UIUC Capstone

Fundamentals of Energy Markets

The core of energy markets

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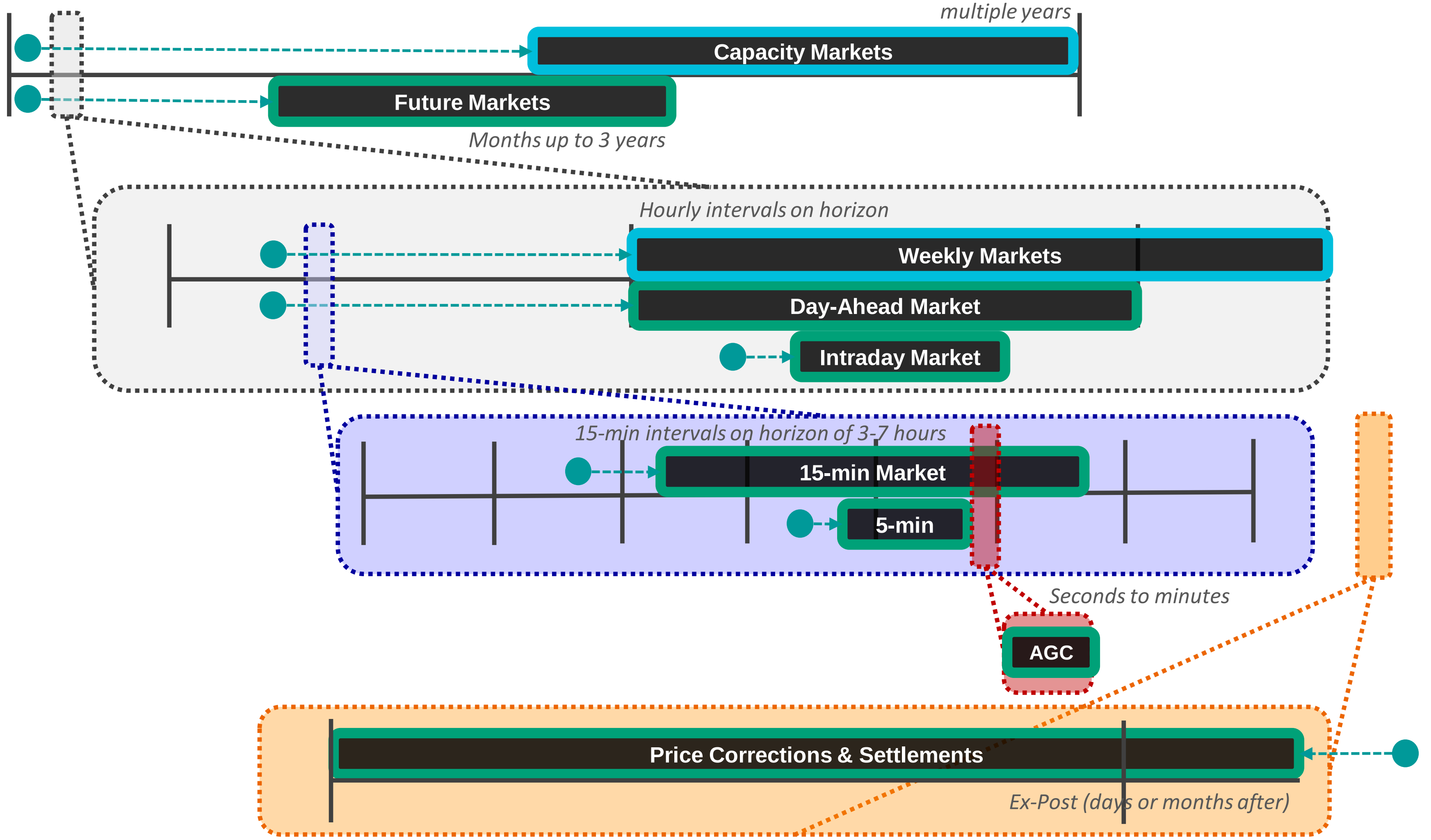
What should we consider in our marketplace as a resources optimization problem to achieve **efficiency** and **reliability**?

