ORF360 Decision Modeling in Business Analytics

Lecture 21: Energy Applications

Mengdi Wang

ORFE, Princeton

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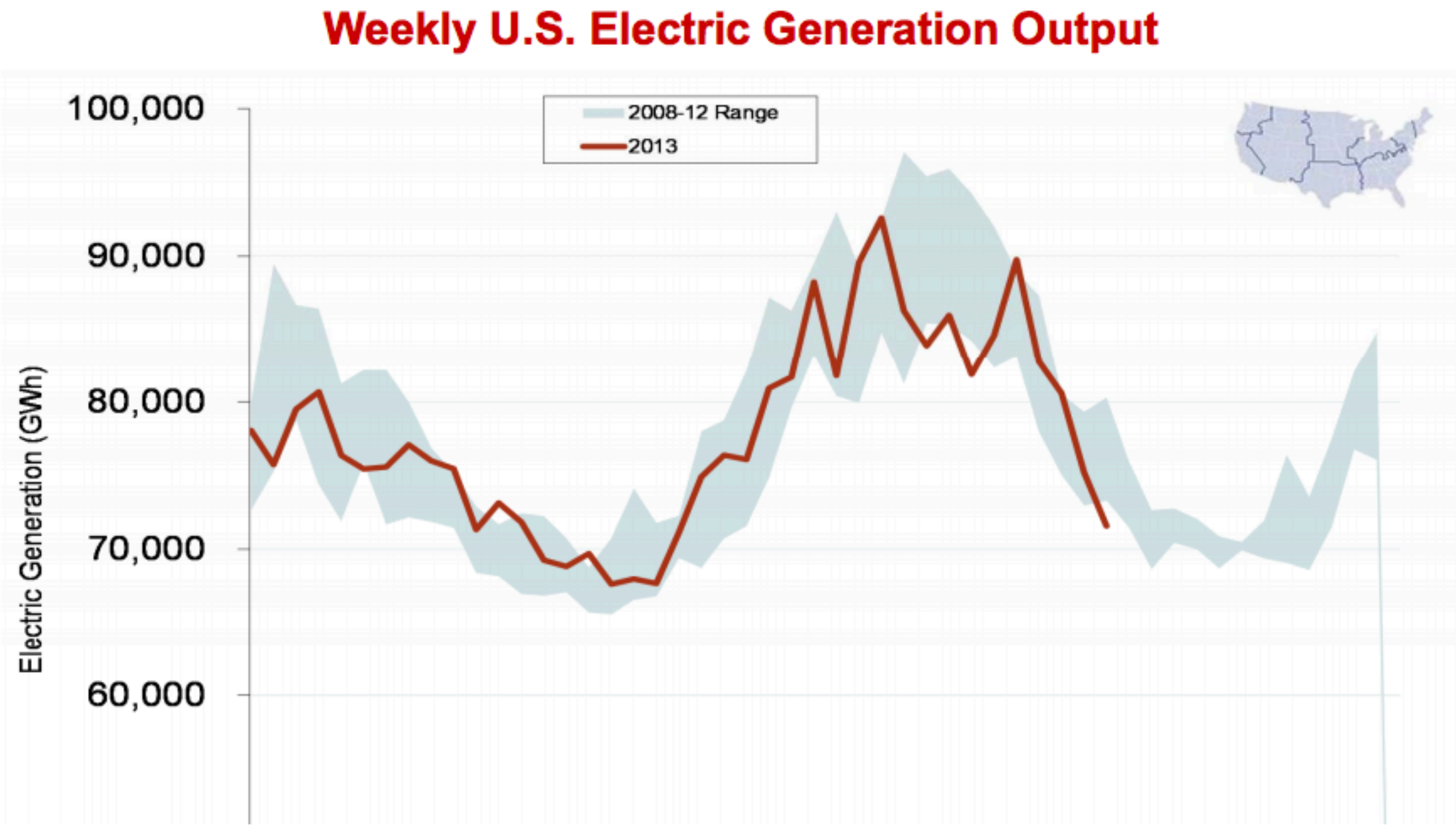
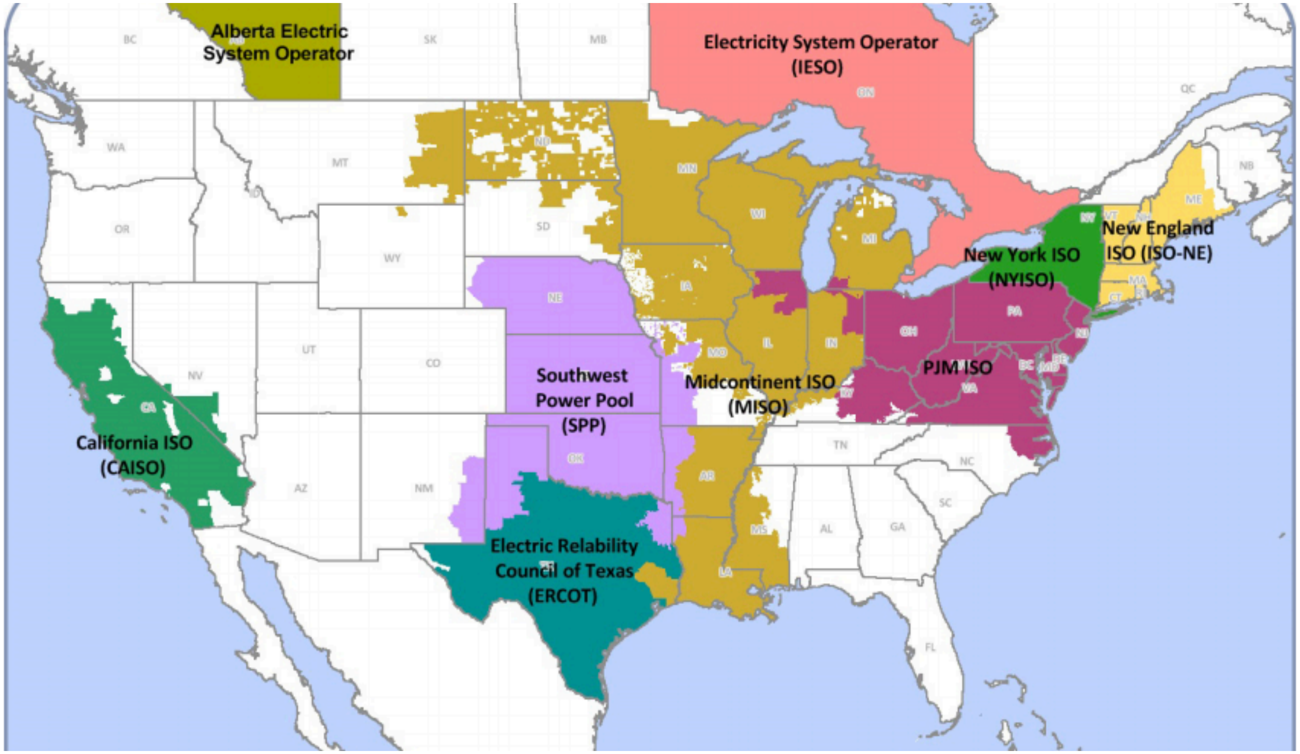
U.S. energy sources: natural gas + electricity



U.S. Electricity Market



- A regional transmission organization (RTO) in the United States is an organization that is responsible for moving electricity over large interstate areas.
- A RTO coordinates, controls and monitors an electricity transmission grid.
- Each region has its own policies on dynamic pricing, wholesale/retail, transmission, trading, etc.

