Technology Paths Through the Energy Transition: How not to Get Stuck

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Outline

1. Motivation and Research Questions
2. How we will Answer
3. Case Study: Results and Insights
4. Conclusion and Future Work

Motivation

- US has stated goal of transitioning from ***carbon-emitting*** to ***carbon-free*** electricity generation by 2035
  - Realistically, this is likely to be modified in about 55 days
  - How to manage the energy transition will remain an important question
- A primary method used to incentivize the energy transition is credits for generating carbon-free energy (RECs)
  - Firms can voluntarily buy credits to offset their carbon emissions
  - Firms can be compelled to do so

Research Questions

1. How do such credits affect the energy transition?

2. What sort of *paths* are *likely* to be traced under different REC prices?

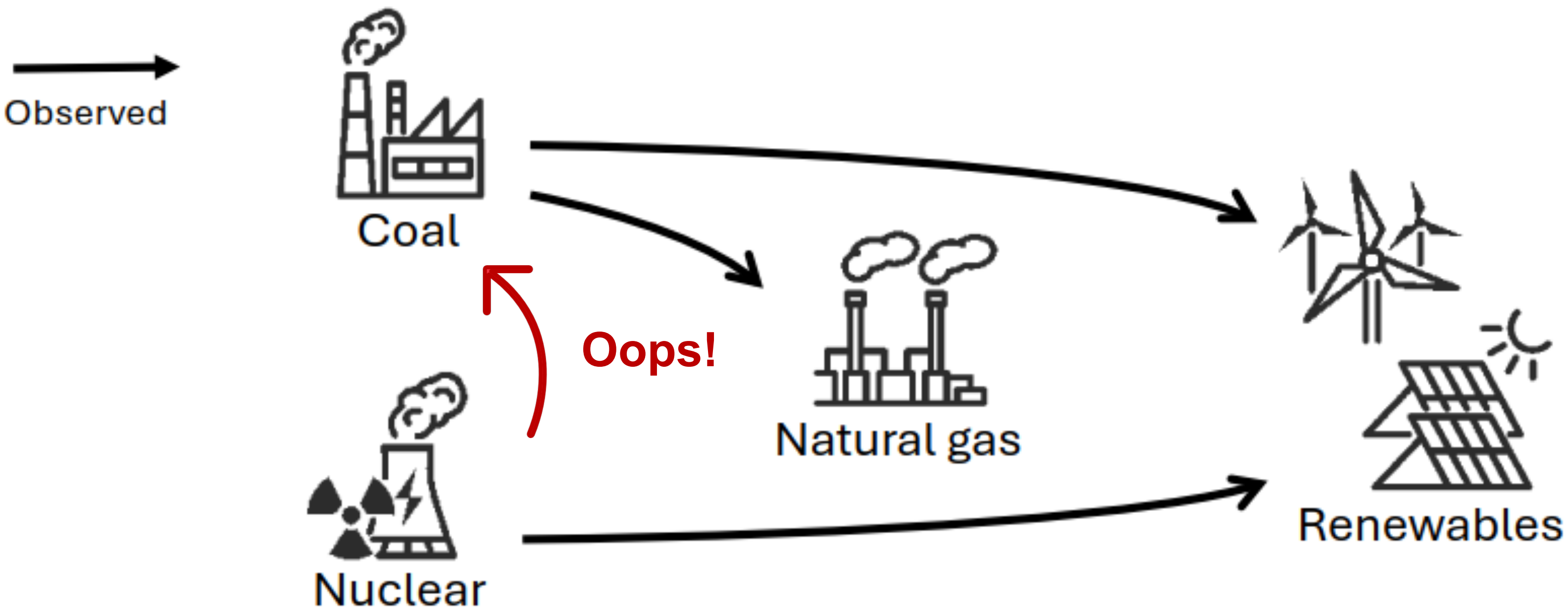
Paths: We need to consider multiple technology transitions, not just the first one!

- Research (and arguably policy) seems to by somewhat myopic

Likely: There is all sorts of uncertainty in the system!

