EE 459/611: Smart Grid Economics, Policy, and Engineering

Lecture 1: Course Information and Overview

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Fall 2020

University at Buffalo

Course Information

- **Instructor:** Luis Herrera
- **Contact Info:** 224 Davis Hall, lcherrer@buffalo.edu , 716 431-2832
- **Class Times:** Tu/Th 12:45 pm – 2:00 pm
- **Class Location:** Online/Zoom (Record)
- **Office Hours*:** TBA (will send email when decided)
- **TAs:** Lalit Marepalli
- **Website:** UBLearns blackboard (will upload blank notes prior to class), **please use them to follow along**

Course Information

- **Course Information:**
  - ✓ This course provides an introduction to electric power markets and the mathematical techniques to better use available energy resources.
  - ✓ Topics include the description of thermal power plants and renewable energy sources.

    Cost operation → $/kW

  - ✓ Formulation of the cost associated with generation will be presented.
  - ✓ Optimization theory will be introduced with the aim of minimizing cost of supplying loads.
  - ✓ Particular methods include economic dispatch, unit commitment, and optimal power flow.

Grading Policy

489/611

- **Homework (35%)**
  - Assigned approximately every two weeks
  - Most will use Matlab (may use CVX toolbox – instructions will be provided)

- **Quizzes (10%):** approximately 7-10, 20 mins quizzes on UBLearns

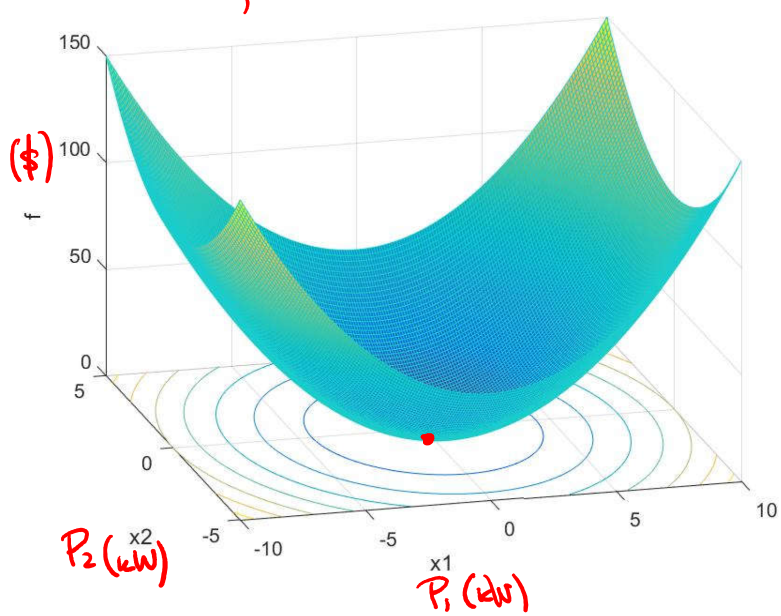
- **Midterm (25%)**: Exam

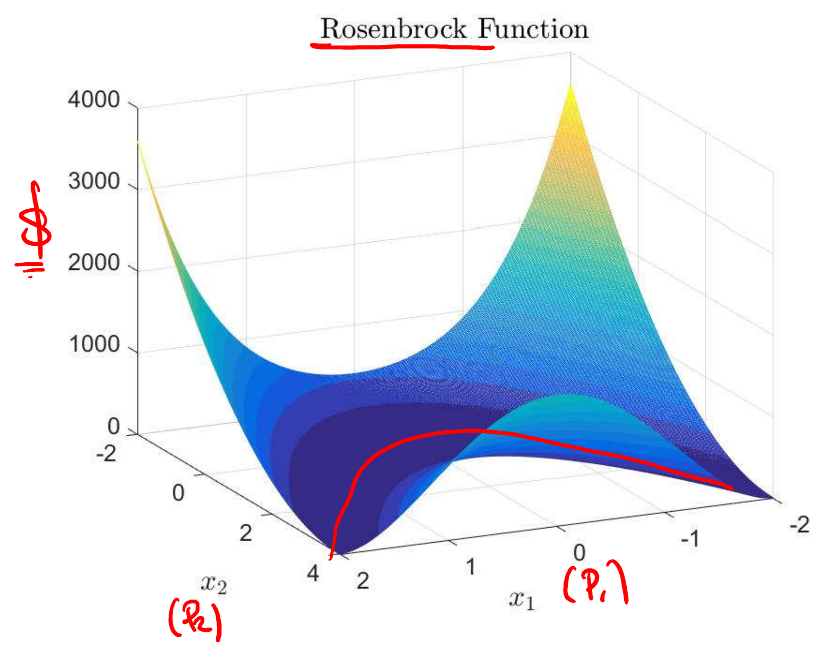
- **Final Project (30%)**

  Matlab

Course Materials

- **Textbook:**
  - A. Wood, B. Wollenberg, and G. Sheble, "Power generation, operation, and control." Wiley, 3rd Edition, 2013.
    (Book not strictly required but it is a very good reference)
  - Matlab + **Optimization Toolbox**
  - Optional optimization software:
    CVX (convex optimization) http://cvxr.com/cvx/





Tentative Topics

- **Power System Economics** (1-2 lectures)
  - Power generation terminal characteristics ($/kW)
  - Cost of power generation
- **Mathematical Background:** (2-3 lectures)
  - Linear Algebra
  - Multivariable Calculus
- **Optimization Theory**
- **Economic Dispatch**
- **Unit Commitment**
- **Optimal Power Flow**
- **Other Topics**
  - State Estimation
  - Power electronics
  - Automatic Generation Control

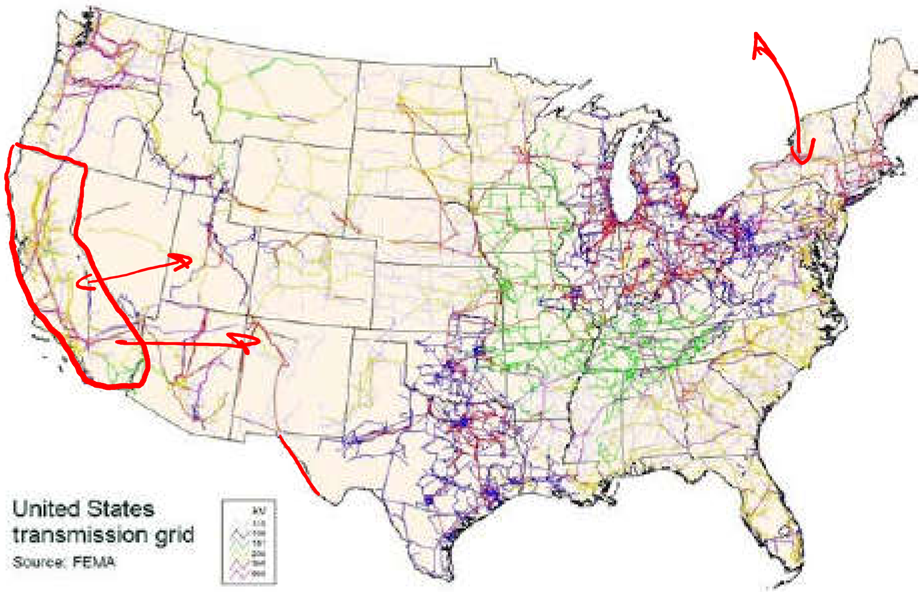
Today – 09/01/2020

- Today we will mainly look at an overview of the topics we will cover in class
- Motivation from power systems