Electricity Market Players

- Electricity generators - traditional generators: nuclear power stations, combined-cycle gas turbine facilities or combined heat and power plants: renewables: wind or solar farms and thermal, hydroelectric power stations. Current 'created' by these generators is then injected into the (high-voltage) transmission system or directly into (medium or low-voltage) distribution systems.
- Power exchanges - platforms used by market players to anonymously negotiate same-day or next-day purchases and sales of electricity. This provides an open market, organizes competition and establishes a transparent reference price for market participants.
- Transmission system operators (TSOs) - responsible for reliably and efficiently running high and very-high voltage transmission systems.
- Distribution system operators (DSOs) - DSOs are tasked with reliably and efficiently running medium to low-voltage distribution systems. DSOs transmit electricity to residential customers and SMEs, for example, as well as being responsible for public lighting, among other things.
- Regulators - guaranteeing transparency and competitiveness on the energy market; checking that the market operates in line with public interest and overall energy policy; defending consumers' interests;advising authorities on energy issues.
- End users - anyone from individuals to major industrial players. Industrial users are often directly connected to the high-voltage grid, whereas individual users or SMEs, for example, are connected to the distribution system.
- Market makers/prop traders/arbitragers – of course, there they are

Today

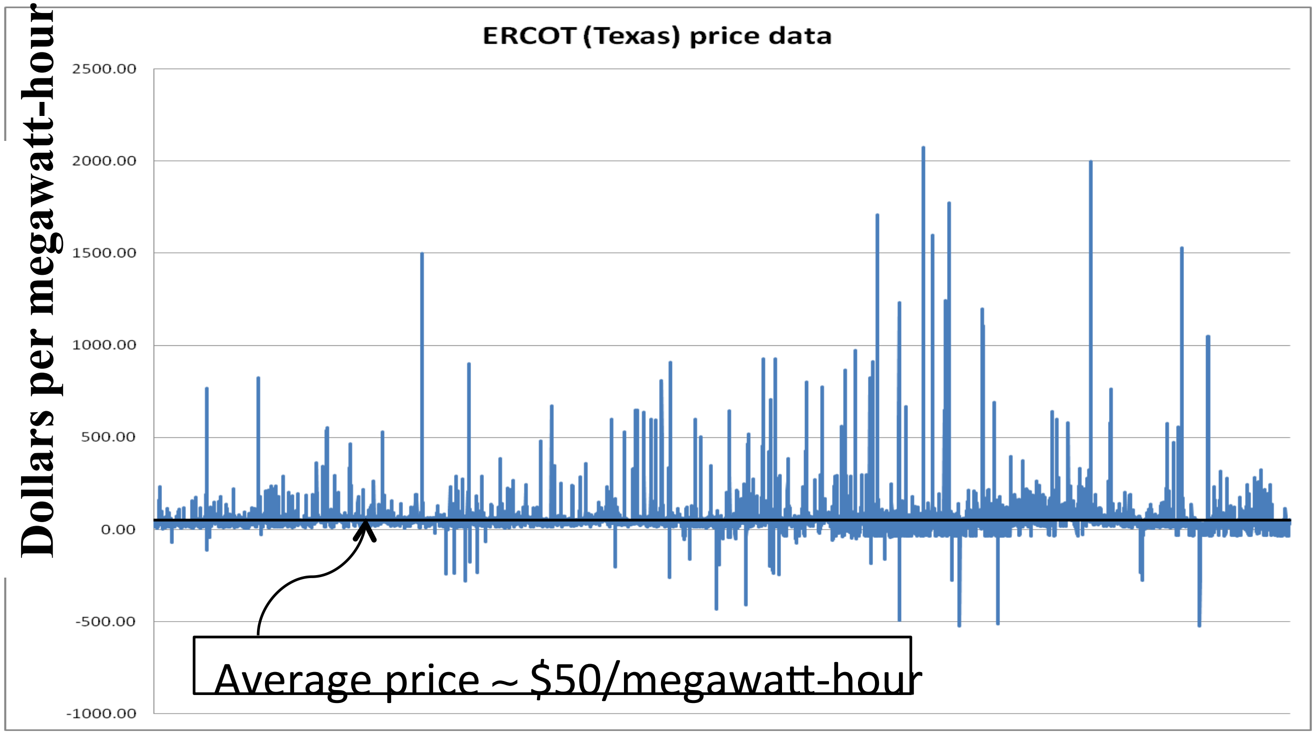
- A micro problem:

  Optimizing Energy Storage

- A macro problem:

  National Energy Planning

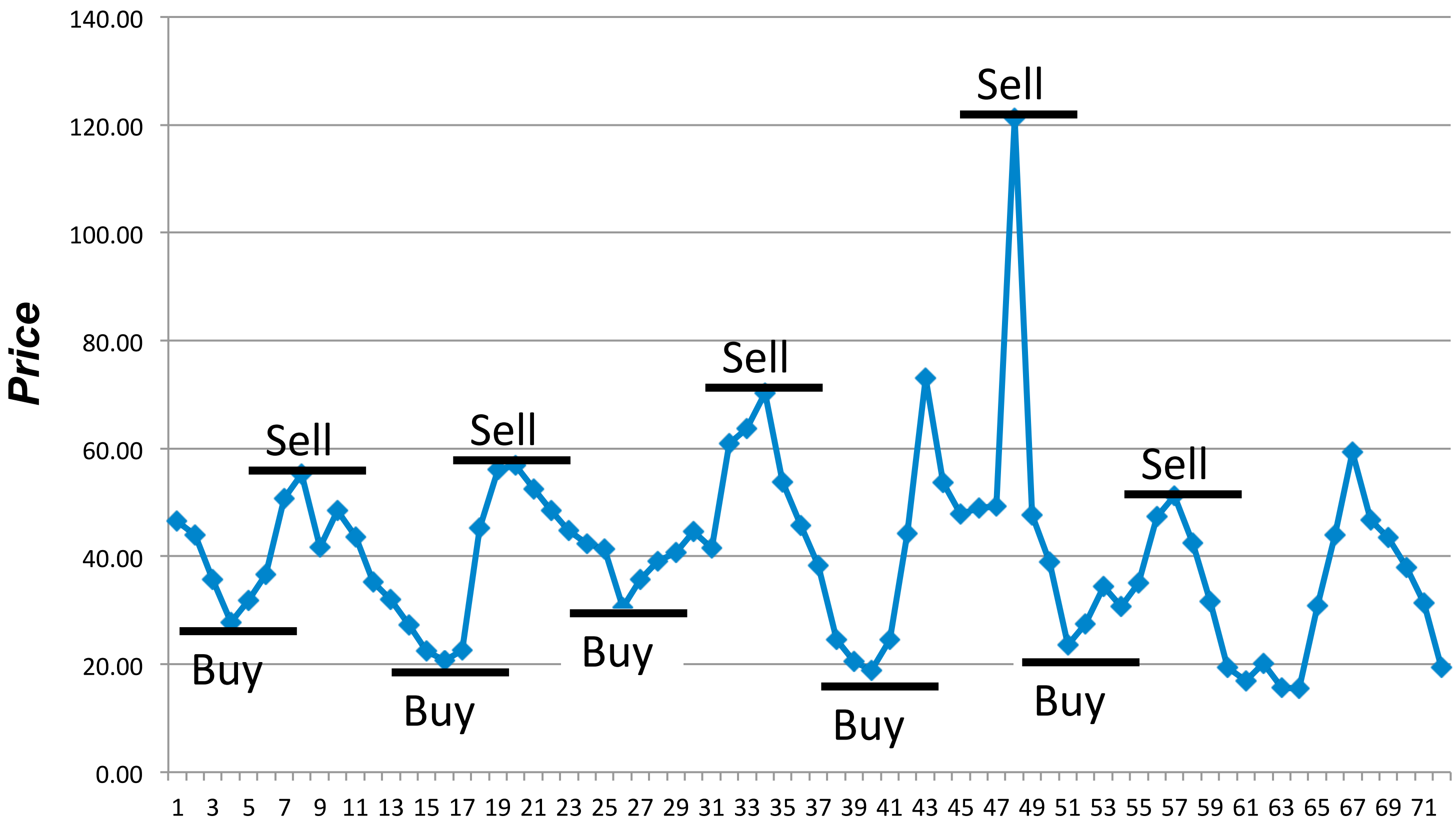
Electricity Prices



- Electricity prices are very volatile.
- Very difficult to store electricity.
- Spiky price with heavy load (hot summer, freezing winter, …)
- Average/median price fairly cheap
- Related to weather, season, time of day, etc

Battery Storage

- Suppose that you operate a battery and participate in the regional electricity market
- Challenge: find a policy for charging and discharging the battery
  - Strategy posed by the battery manufacturer: “Buy low, sell high”



How to find the best strategy?

- There are many approaches that based on DP.
- Solving DP requires full knowledge of the model:
  - how price changes?
  - how the storage impacts on future price?
  - if there is forecast, how good is the forecast?
  - what are the uncertainties and what are their distribution?
- To gain this knowledge, we could fit a time series model for the price dynamics.
- Then we formulate a DP problem and find an optimal policy of the DP problem.

DP Model

- State: price p_t, storage capacity c_t
- Action: buy $u_t = -1$, sell $u_t = 1$, do nothing $u_t = 0$
- Action constraint: if $c_{t+1} = 0$, cannot sell; if $c_t = C$, cannot buy
- State transition of storage inventory:

$$c_{t+1} = c_t - u_t$$

- State transition of electricity price (learned from data)

$$p_{t+1} = p_t + f(p_t) + \epsilon_t$$

DP Model

- The overall objective

$$\max_{\{u_t\}} \mathbb{E}\left[\sum_{t=1}^{T} u_t p_t\right]$$

- DP algorithm

$$V(p_t, c_t) = \max_{u_t}\{u_t p_t + \mathbb{E}\left[V(p_{t+1}, c_t - u_t)\right]\}$$

- Curse of big data: Formulating the DP takes a lot of work.
- Curse of dimensionality: Solving the DP takes more work.
- Any other approach?

The High-Level Math Problem

- The ultimate problem is find a function/policy/strategy

$$\mu : \{state\} \mapsto \{action\}$$

such that

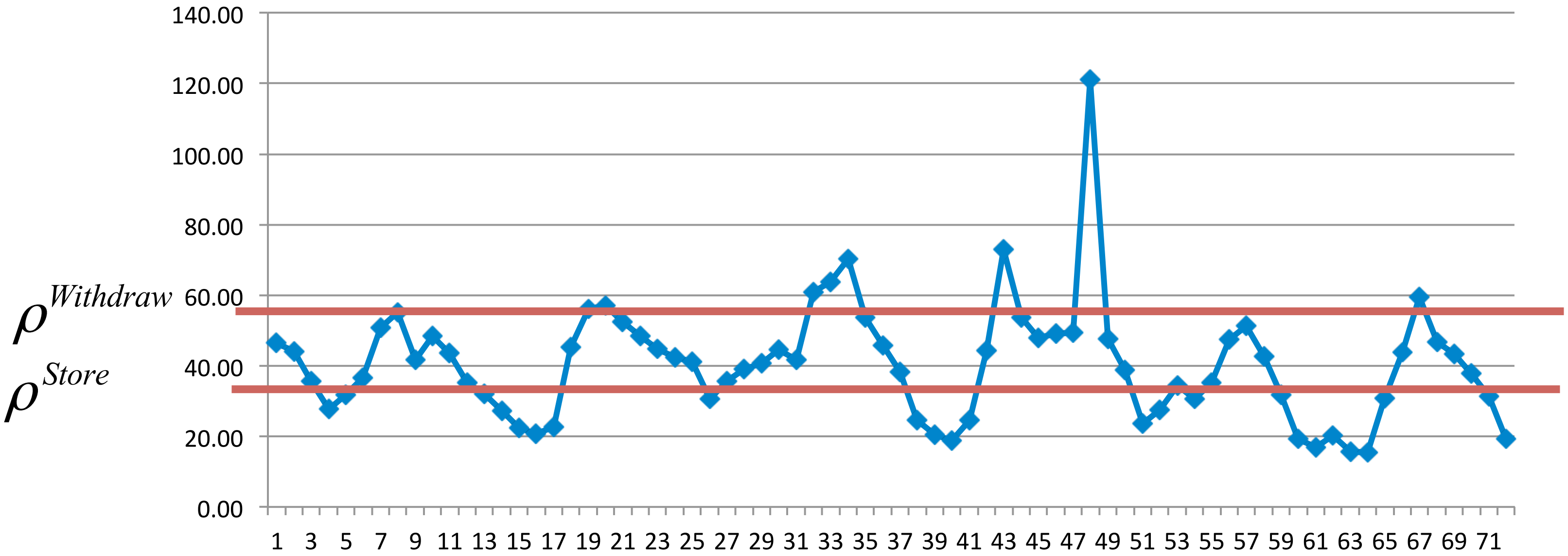
$$\max_{\mu} \mathbb{E}\left[\sum_{t=1}^{T} \mu(p_t, c_t) p_t\right]$$

subject to the state transitions as constraints

- Difficulty I: We do not know the distribution and dynamics of the time series p_t
  $\Rightarrow$ Need data-based approach
- Difficulty II: Searching over a space of functions is hard
  $\Rightarrow$ Need to narrow the search zone to simple parametric family