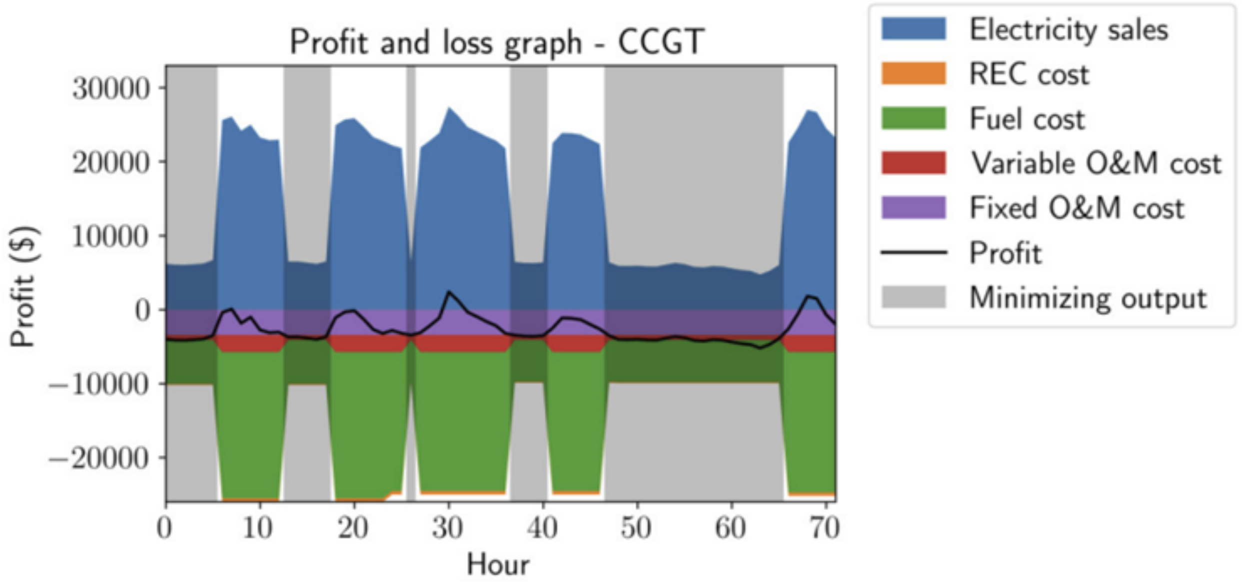
- Prices of fuel, electricity, RECs
- Macro-effects, weather
- Correlations!

Pictorially

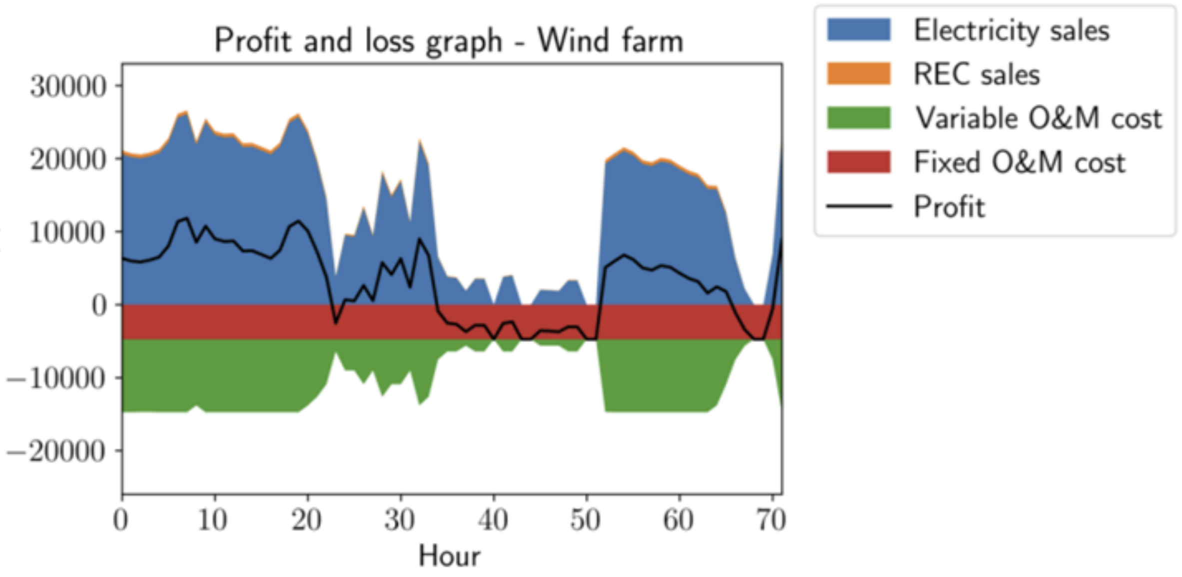


What Makes this Question Complicated?