The role of Resources Optimization on Energy Markets
Temporal Dependencies and Adaptability

Forward Markets Timeline:



- *Long term capacity*
- *Resource adequacy*

- *Outage Analysis & Reliability*
- *Energy & Reserve Scheduling*
- *Unit Commitment*
- *Reliability Analysis*

- *Near-term Reliability*
- *Synchronized Reserve*
- *Imbalance Energy*
- *Regulation & Flexibility*

- *Control Actions for Stability*
- *Reserve Activation*

- *Bilateral transactions*
- *Price Corrections*

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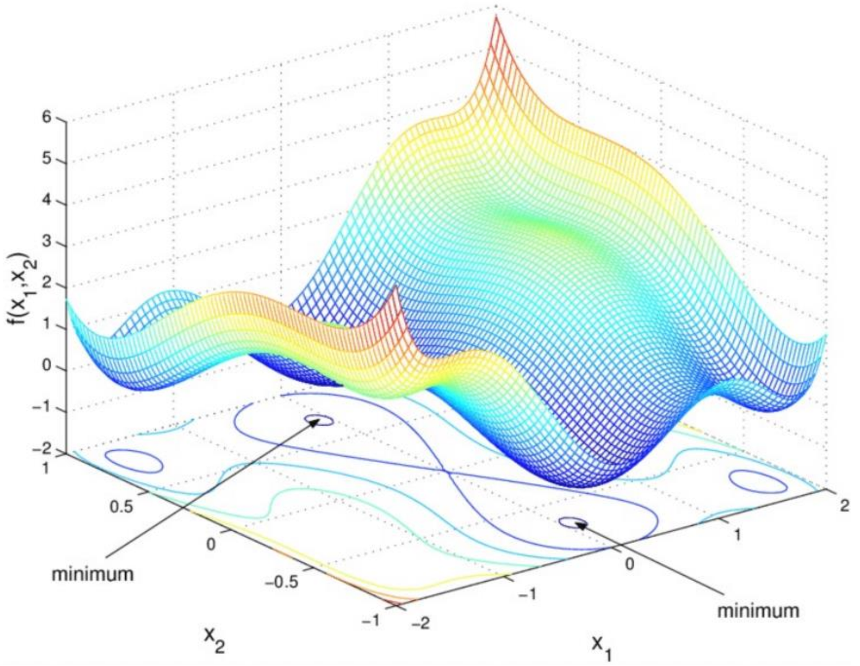
Fundamentals Concepts about Optimization
Canonical form and Notation of Optimization Problems

What is an optimization problem?

"A computational problem in which the object is to find the best of all possible solutions. More formally, find a solution in the feasible region which has the minimum (or maximum) value of the objective function." (NIST)

Comprises a search for "the best" values for design variables *x*, while respecting certain constraints / boundaries, in the canonical form:

$minimize$	$f(x)$		[Cost or Objective Function]
$subject\ to$	$g_{\mathrm{i}}(x) \leq 0$	$i = 1, \ldots, m$	[Inequality Constraints]
	$h_j(x) = 0$	$j = 1, \ldots, l$	[Equality Constraints]



Variables can be Continuous values ($x \in R^n$), Integer values ($x \in Z^n$) or Discrete values ($x \in \{0, 1\}$) or mixed

One can always re-formulate a maximization problem, e.g. *max f(x)* into a minimization problem by defining $\tilde{f}(x) = -f(x)$ and solving min $\tilde{f}(x)$