Power Systems in US

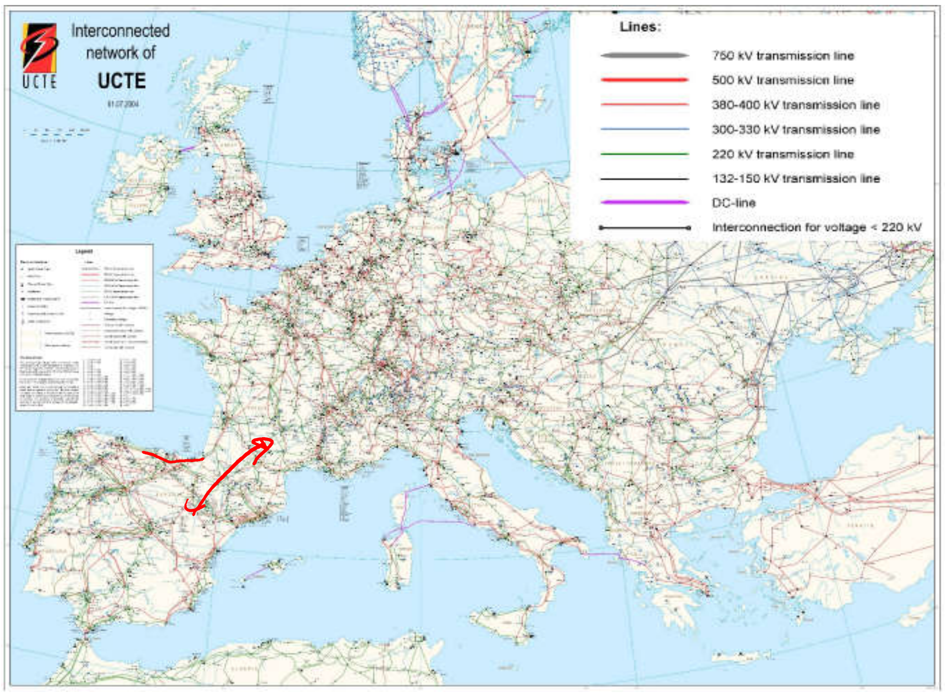
- Power system in the US: colors represent transmission line voltages