Simulated profit functions over 72-hour period:



(a) Combined cycle gas turbine hourly profits and losses.



(b) Wind farm hourly profits and losses.

How will we Answer

1. Bi-level Model
2. Markov Decision Process
3. Analytical Results
4. Fitting Empirical Data
5. Finding Other Supporting Data
6. Case Study

Bi-Level Model

- We consider a single power plant in competitive market (ERCOT)
- Bi-level model
  - Upper (Strategic) Level -- N periods
    - Possible Actions: Operate, Mothball, Activate, Renew, Upgrade, Switch, Decommission, Commission
  - Lower (Operational) Level -- T periods for each N
    - Fixed price and generation each (short) period
    - Possible Actions: Choose amount to produce (if *dispatchable*)

WHY?

We need to capture detailed operational costs of different plant features to accurately evaluate strategic options

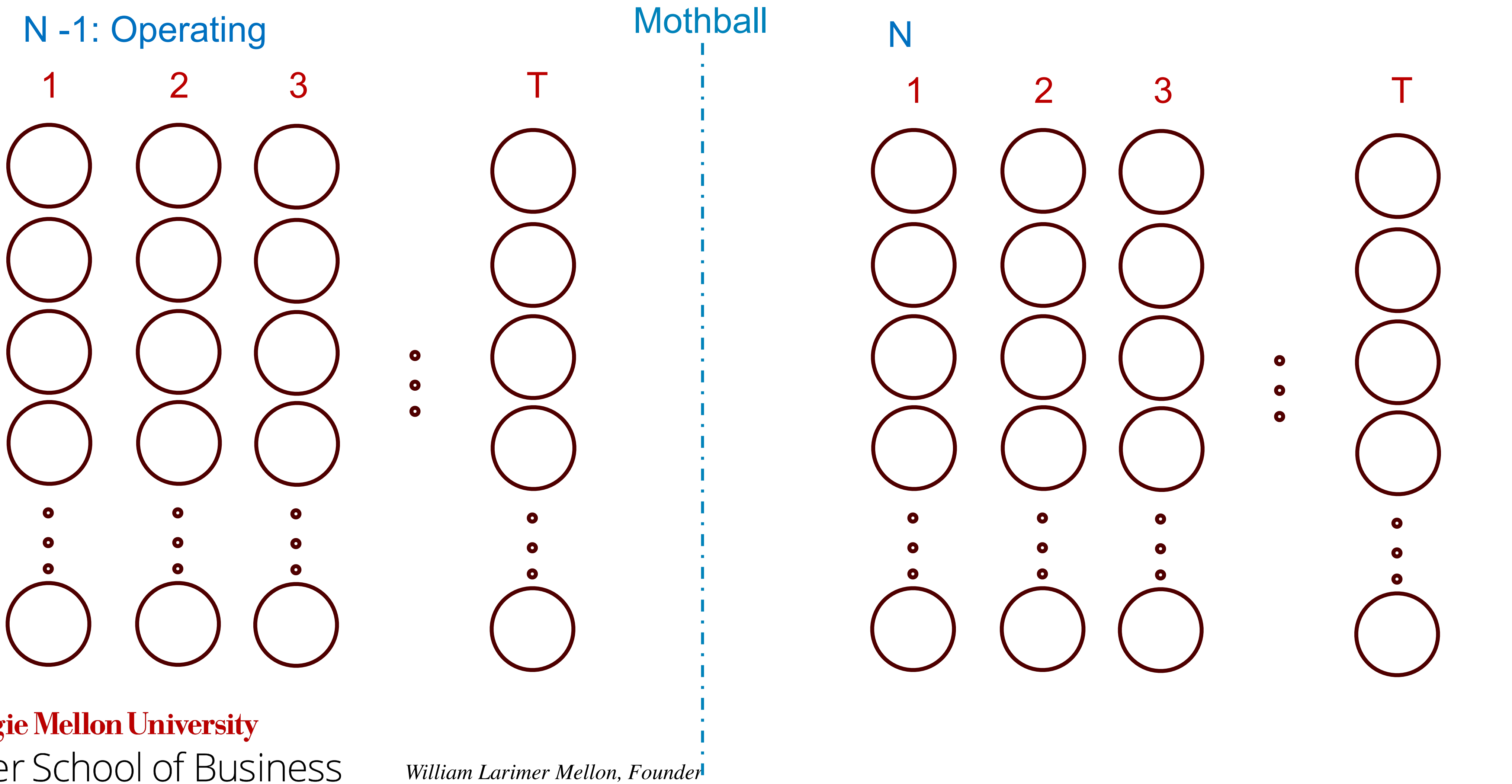
Markov Decision Process

- World is in a given "State"
  - State contains **all** the information we need to make decisions
- Make decision (to maximize expected total profit)
  - Earn random rewards
  - System transitions to next random state
- Optimal action balance immediate reward plus expected future rewards
- Can become intractable quickly, but efficient solvers exist

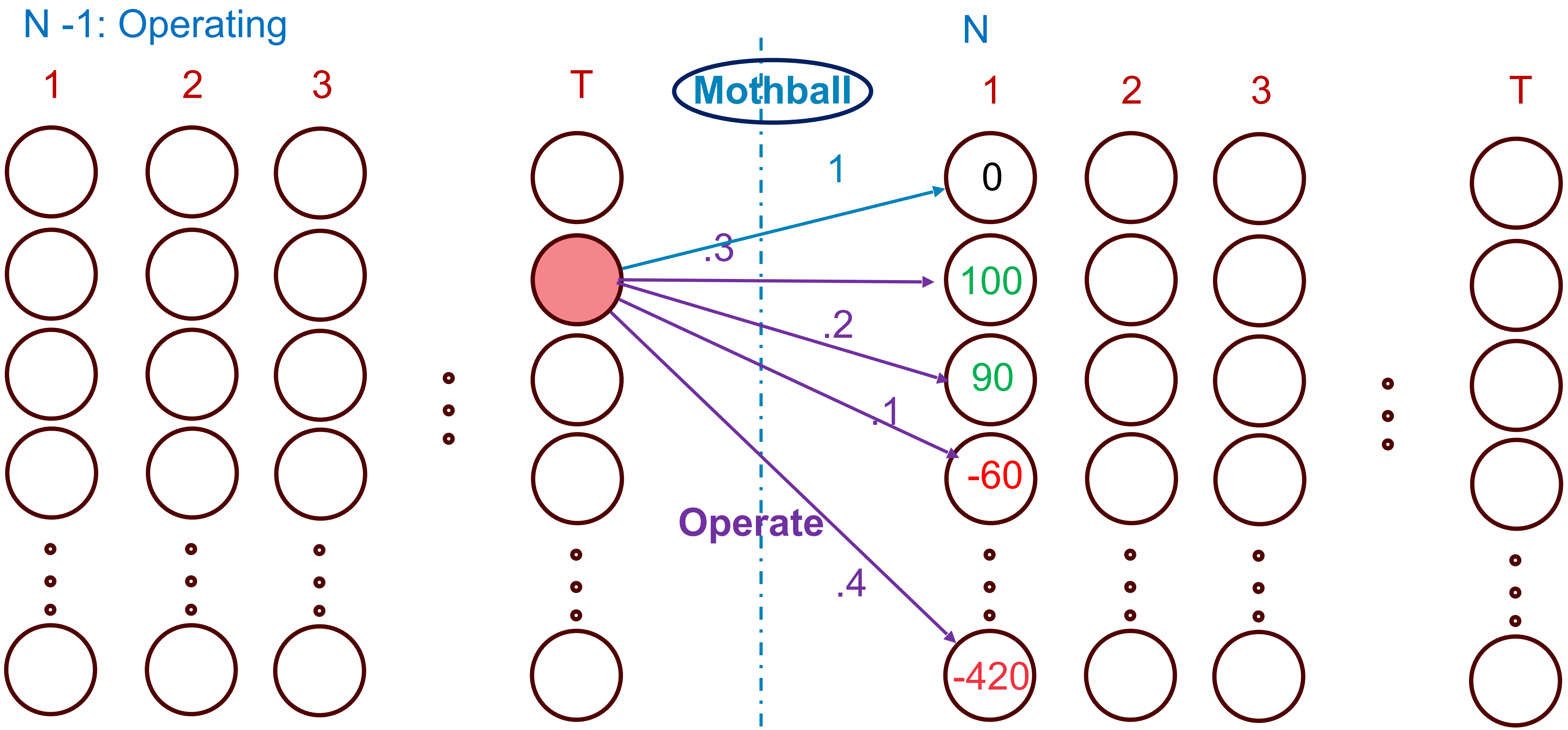
WHY?