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Fundamentals Concepts about Optimization
Optimization Frameworks

v · t · e	Mathematical optimization software [hide]
Data formats	Mathematica · MPS · nl · sol
Modeling tools	AIMMS · AMPL · APMonitor · ECLiPSe-CLP · GEKKO · GAMS · GNU MathProg · JuMP · LINDO · OPL · Mathematica · OptimJ · PuLP · Pyomo · TOMLAB · Xpress Mosel · ZIMPL
LP, MILP* solvers	APOPT* · ANTIGONE* · Artelys Knitro* · BCP* · CLP · CBC* · CPLEX* · FortMP* · GCG* · GLOP* · GLPK/GLPSOL* · HiGHS* · LINDO* **+Gurobi** Lp_solve · LOQO · Mathematica · MINOS · MINTO* · MOSEK* · NAG · SCIP* · SoPlex · Octeract Engine* · SYMPHONY* · Xpress Optimizer*
QP, MIQP* solvers	APOPT* · ANTIGONE* · Artelys Knitro* · CBC* · CLP · CPLEX* · FortMP* · HiGHS · IPOPT · LINDO* · Mathematica · MINOS · MOSEK* · NAG · Octeract Engine* · SCIP* · Xpress Optimizer*
QCP, MIQCP* solvers	APOPT* · ANTIGONE* · Artelys Knitro* · CPLEX* · IPOPT · LINDO* · Mathematica · MINOS · MOSEK* · NAG · SCIP* · Octeract Engine* · Xpress Optimizer* · Xpress NonLinear*
SOCP, MISOCP* solvers	Artelys Knitro* · CPLEX* · LINDO* · LOQO · Mathematica · MOSEK* · NAG · SCIP* · Xpress Optimizer* **+ECOS**
SDP, MISDP* solvers	Mathematica · MOSEK · NAG
NLP, MINLP* solvers	AOA* · APOPT* · ANTIGONE* · Artelys Knitro* · BARON* · Couenne* · Galahad library · IPOPT · LINDO* · LOQO · MIDACO* · MINOS · NAG · NLPQLP · NPSOL · SCIP* · SNOPT* · Octeract Engine* · WORHP · Xpress NonLinear*
GO solvers	ANTIGONE* · BARON · Couenne* · Mathematica · LINDO · SCIP · Octeract Engine
CP solvers	Artelys Kalis · Comet · CPLEX CP Optimizer · Gecode · Mathematica · JaCoP · Xpress Kalis
Metaheuristic solvers	OptaPlanner
	List of optimization software · Comparison of optimization software

https://en.wikipedia.org/wiki/List_of_optimization_software

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Optimal Power Flow Conceptualization
Conceptual Formulation

Conceptual formulation

Minimize: *Total Cost of Generation or Losses of the Network or Control Actions, …*
Total Investment or Minimal Expected Loss of Load or Risk of Supply, …

Considering:
AC ***Power Balance*** *for Active and Reactive Power*

AC Power Flow equations with ***network physical model***

Generator should operate within their ***physical limits***

Network should operate within their ***physical limits***

Voltage limits *should be respected for power quality and stability*

Find: ***Generation Schedule*** *and* ***Network Conditions***

Power System Operation: Decision making in very-short and short-term timescales (safety and efficiency)
Power System Planning: Decision making in medium and long-term timescales (reliability and adequacy)

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Optimal Power Flow Formulation
Objective Function, Constraints, Decision Variables

Basic formulation of ACOPF: Nonlinear Continuous Optimization Problem

Objective

$$\min \sum_{i \in G} F_i\left(P_i^g, Q_i^g\right)$$

Constraints

Power Flow Equations:

$$S_{km} = (G_{kk} - jB_{kk})|V_k|^2 + (G_{km} - jB_{km})|V_k||V_m|(\cos\theta_{km} + j\sin\theta_{km}) \qquad \forall\ branch\ km$$

$$\sum_{km \in \Omega_k} S_{km} = \sum_{i \in G_k} P_i^g - P_k^d + j \sum_{i \in G_k} Q_i^g - Q_k^d$$

Power Flow limit on branch *km:*

$$\underline{S_{km}} \le |S_{km}|^2 = Re\{S_{km}\}^2 + Im\{S_{km}\}^2 \le \overline{S_{km}}$$

Voltage limit on bus *k:*

$$\underline{V_k} \le |V_k| \le \overline{V_k}$$

Generator output limits*:*

$$\underline{S_i} \le S_i^g \le \overline{S_i}$$

Solution Variables

Decision Variables: $\{P_i^g, Q_i^g\}$

State Variables: $\{V, \theta\}$

Constrained Nonlinear Programming

Lagrangian and Penalty Methods
Barrier/Interior Point Method
Primal-Dual Method
Sequential Linear/Quadratic Methods
Convex Optimization Methods
Decomposition Techniques
Derivative-free methods
…