ISOs / RTOs

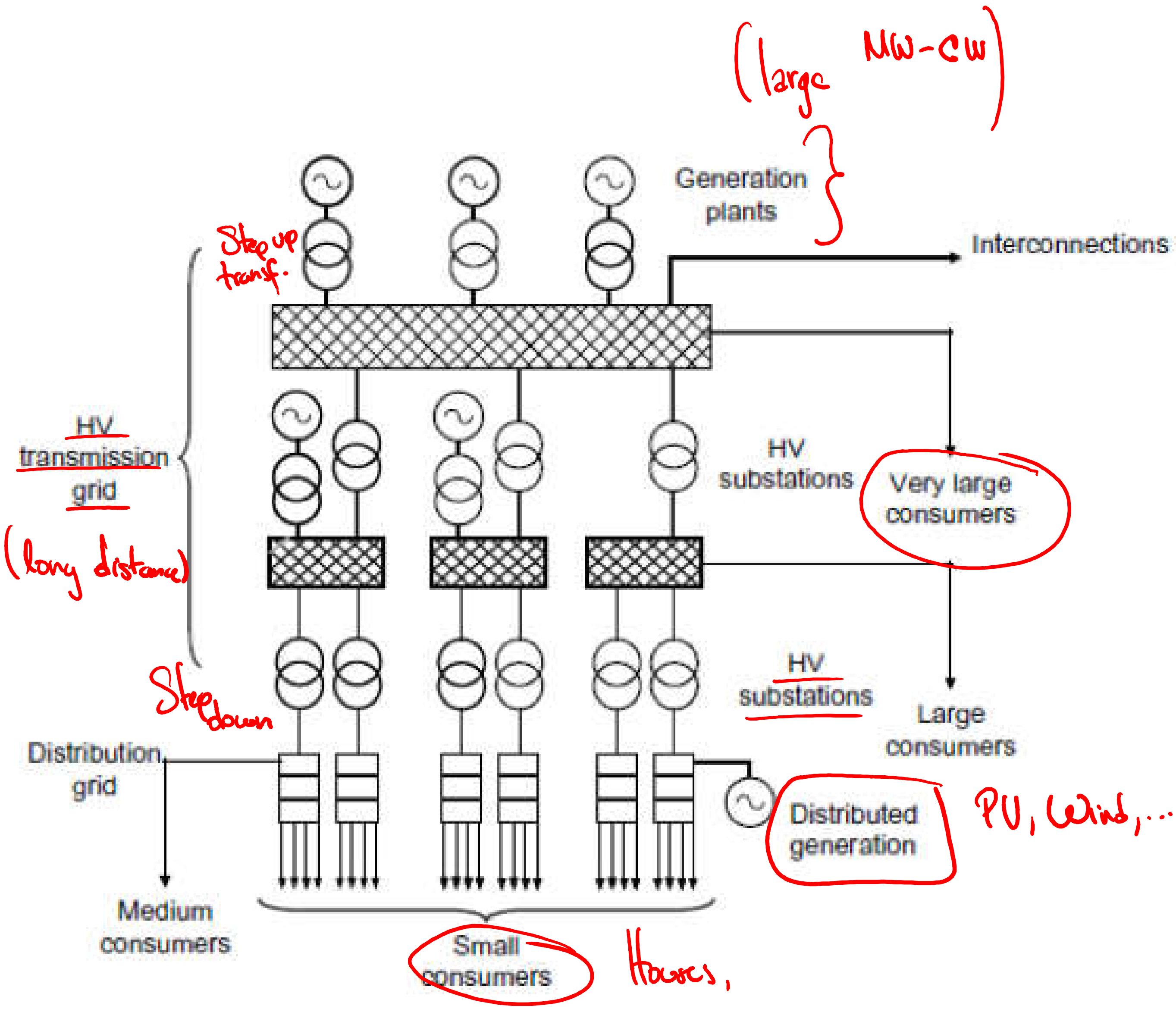


Power Systems in Europe

- Power system in the Europe: colors represent transmission line voltages



Power System Components



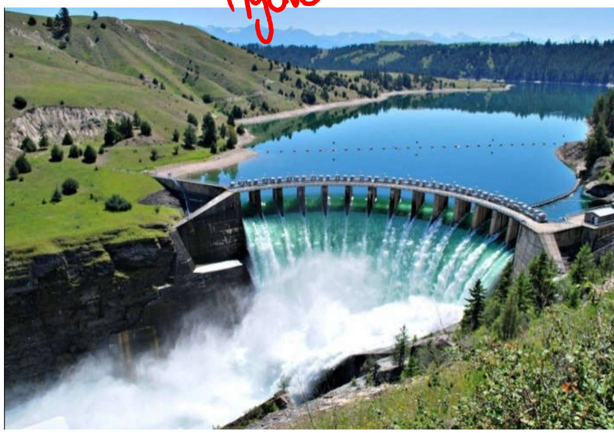
Example Energy Sources

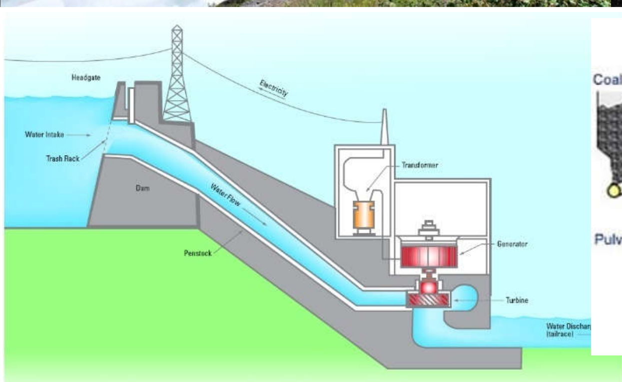
Power output vs. Cost

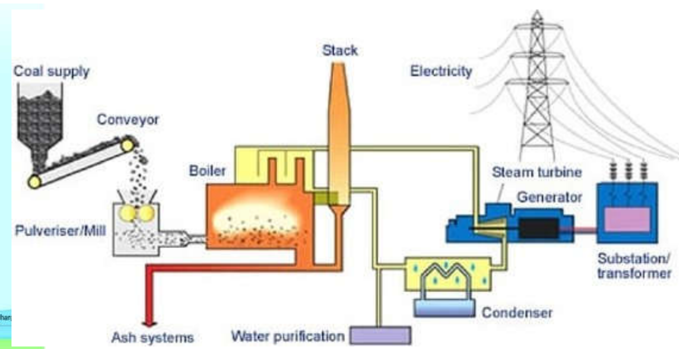
Hydro

Coal (Thermal)

Wind







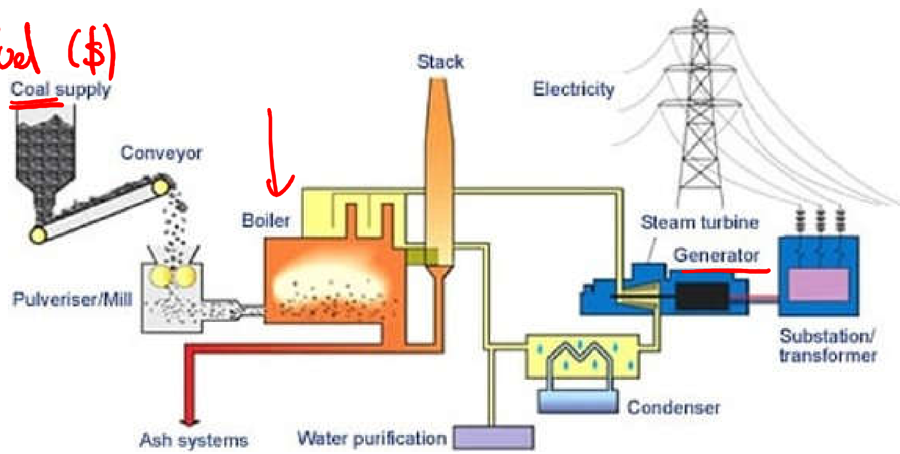
Soler

Cost Associated with Source Operation

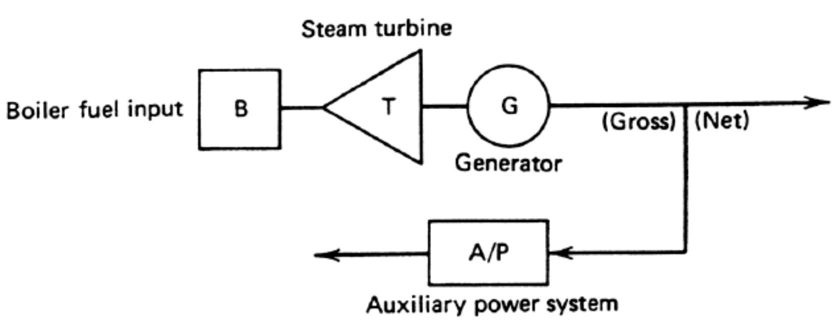
- Cost associated with running a generation plant

Cost

fuel ($)