Optimizing A Storage Policy

- Consider a simple policy in which we choose a sell price and a buy price



Optimizing over Simple Policies

- Now let search over simple threshold policies
- The modified problem is

$$\max \mathbb{E}\left[\sum_{t=1}^{T} \mu(p_t, c_t) p_t\right]$$

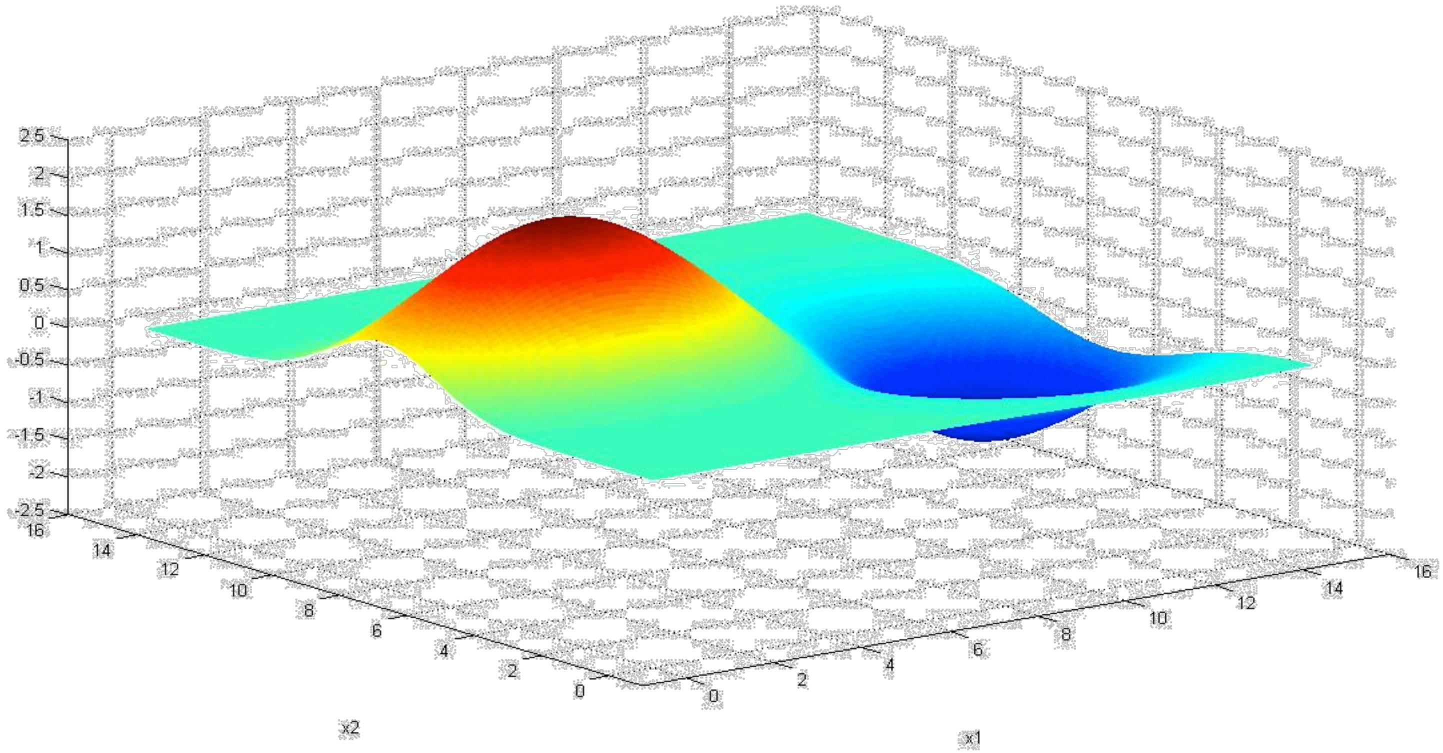
subject to

$$\mu(p,c) = \begin{cases} \text{-1} & \text{if } p < \rho^{store} \text{ and } c < C \\ 1 & \text{if } p < \rho^{withdraw} \text{ and } c > 0 \\ 0 & \text{otherwise} \end{cases}$$

as well as the state transition constraints

- We search for threshold values ρ^{store} and $\rho^{withdraw}$ by backtesting

Optimizing Storage Policy



- Average historical profit as function of the two policy parameters.
- For a given pair of (rho^store,rho^withdraw), the profit value is calculated by one simulation run on the entire price history.
- The optimal policy stands out!

Making the problem harder

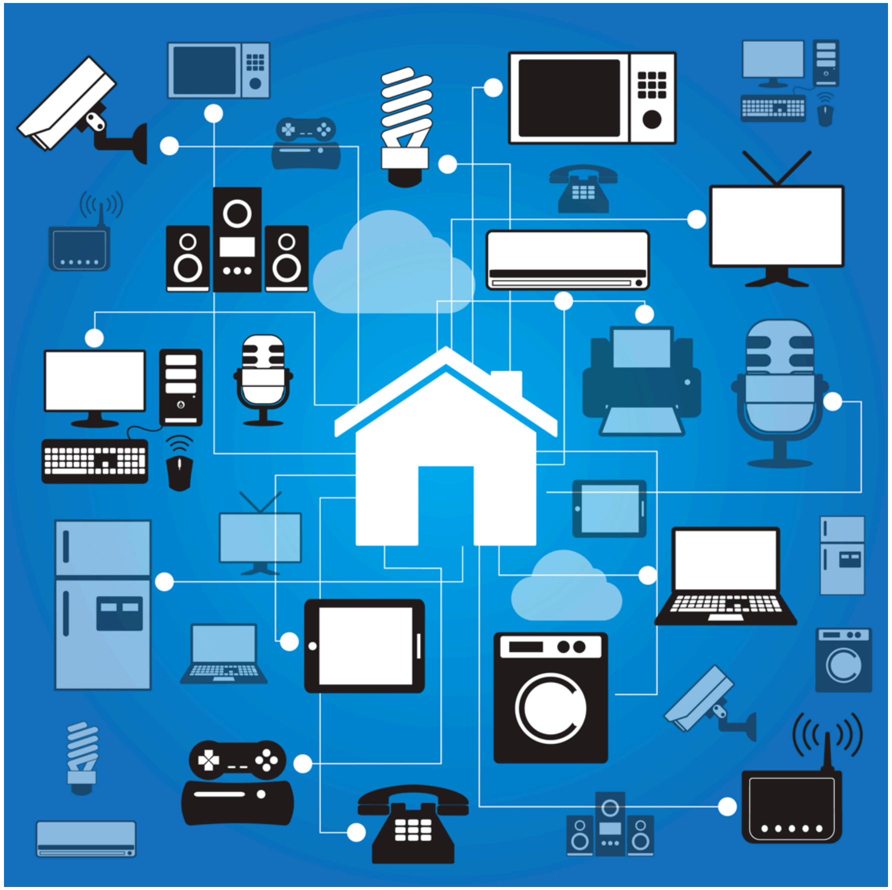
- Battery charge/discharge initial time
  - In practice, we can not turn on and off the battery or generator immediately. The battery of generator need to warm up for some time before charging/generating.
- Using forecast
  - Suppose that we have an 1-hour price forecast. We want the policy to make use of the forecast.
  - The policy could be: to charge if a weighted combination of current price and forecast price is smaller than a threshold; and to withdraw if the weight combo is greater a threshold.
  - The parameters are: two threshold prices; weights of the combination
- Any project idea?