We need to make decisions weighing current rewards and uncertain future rewards, factoring in uncertainty

Markov Decision Process



Solving Markov Decision Process



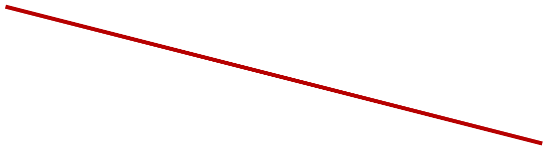
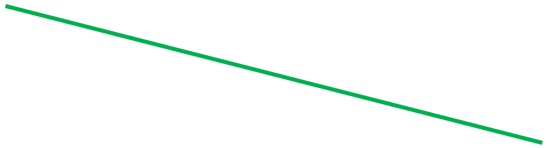
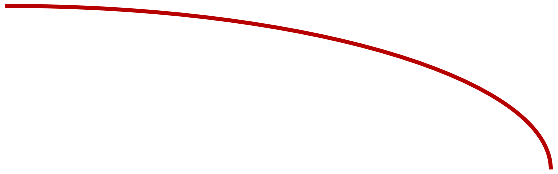
Analytical Results

We are interested in technology paths as a function of REC price policy

Hey Ragnar, you should be able to show that there is a threshold policy: For any two technologies we move from one to the other at a single REC price!

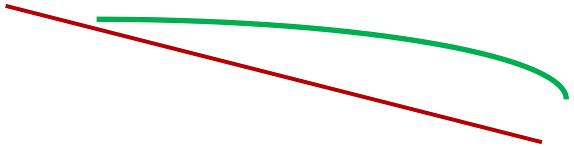
Analytical Results

1. There are four types of profit curves versus REC price

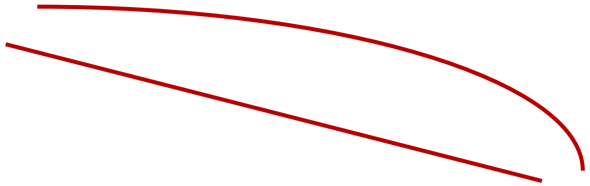
	Carbon-emitting	**Carbon-free**
Non-dispatchable		
Dispatchable		