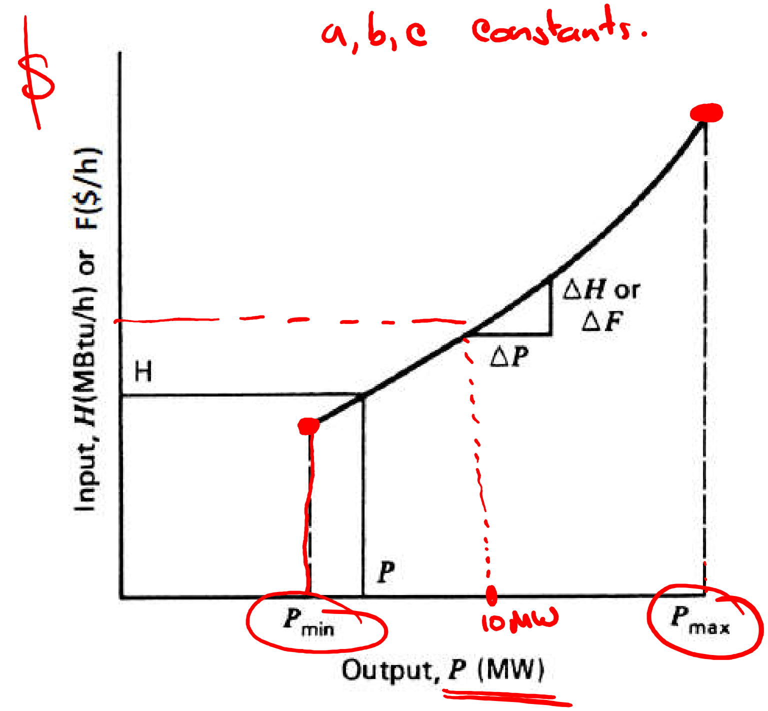


don't want to turn on/off frequently



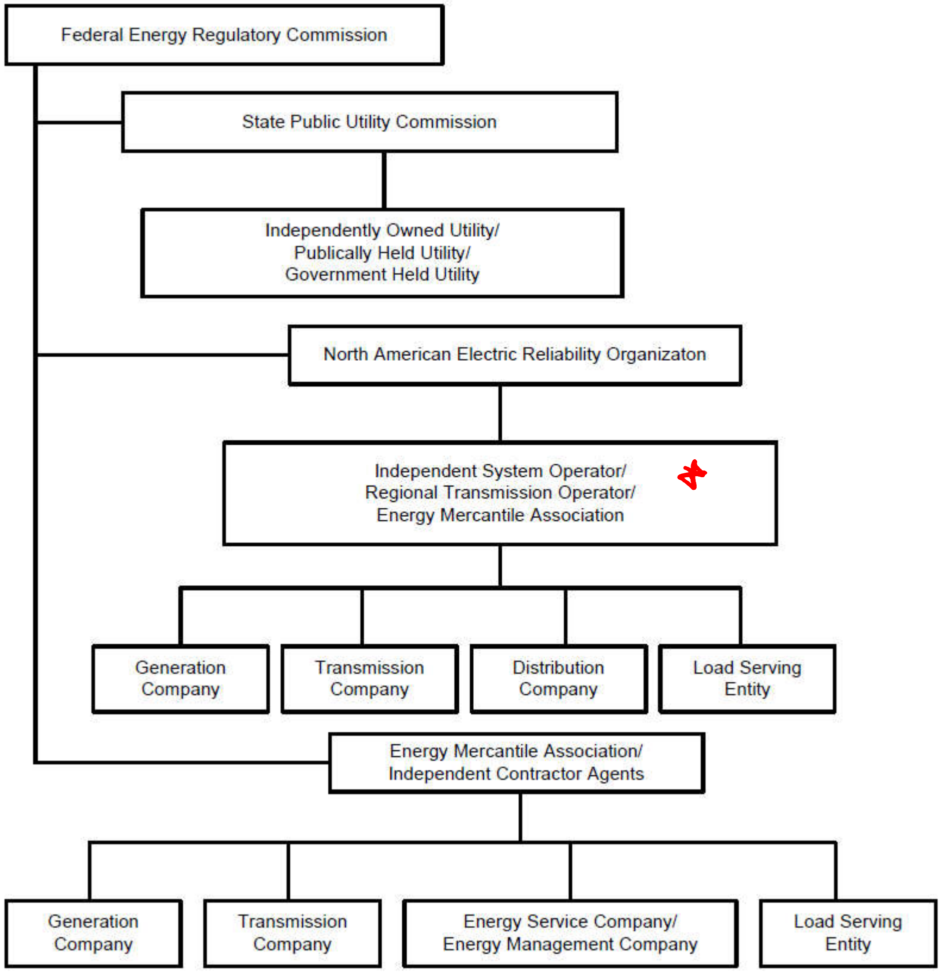
$C(P) = aP^2 + bP + c$

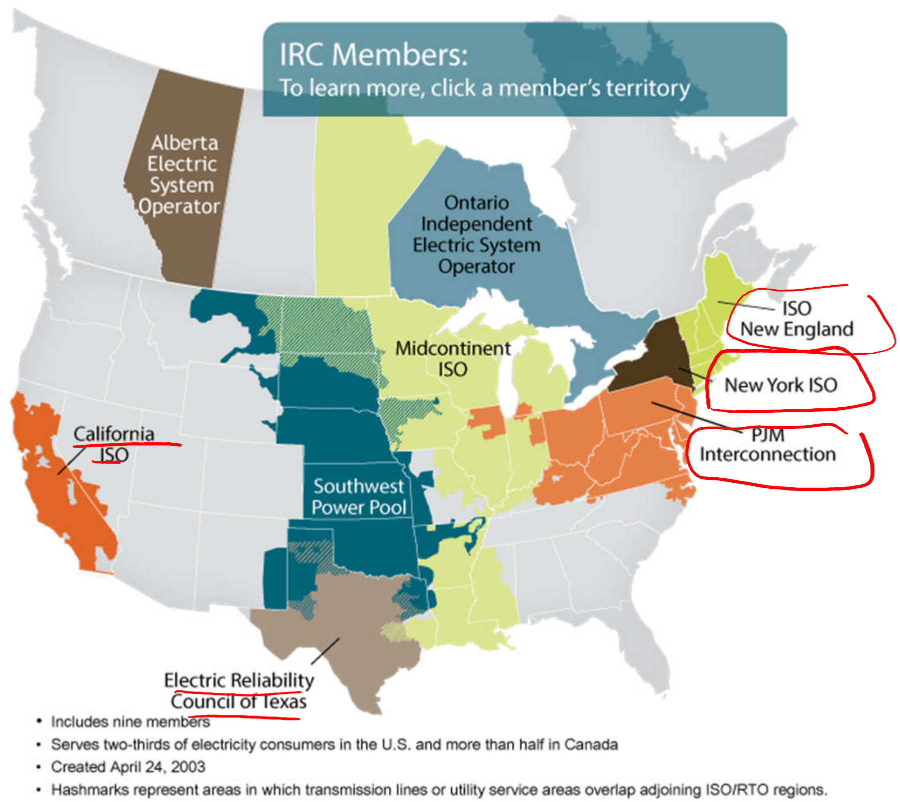
a, b, c constants.



