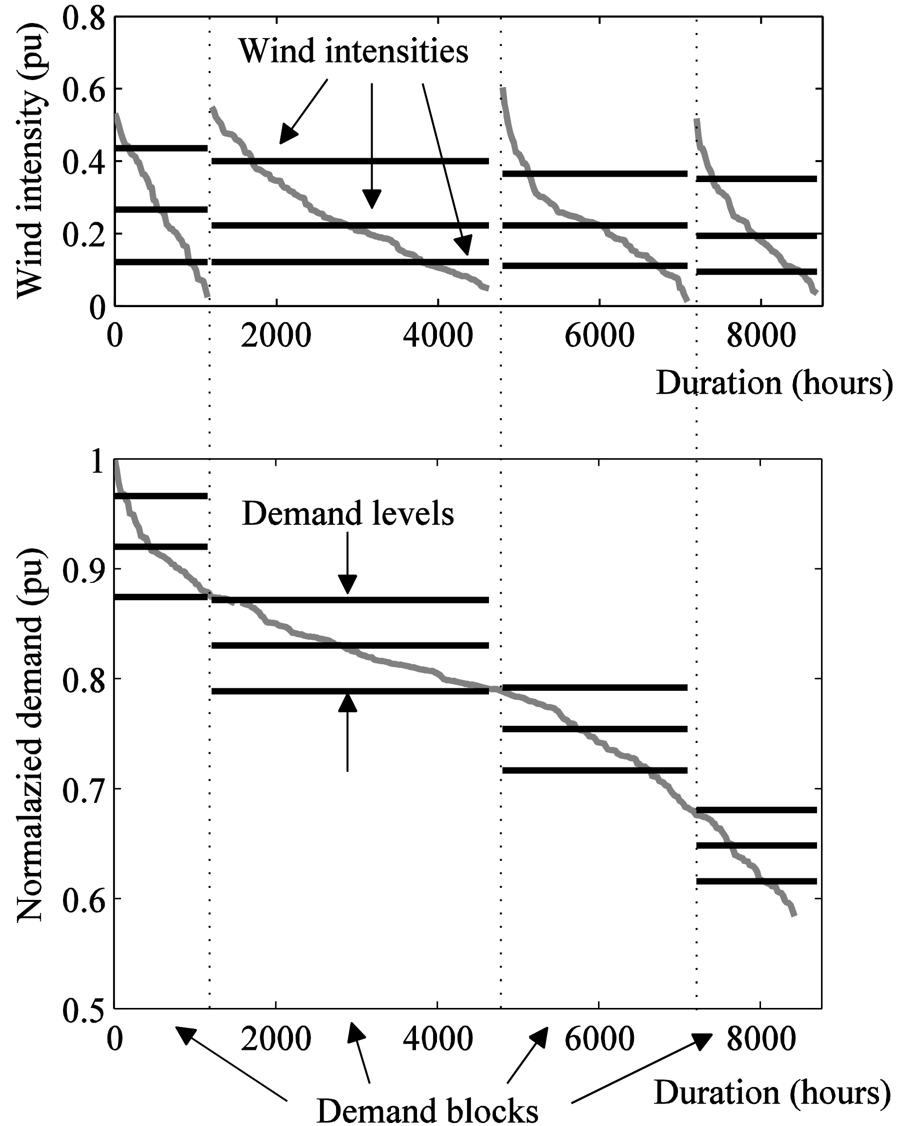
RGI (who is interested?)

- ✓ Renewable generation investors
- ✓ Regulators

RGI
(market framework)

- ✓ Price-taker producer
- ✓ Uncertain production level

Uncertainty (modeling)