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Optimal Power Flow Formulation
Objective Function, Constraints, Decision Variables

Linearized Formulation: DC Optimal Power Flow

Objective

$$\min \sum_{i \in G} F_i\left(P_i^g\right)$$

Constraints

Power Flow Equations:

$$P_{km} = y_{km}(\theta_k - \theta_m) \qquad \forall \; branch \; km$$

$$\sum_{km \in \Omega_k} P_{km} = \sum_{i \in G_k} P_i^g - P_k^d$$

Power Flow limit on branch *km:*

$$\underline{P_{km}} \leq |P_{km}| \leq \overline{P_{km}}$$

Generator output limits:

$$\boxed{\underline{P_i} \leq P_i^g \leq \overline{P_i}}$$

Very simplified physical model of generators

Solution Variables

Decision Variables: $\{P_i^g\}$

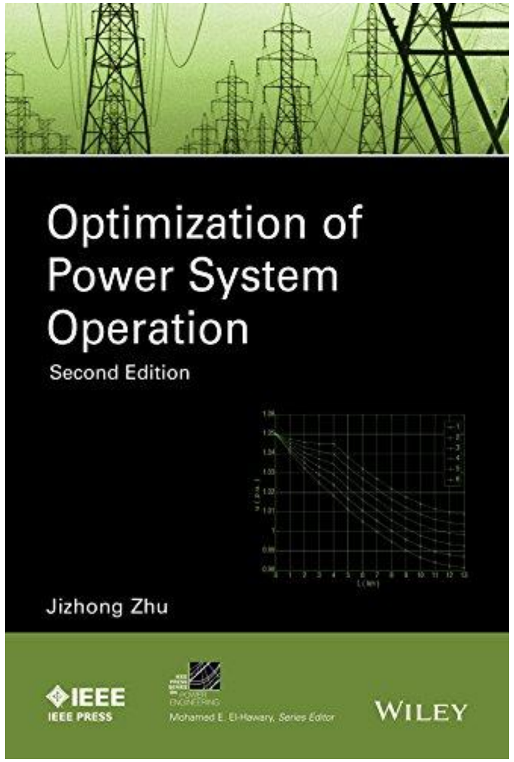
State Variables: $\{\theta\}$

Allows extending the temporal dimensionality and more constraints.

Constrained Linear Programming

Simplex Method
Lagrangian and Penalty Methods
Barrier/Interior Point Method
Primal-Dual Method
…

Cool Places to Look:



- Power flow analysis (Chapter 2)
- Sensitivity calculation (Chapter 3)
- Classical economic dispatch (Chapter 4)
- Security-constrained economic dispatch (Chapter 5)
- Multiarea systems economic dispatch (Chapter 6)
- Unit commitment (Chapter 7)
- Optimal power flow (Chapter 8)
- Steady-state security regions (Chapter 9)
- Application of renewable energy (Chapter 10)
- Optimal load shedding (Chapter 11)
- Optimal reconfiguration of electric distribution networks (Chapter 12)
- Uncertainty analysis in power systems (Chapter 13)
- Operation of smart grids (Chapter 14)

(1) Conventional optimization methods including
  - Unconstrained optimization approaches
  - Nonlinear programming (NLP)
  - Linear programming (LP)
  - Quadratic programming (QP)
  - Generalized reduced gradient method
  - Newton method
  - Network flow programming (NFP)
  - Mixed integer programming (MIP)
  - Interior point (IP) methods.

(2) Intelligence search methods such as
  - Neural network (NN)
  - Evolutionary algorithms (EAs)
  - Tabu search (TS)
  - Particle swarm optimization (PSO).

(3) Nonquantitative approaches to address uncertainties in objectives and constraints including
  - Probabilistic optimization
  - Fuzzy set applications
  - Analytic hierarchical processes (AHPs).

Disclaimer

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Thank You

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