Types of Markets

- Nowadays, most markets are **competitive**
- The Independent System Operators (ISO) ensure the grid operation, market administration and **planning**





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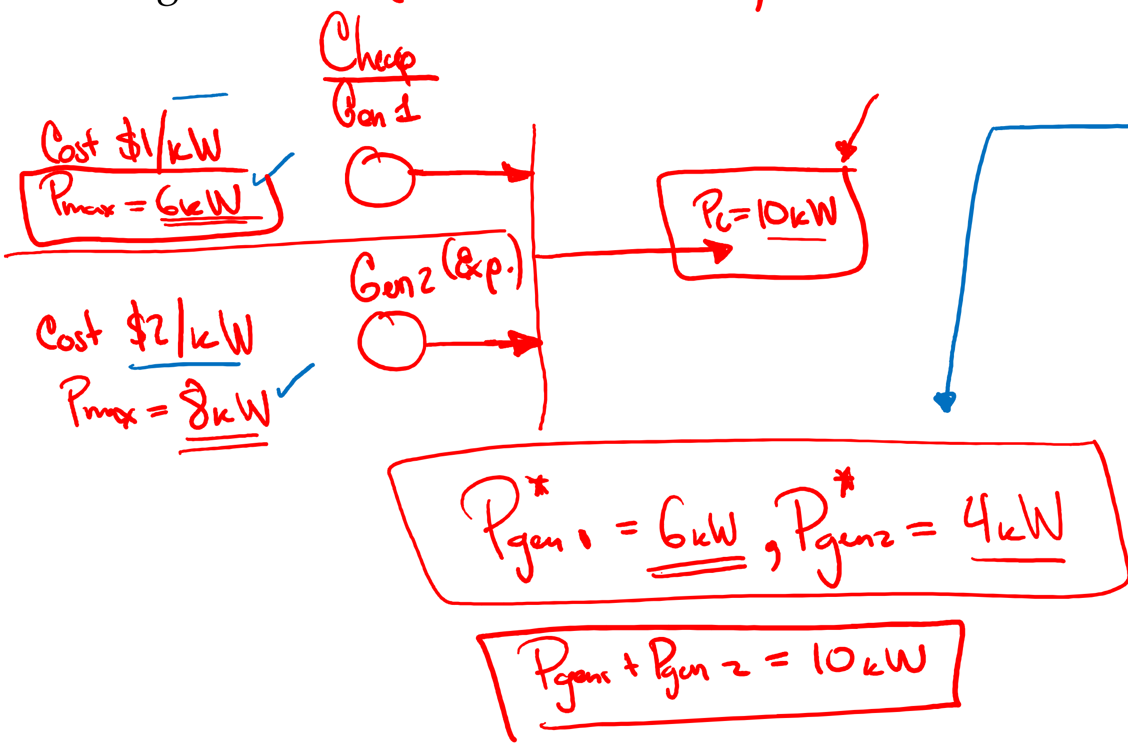
Economic Dispatch Example

- **Economic Dispatch** is to find out, for a **single period of time** (1 hour), the output power of every generation unit so that demands are satisfied at a **minimum costs**

- Example: Two generators must supply a load which is consuming 10 kW. Generator 1 can provide a maximum power of 6 kW at a cost of $1/kW, Generator 2 can provide a maximum power of 8 kW at a cost of $2/kW. What should be the output power of each generator? (to minimize cost)



Pgen1	Pgen2	Cost
6kW	4kW	$6+$8=$14
5kW	5kW	$15
4.5	5.5	

Economic Dispatch Example – Mathematical Formulation

- Example: Two generators must supply a load which is consuming 10 kW. Generator 1 can provide a maximum power of 6 kW at a cost of $1/kW, Generator 2 can provide a maximum power of 8 kW at a cost of $2/kW. What should be the output power of each generator?

minimize total Cost

subject to:

$$P_1 + P_2 = 10\,kW$$

$$0 \le P_1 \le 6\,kW$$

$$0 \le P_2 \le 8\,kW$$

Cost 1, Cost 2

$$\min_{P_1, P_2} \left(1P_1 + 2P_2 \right)$$ } Cost function

s.t.

1) $P_1 + P_2 = 10\,kW$

2) $0 \le P_1 \le 6\,kW$

3) $0 \le P_2 \le 8\,kW$

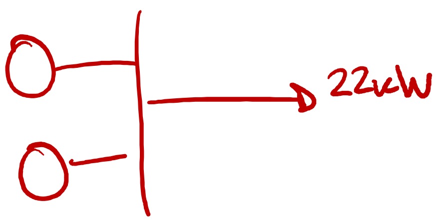
} Constraints

- This formulation falls under a **linear programming problem** (optimization)

Economic Dispatch Example 2

- Generator 1 provides power at a cost of $C_1(P_1) = 0.5P_1^2 + 2P_1$ and generator 2 provides power at a cost of $C_2(P_2) = 0.25P_2^2 + 0.2$
- Generators 1 and 2 capacity are at 8 kW and 15 kW respectively
- They must stuply a load of 22 kW. What should be the output power of each generator?

(not so trivial)



$$\min_{P_1, P_2} \; C_1(P_1) + C_2(P_2) = 0.5P_1^2 + 2P_1 + 0.25P_2^2 + 0.2$$

s.t.

$$P_1 + P_2 = 22\text{kW}$$

$$0 \le P_1 \le 8\text{kW}$$

$$0 \le P_2 \le 15\text{kW}$$

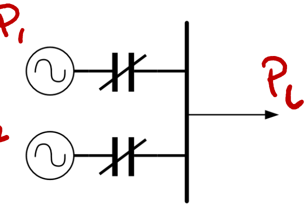
Unit Commitment Example

(Planning)

- **Unit Commitment** problem consists of determining, for a planning horizon (typically 1 day), the start-up and shut-down schedule of all production units so that the electric demand is supplied and total operating costs are minimized

	Gen.	$P_{\min}$	$P_{\max}$	Cost/power	Start-up cost
Cheap	1	1.5	7	7.2	4
Expensive	2	1	6	7.8	4

Hour	1	2	3
P_L	5.5	8	4

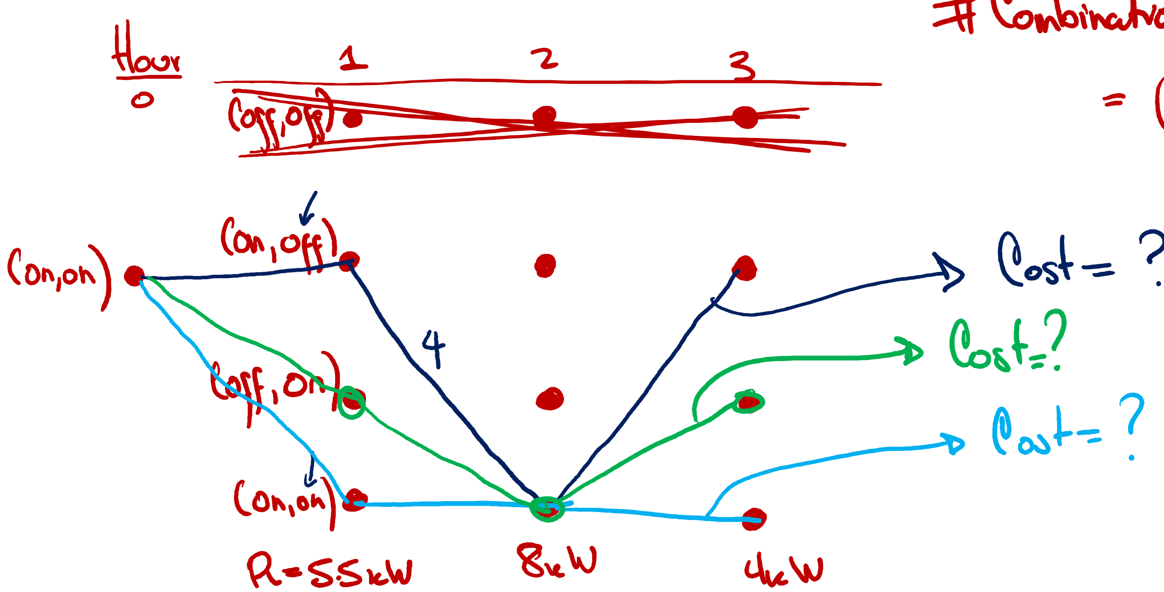


$2^2 = 4$

Initial condition (on, on)

$$\# \text{Combinations} = \left(2^{N_{gen}} - 1\right)^{N_{hours}} = (2^2-1)^3 = 27$$