Smart home solution

- A smart home/organization involves multiple devices and a storage battery
- Each device has its individual schedule, which may or may not be flexible

- The problem is to optimize the schedule together with energy storage
- States: fulfillment of device usages/ schedules, battery inventory level, price forecasts, …
- Decisions: to turn on and off specific device, to charge/discharge the battery
- Objective: minimize the total electricity cost while meeting all the demands

- This is a much harder problem with more decision variables and states
  – Curse of dimensionality



Today

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  National Energy Planning

Think Big

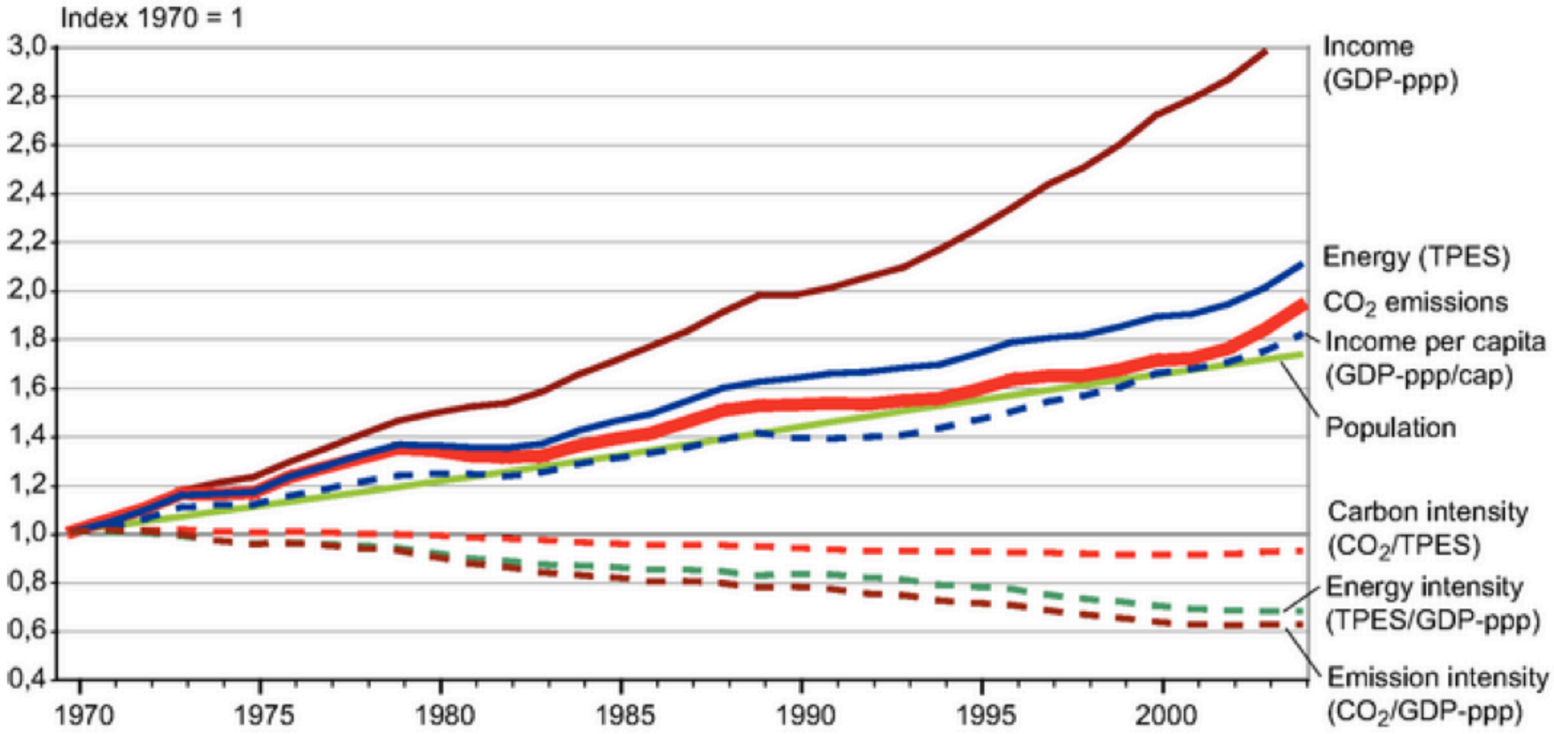
- Man wants to make energy decisions.
- Questions:
- How to evaluate the impact on climate due to carbon emission?
- How to evaluate the GDP loss/gain due to change in global climate (carbon emissions, global warning, …)
- How to evaluate the risk associated with nuclear power plant?
- How to account for future technology breakthrough?
- How to invest in energy-related research?
- How does a region/nation/global society determine the deployment of power plants?
- How to deploy power plants for alternative energy sources?

Integrated Assessment Model (IAM)

- Integrated assessment modeling is a type of scientific modeling that is increasingly common in the environmental sciences and environmental policy analysis (global warming, pollution, ...)
- Integrate knowledge from two or more domains into a single framework.
- Integrated modeling is referred to as assessment because the activity aims to generate useful information for policy making, rather than to advance knowledge for knowledge's sake.
- Integrated assessment modeling relies on the use of data analytics and numerical models (e.g., DP).