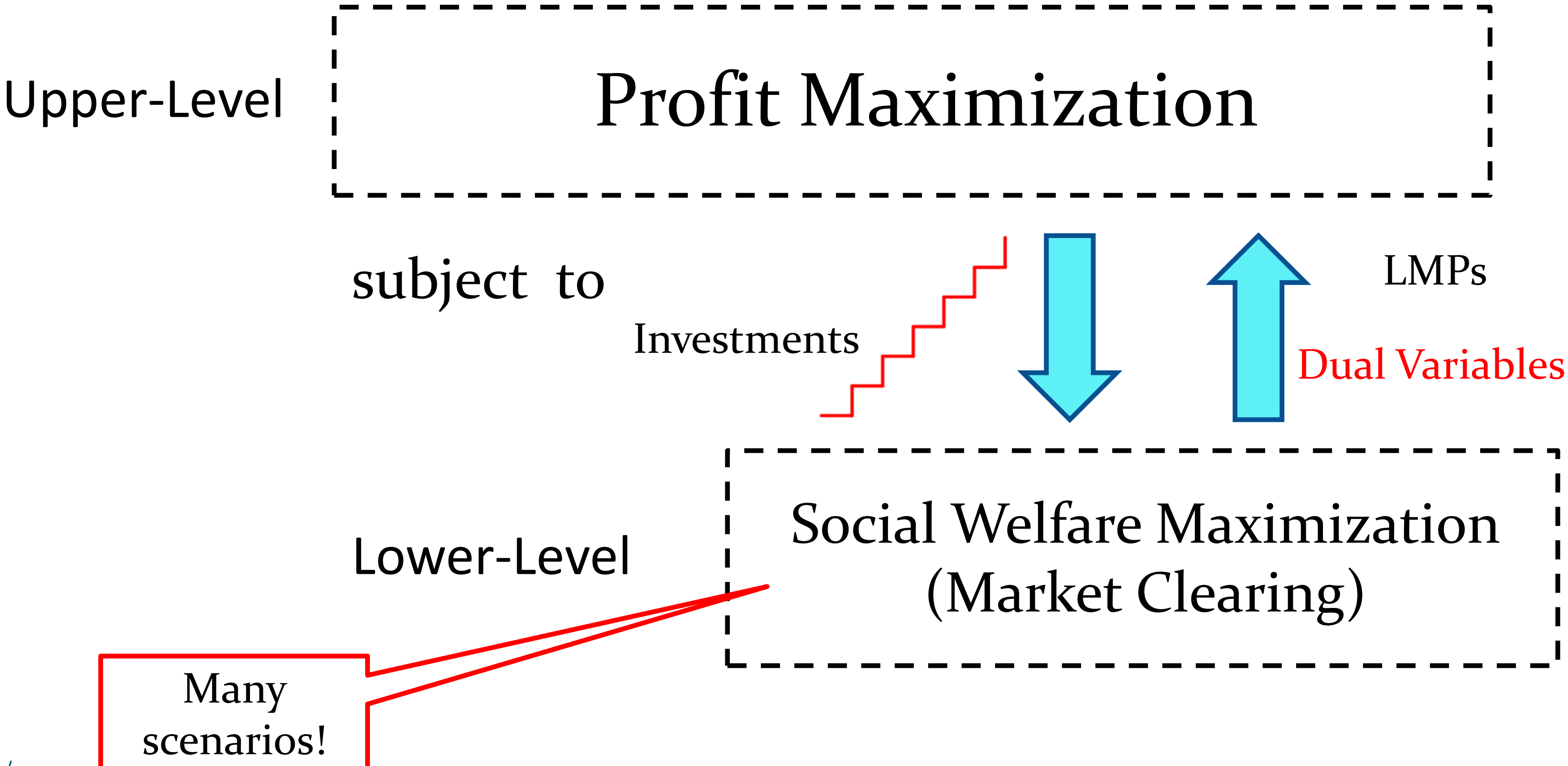


RGI (model)

- ✓ Uncertainty modeling
- ✓ Complementarity approach

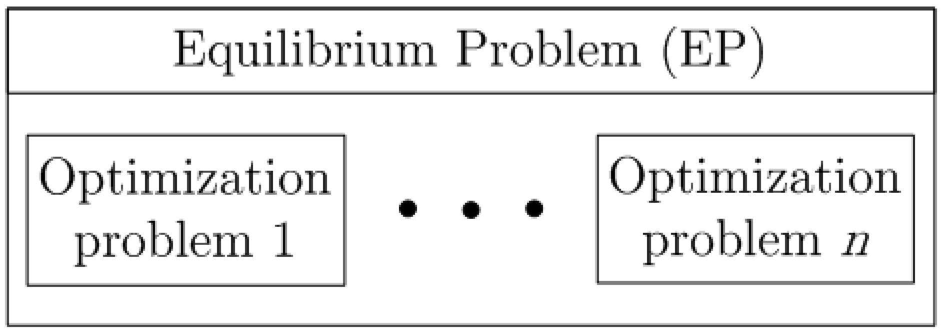
Approach

Complementarity model:

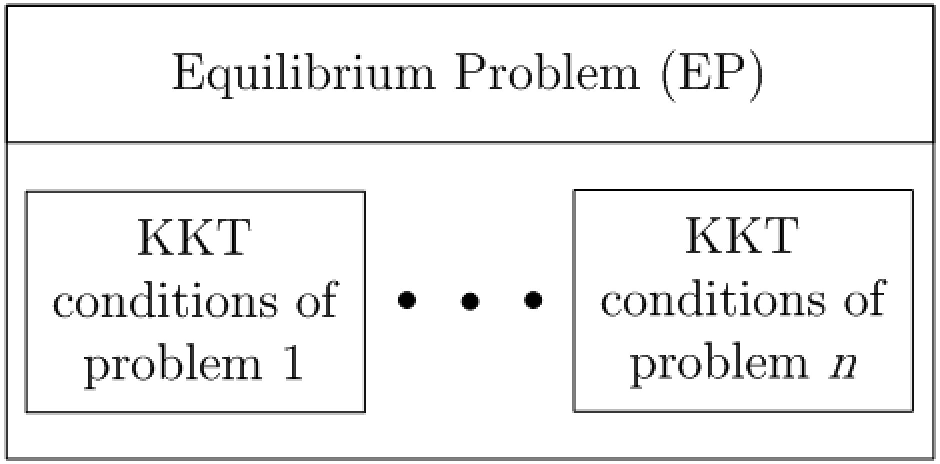


Equilibria
for
investment problems

Equilibria


Equilibrium Problem (EP)
Optimization problem 1
Optimization problem n

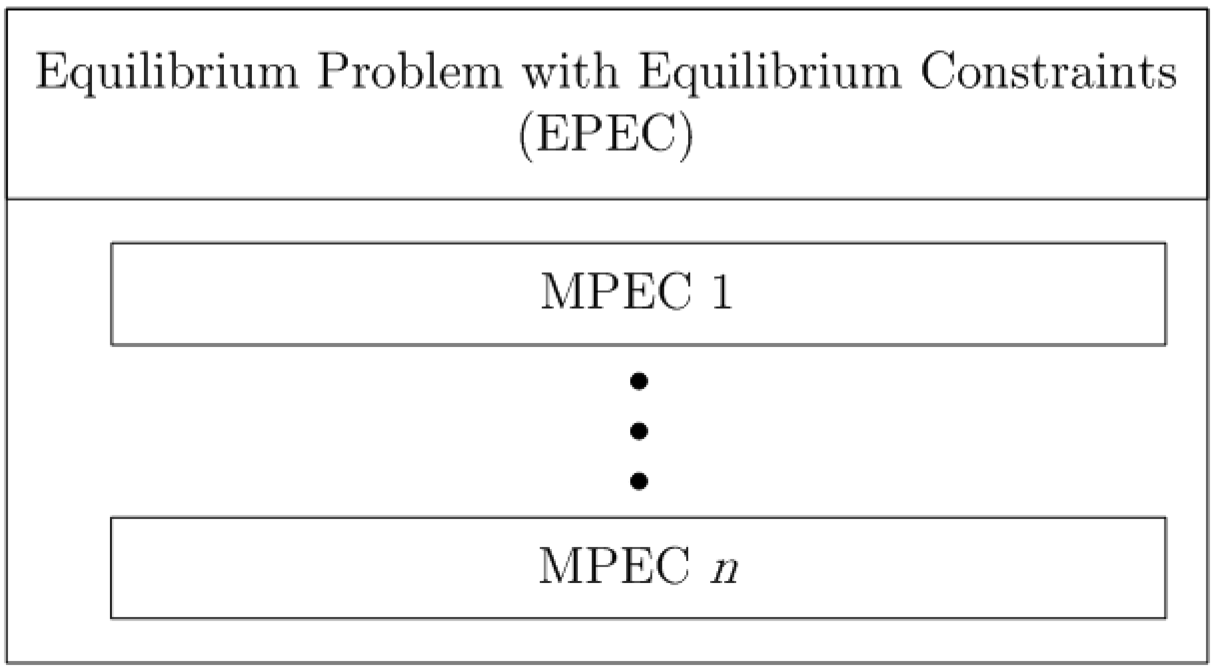
Equilibria


Equilibrium Problem (EP)
KKT conditions of problem 1
KKT conditions of problem n

Equilibria

- ✓ Solving simultaneously a collection of optimization problems
- ✓ For instance, solving simultaneously the investment problems of several producers

EPEC


Equilibrium Problem with Equilibrium Constraints
(EPEC)
MPEC 1
MPEC n

EPEC

- ✓ Solving simultaneously a collection of MPECs
- ✓ For instance, solving simultaneously the investment problems of several oligopolistic producers

EPEC

✓ Multi-Leader-Common-Follower Games

1. Sven Leyffer and Todd Munson “Solving Multi-Leader-Common-Follower Games”. Mathematics and Computer Science Division. Preprint ANL/MCS-P1243-0405. April 2005; Revised March 2007.

2. Frederic Murphy and Yves Smeers, "On the Impact of Forward Markets on Investments in Oligopolistic Markets with Reference to Electricity", Operations Research, Vol. 58, No. 3, May–June 2010, pp. 515–528.

Challenges

Challenges (research!)

- ✓ Uncertainty characterization
- ✓ Tractability
- ✓ Multi-stage decision making
- ✓ Risk management
- ✓ Stochastic MPEC/ EPEC modeling

Research needed!

Power & Energy Society®