Shortest Path Problem



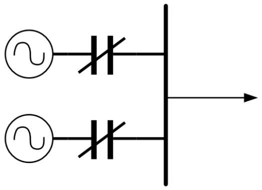
N_{gen}	No. of Combinations for 24 hours
5	6.2×10^{35}
10	1.73×10^{72}
20	3.12×10^{144}
40	(too big)

Unit Commitment Example (cont'd)

- What is the best way to operate the generators for the specified 3 hours?

Gen.	$P_{\min}$	$P_{\max}$	Cost/power	Start-up cost
1	1.5	7	7.2	4
2	1	6	7.8	4

Hour	1	2	3
P_L	5.5	8	4



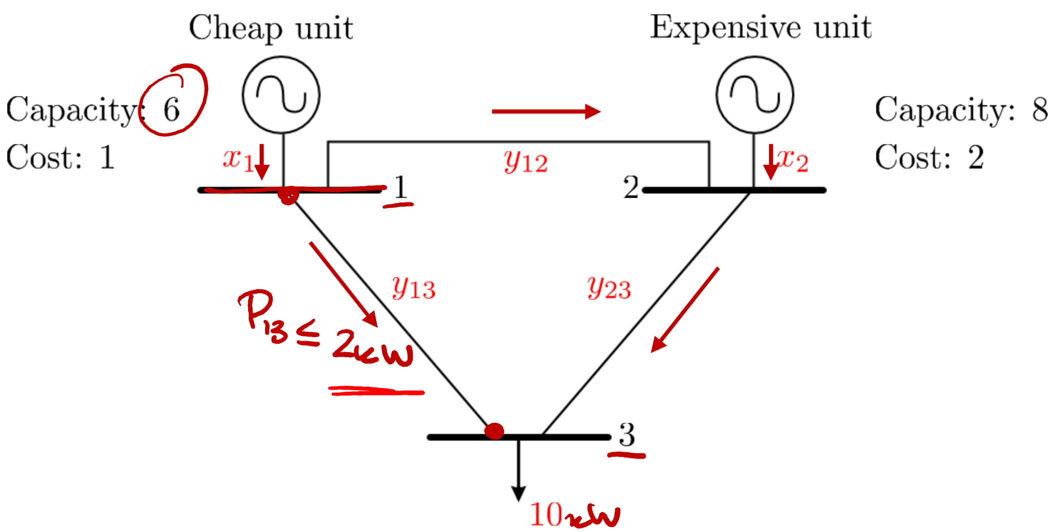
N_{gen}	No. of Combinations for 24 hours
5	6.2×10^{35}
10	1.73×10^{72}
20	3.12×10^{144}
40	(too big)

Optimal Power Flow Example

(for 1 hour)

- The goal of the **Optimal Power Flow (OPF)** problem is to find out the power output of every unit (including active and reactive) so that all loads are supplied at a minimum costs while satisfying network constraints* (same as Econ. Dispatch + Network Const.)

- **Example:** Same as economic dispatch example, but make sure that the maximum power flowing through line 1-3 is 2 kW!



$$\min_{P_1, P_2} \; 1P_1 + 2P_2$$

s.t.

* {Power flow eqns.} — nonlinear (sin, cos)