DICE Model

- DICE is a computer-based IAM developed by William Nordhaus that
  - "integrates in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allows a weighing of the costs and benefits of taking steps to slow greenhouse warming."
  - it represented the time paths of the supply of energy from various fuels and the demand for energy in different sectors of the economy and the associated emissions and atmospheric concentrations of carbon dioxide.
- It is a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long term future climate impacts from climate change



- Historical data show that almost all the gains in emissions to GDP intensity come from improvements in energy to GDP intensity (energy efficiency of GDP growth) with a very small contribution from the decarbonization of energy.. We assume that there will be no autonomous (or automatic) improvements in emissions intensity of energy.
- Only nuclear deployment and carbon mitigation (both, decision variables) cause a change in emissions intensity of energy.
- 90% of CO2 emissions are energy related, with cement, steel and some industrial processes making up the rest. **We will assume that all CO2 emissions are energy related.**

Basic Model Structure

- “Unnatural capital”—the atmospheric concentration of CO2—has a negative effect on economic output through its influence on the global average surface temperature.
- Global economic output is represented by a Cobb-Douglas production function using physical capital and labor as inputs.
- Labor is assumed to be proportional to the total global population, which grows exogenously over time.
- Total factor productivity also increases exogenously over time.
- The carbon dioxide intensity of economic production and the cost of reducing carbon dioxide emissions decrease exogenously over time.
- In each period a fraction of GDP output is lost according to a Hicks-neutral climate change damage function.
-

DICE Model

Exogenous vector parameters:

$$\begin{aligned}
l_t &= l_\infty (l_0/l_\infty)^{\exp(-d_l \Delta t)} && \text{population (B)} && (1) \\
g_t^l &= \log(l_\infty/l_0) d_l \Delta \exp(-d_l \Delta t) && \text{marginal rate of change of population} && (2) \\
a_t &= a_0 \exp\left[g_{a0}(1-\exp(-d_a \Delta t))/d_a\right] && \text{total factor productivity (tfp)} && (3) \\
g_t^a &= g_{a0} \Delta \exp(-d_a \Delta t) && \text{marginal rate of change of tfp} && (4) \\
\epsilon_t &= \epsilon_0 \exp\left[g_{\sigma 0}(1-\exp(-d_\sigma \Delta t))/d_\sigma\right] && \text{energy intensity (BTOE/T)} && (5) \\
g_t^\epsilon &= g_{\sigma 0} \Delta \exp(-d_\sigma \Delta t) && \text{marginal rate of change of energy intensity} && (6) \\
E_t^f &= E_0^f \exp(-d_f \Delta t) && \text{emissions from deforestation } (\mathrm{GtCO_2}) && (7) \\
F_t^o &= \begin{cases} F_0^o + (F_\infty^o - F_0^o)\Delta t & \Delta t \le 90 \\ F_\infty^o & \Delta t > 90 \end{cases} && \text{forcing of other greenhouse gases } (\mathrm{W/m^2}) && \\
\Psi_t &= \Psi_0 \exp(-g_b \Delta t)/\alpha && \text{cost of green energy } (\mathrm{T/GtCO_2}) && (8)
\end{aligned}$$

Basic Model Structure Continued

- The GDP output in each period is then divided between consumption, investment in the nuclear power or other green energy (savings), and expenditures on emissions reductions (akin to investment in the natural capital stock).
- Abatement Options:
  - Nuclear power: marginal cost of nuclear power is \$10/MWh (\$12.9/tCO_2) in the zero-accident case, and rising rapidly when deployment is close to 4 TW.
  - Other green energy: very low initial cost rising to \$80/tCO_2.
- DICE solves for the optimal path of savings and emissions reductions over a multi-century planning horizon, where the objective to be maximized is the discounted sum of all future utilities from consumption.
- Total utility in each period is the product of the number of individuals alive and the utility of a representative individual with average income in that period.
- Utilities in future periods are discounted at a fixed pure rate of time preference.

DP Model for Nuclear Deployment

State variables

t :	time (period index)
K_t :	capital (T)
M_t :	total CO_2 in the atmosphere (Gt)
M'_t :	CO_2 reservior 2 (Gt)
T_t :	temperature
N_t :	current nuclear capacity (TW)
$I_t \in \{0, 1, 2, > 3\}$	accidents states (discrete)

Decision variables

C_t :	consumption (T)
μ_t :	other green abatement (ratio)
n_t :	new nuclear capacity (TW)

μ_t is the ratio of current green abatement to maximum possible abatement, net of nuclear abatement.

- The optimization problem is to maximize the expected total discounted utility, where the expectation value is taken over the probability distribution of nuclear accidents

$$V_0 = \max_{(C_t,\mu_t,n_t)} \mathbb{E}[\sum_{t=0}^{\infty} e^{-rt} \Delta l_t (C_t/l_t)^{(1-\gamma)}/(1-\gamma)] = \max_{(C_t,\mu_t,n_t)} \mathbb{E}[\sum_{t=0}^{\infty} e^{-rt} \Delta l_t U_t]$$

DP Model: State Transitions

Equations of state:

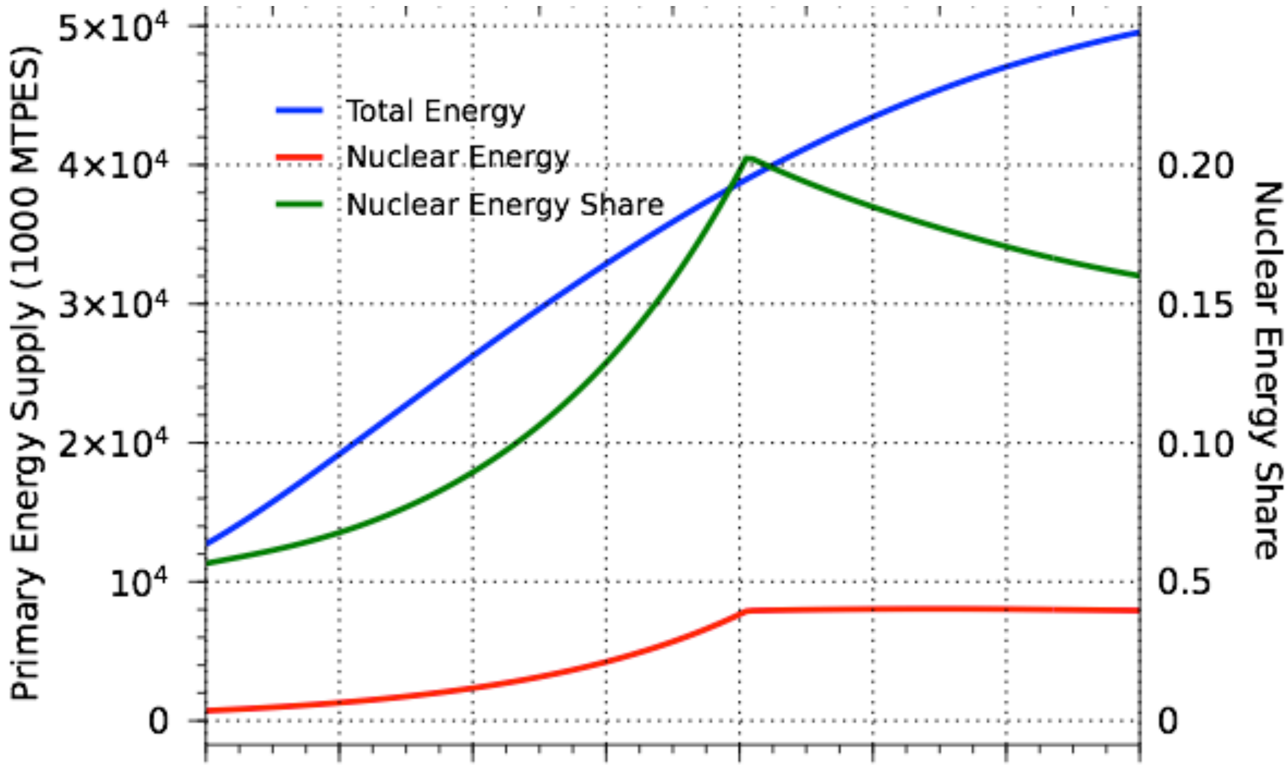
$$K_{t+1} = (1-\delta_K)^{\Delta} K_t + \Delta(Y_t - C_t) \tag{17}$$
$$M'_{t+1} = e^{-\Delta/\tau 2} M'_t + b\Delta E_t \tag{18}$$
$$M_{t+1} = e^{-\Delta/\tau 1} M_t + (e^{-\Delta/\tau 2} - e^{-\Delta/\tau 1}) M'_t + \Delta E_t \tag{19}$$
$$T_{t+1} = e^{-\Delta/\tau} T_t + (b'\Delta/\tau') F_t \tag{20}$$
$$N_{t+1} = (1+\Delta n_t) N_t - \delta_N (I_t - I_{t-1}) N_t \tag{21}$$
$$I_{t+1} = P(I_t, N_t, \omega^I_t, \Delta) \qquad \text{non-homogeneous Poisson process} \tag{22}$$