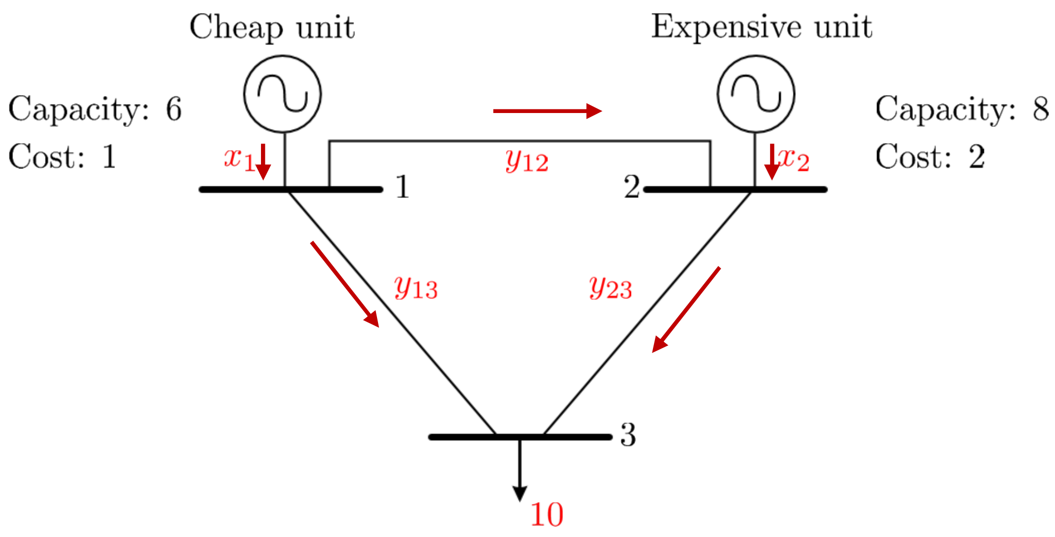
* $0 \le P_1 \le 6$

$0 \le P_2 \le 8$

* $P_{13} \le 2$kW

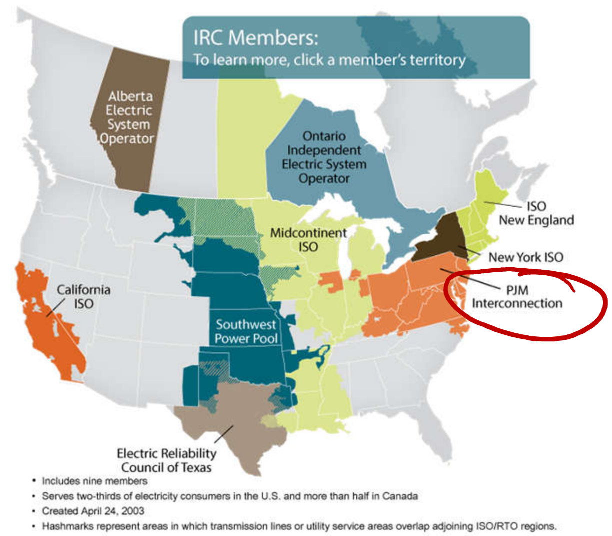
Optimal Power Flow Example

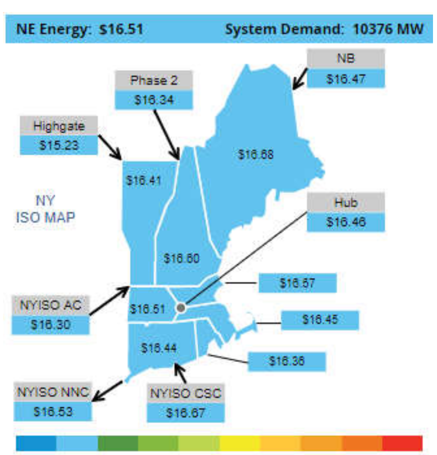
- **Example:** Same as economic dispatch example, but make sure that the maximum power flowing through line 1-3 is 2 kW!



RTO / ISO

- **Regional Transmission Operators:** coordinates, controls, and monitors a **multi-state** electric grid
- **Independent System Operators:** Similar as an RTO but typically within a single state
- The previous optimization problems are utilized by these entities to **control and <u>optimally*</u> plan** the operation of generators





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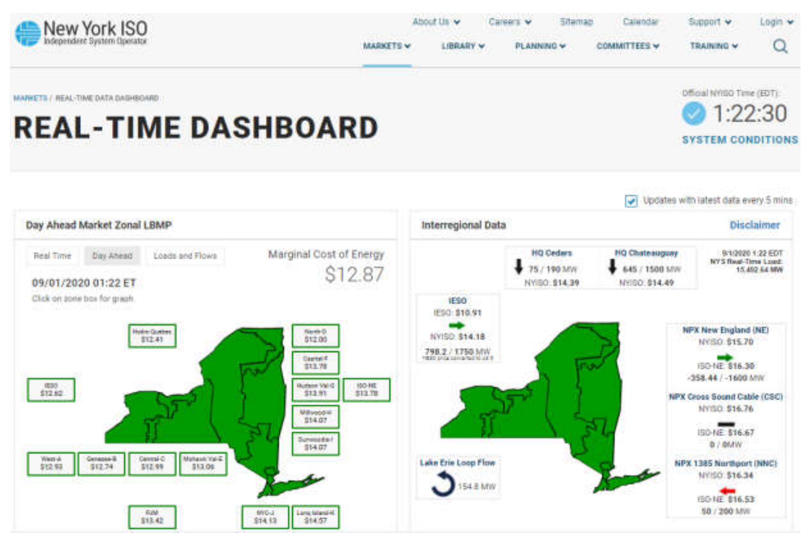
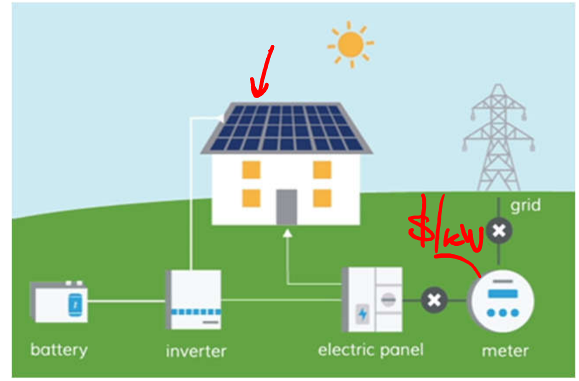


https://www.nyiso.com/real-time-dashboard

Other Applications in Power



1. What is the best way to coordinate PV + Energy Storage?

optimization problem (Final Project)

2. For a Hybrid Electric Vehicle, what is the best way to operate engine vs. electrical motor?

$$\min_{\mathbf{u}} \left(\sum_{i \in \mathcal{T} \setminus \{\mathcal{N}_1\}} \pi_i (x_i - x_{\text{ref}})' Q (x_i - x_{\text{ref}}) + \sum_{i \in \mathcal{T} \setminus \mathcal{S}} \pi_i u_i' R u_i \right) \quad (13a)$$

Cost function

$$\text{s.t.} \quad x_1 = x(k) \quad (13b)$$
$$x_i = A x_{\text{pre}(i)} + B_1 u_{\text{pre}(i)} + B_2 w_i, \; i \in \mathcal{T} \setminus \{\mathcal{N}_1\} \quad (13c)$$
$$y_i = C x_{\text{pre}(i)} + D_1 u_{\text{pre}(i)} + D_2 w_i, \; i \in \mathcal{T} \setminus \{\mathcal{N}_1\} \quad (13d)$$
$$x_i \in \mathcal{X}, \; y_i \in \mathcal{Y}, \; i \in \mathcal{T} \setminus \{\mathcal{N}_1\} \quad (13e)$$
$$u_i \in \mathcal{U}, \; i \in \mathcal{T} \setminus \mathcal{S} \quad (13f)$$

Constraints

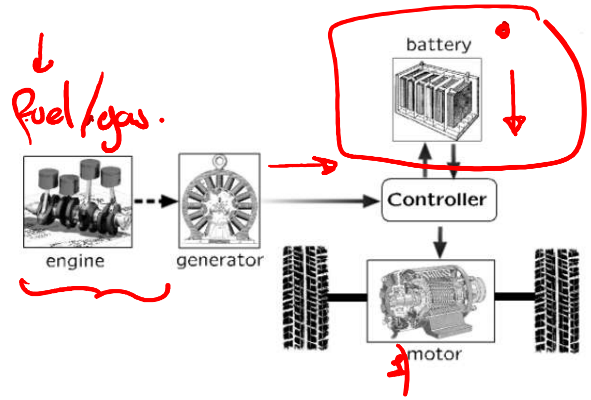
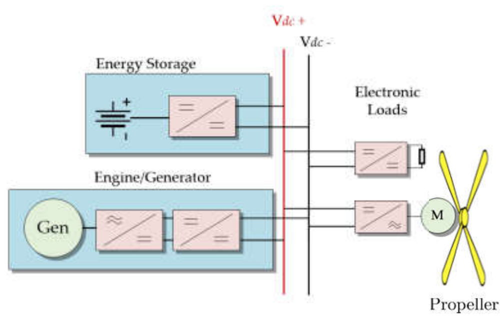
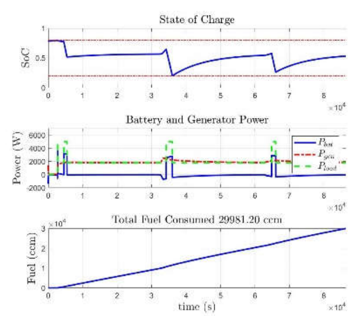


Fig. 3. Schematics of a series hybrid electric powertrain.