Summary of system state transitions:

- The GDP grows at a higher rate with more energy resources
- Deploying new power plants or other green energy generators consume the GDP.
- Accidents are modeled using i.i.d. exponential distribution where accidents happen at a constant rate of λ per reactor.
- A nuclear accident causes a severe shock to the system permanently reducing GDP by a factor of 0.5%.

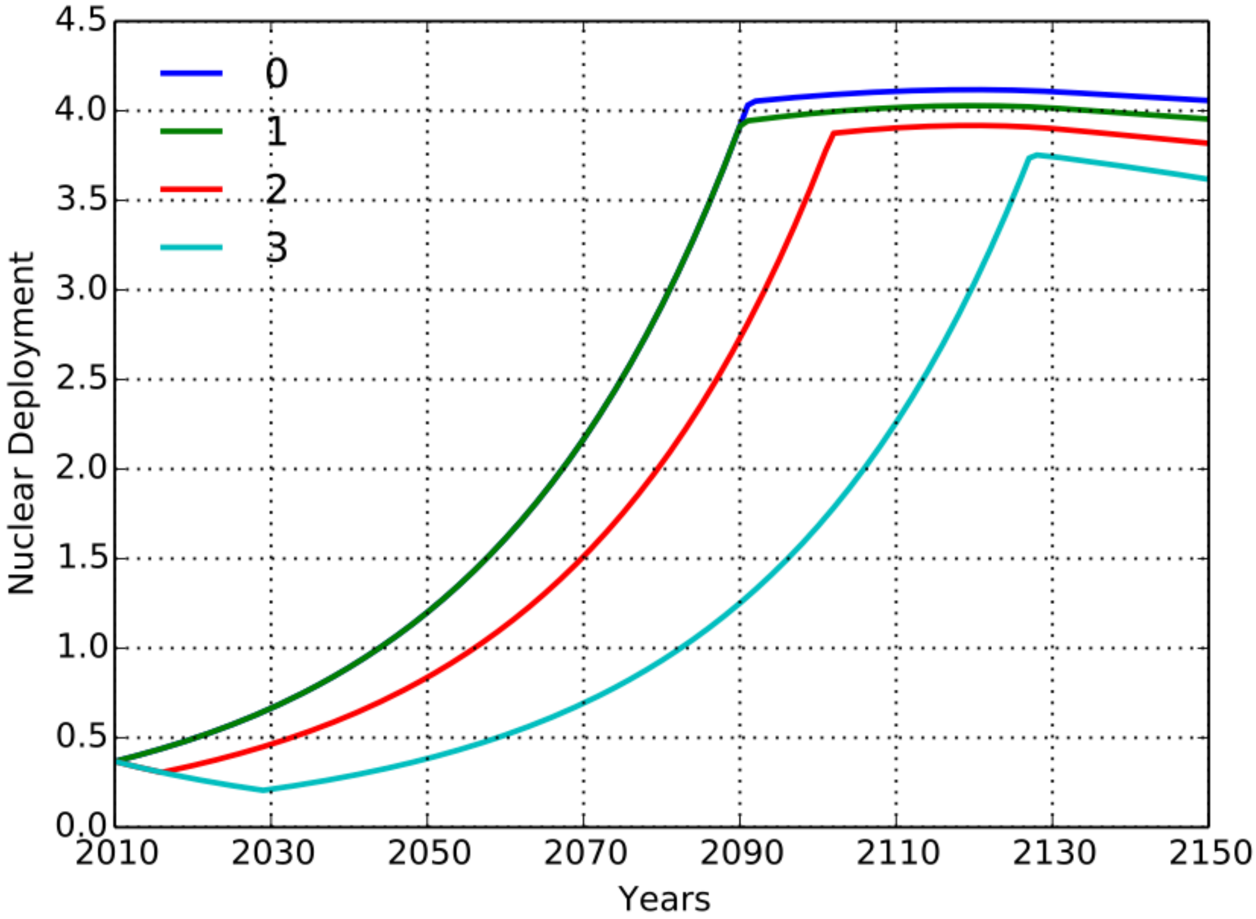
- Details omitted

Solving the DICE using DP

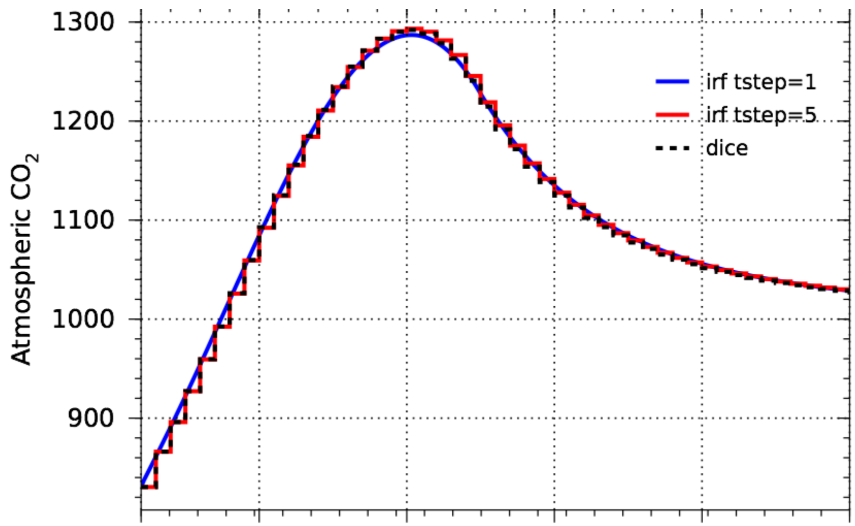


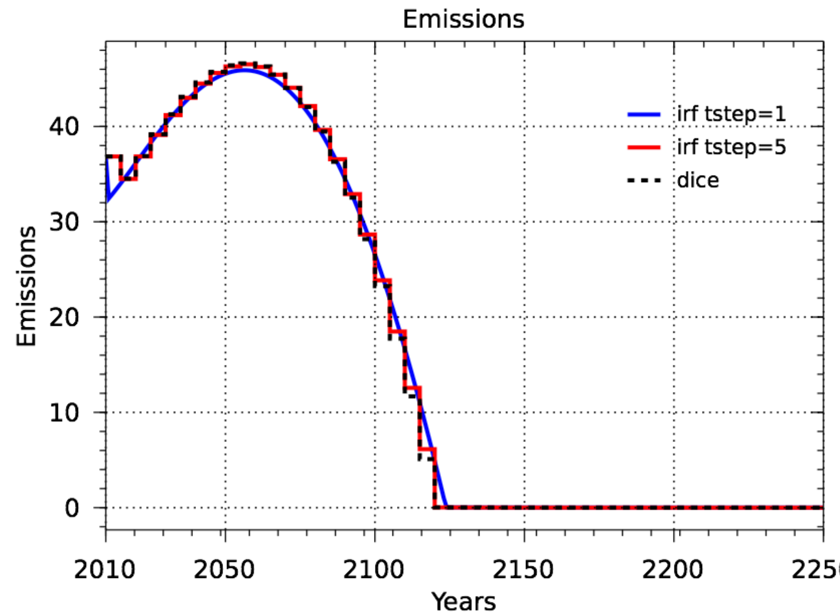
- Relative growth of nuclear and non-nuclear energy supply in NDICE.

Nuclear deployment policy



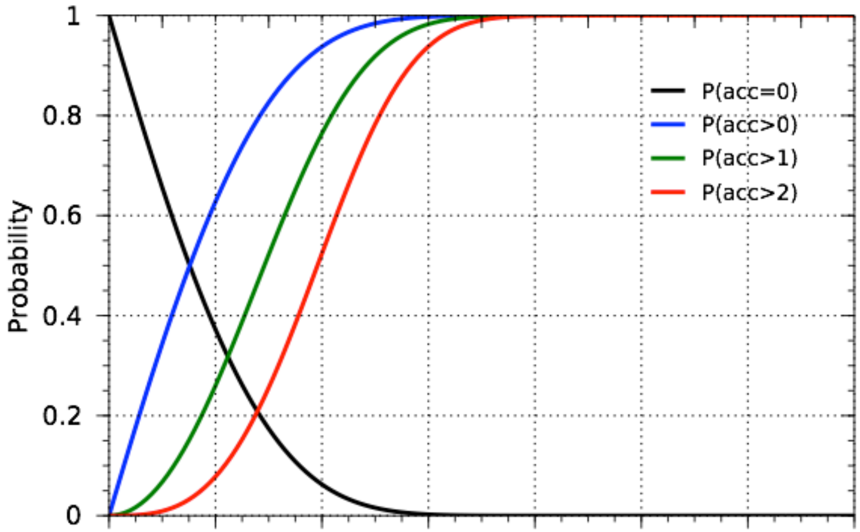
Look into the future:Atmospheric CO2

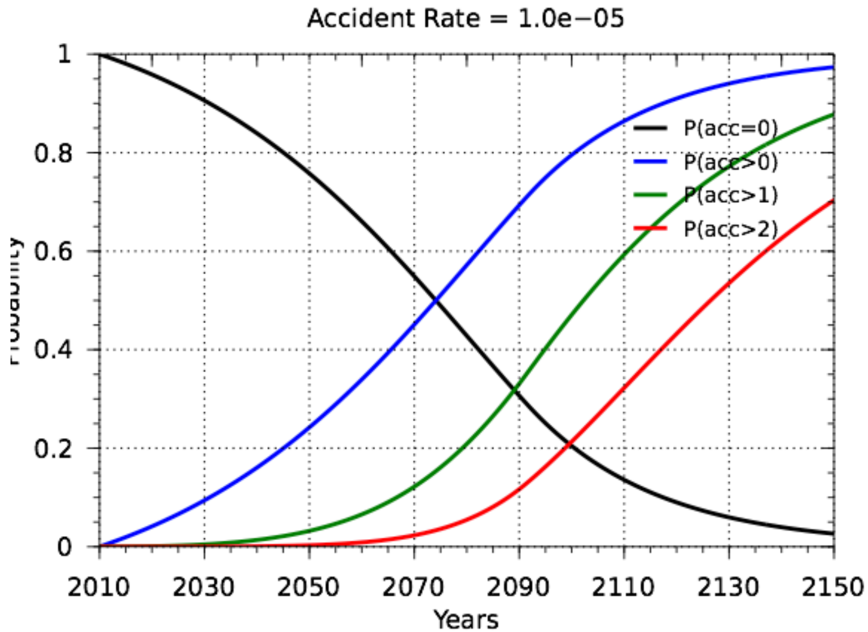




- By optimally deploying alternative power plants, we can achieve CO2 sufficient abatement.
- CO2 concentration will get worse in the next 50 years.
- It will be reduced and maintained it at a reasonable level in 100+ years.

Risk concerns





- Accident risk as a function of time: The curves show the probability of the occurrence of 0, ≥ 1, ≥ 2, ≥ 3 accidents for time starting at year 2010.
- Accident unavoidable.
- Very sensitive to the accident rate assumption.

Discussions

- Risk in dynamic programming
  - DP provides a modeling and computational solution to sequential decision making problems that aim to maximize expected objectives
  - Systematic risk is not accounted in expected return over the future
- Risk-averse dynamic programming
  - Model uncertainty in exogenous variables and exogenous probability distributions
  - Introduce uncertainty set

Between the big and the small

- Unit commitment problem
  - How do (backup) electricity generators determine their on-and-off schedule
- How to trade electricity and other energy commodities?
  - Data analysts have detected a conditional positive correlation between the Manhattan temperature and the U.S. energy market
- How to insure against sudden energy loss?
- How to design and control smart grid?
- A prospering area with many interesting problems. Help needed in understanding data and optimizing decisions!