3. How to operate a Hybrid UAV to maximize flight time?



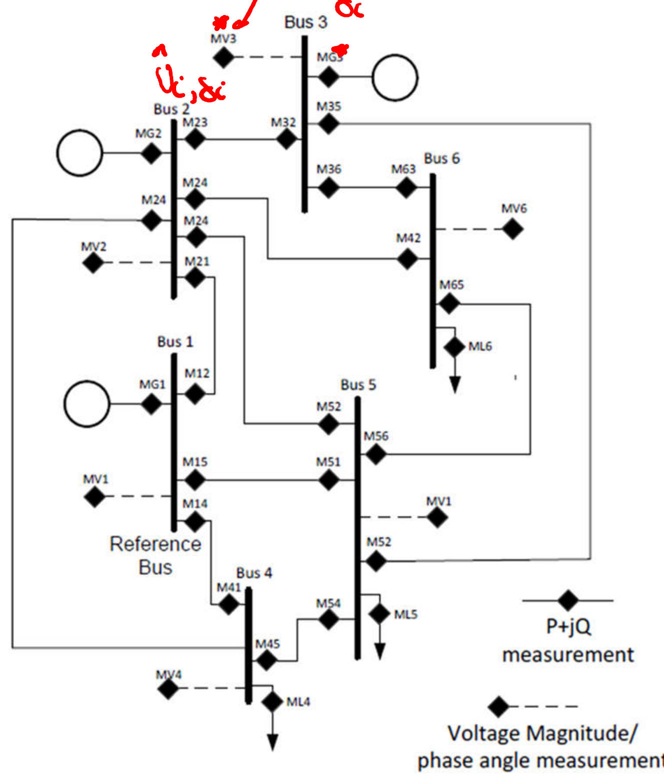


4. Many others

State Estimation Example

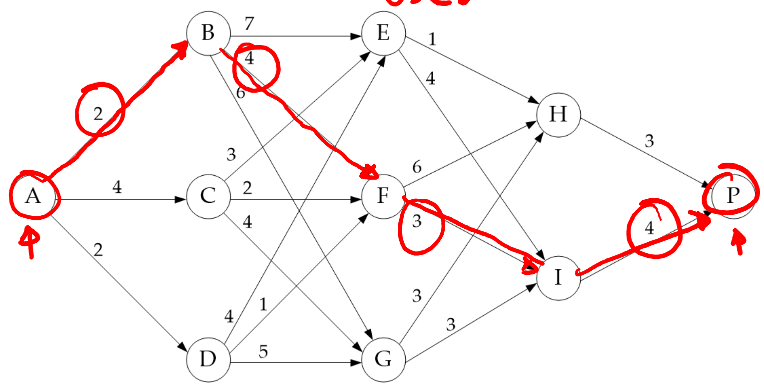
- **Why do we need measurements?** To estimate the state of the power grid in real time for both system security and verify constraints are met
  - Are any lines overloaded?
  - Are any voltages above/under limits?
- If there are any problems with the power systems, the control center can take corrective action

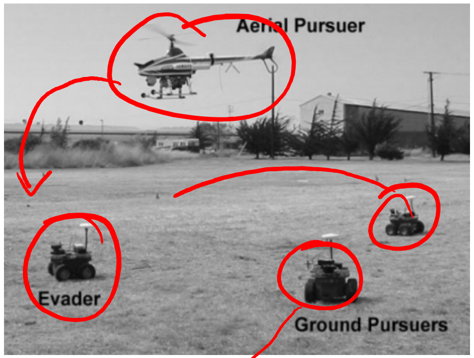
NY ISO control center



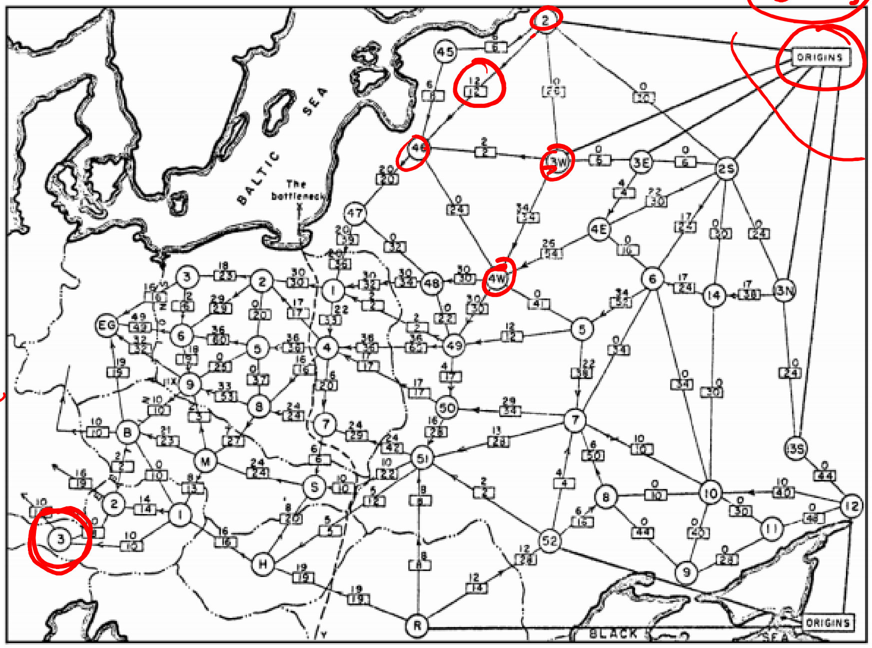
Other Applications of Optimization Theory

- Optimization techniques are used in other many areas, ranging from:
  - Artificial intelligence
  - Control theory
  - Economics
  - Geophysics
  - Chemistry
  - ….





- Example of finding the best path and maximum flow problems
  - Harris and Ross (Air Force - 1955)
  - Railway network of Western Soviet Union going to Eastern Europe
  - Maximum flow is 163k
  - Same problem can be used to solve airline scheduling, image segmentation, etc.



Tentative Topics

- **Power System Economics**
- **Economic Dispatch**
- **Unit Commitment**
- **Optimal Power Flow**
- **State Estimation**
- **Other Topics**
  - Transient analysis
  - Forecasting
- We will **focus more on the application** of **optimization theory in power systems**
- Nevertheless, there will be mathematical theory/techniques that are necessary for this course