Analytical Results

2. So a carbon-emitting would cross a carbon-free once

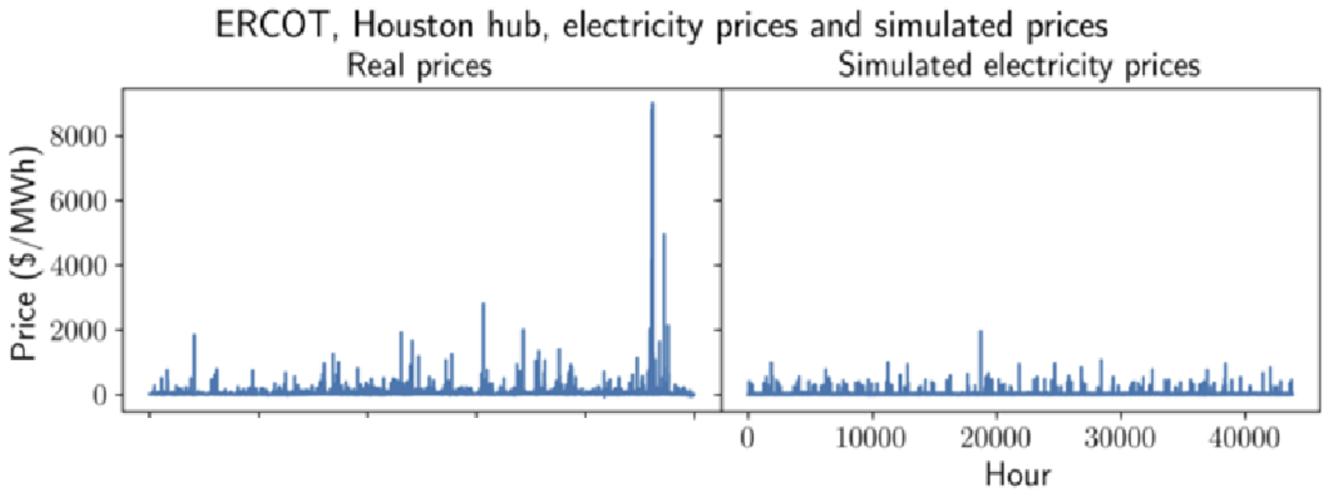


3. But two curves of the same type…

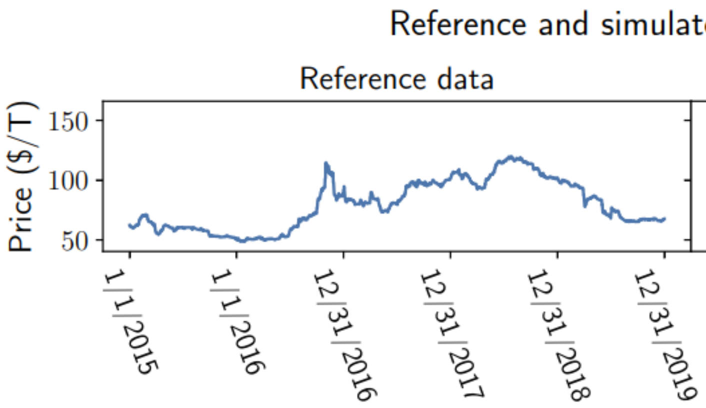


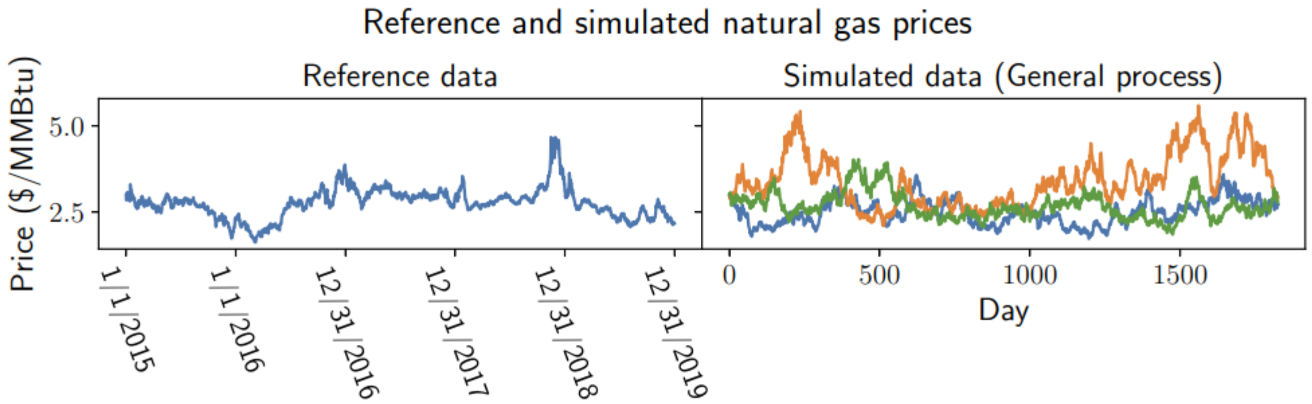
Fitting Empirical Data

- We *need* transition probabilities for our MDP
  - This means we must transform empirical data into probability distributions
  - This turns out to be quite difficult!
  - But Ragnar managed…

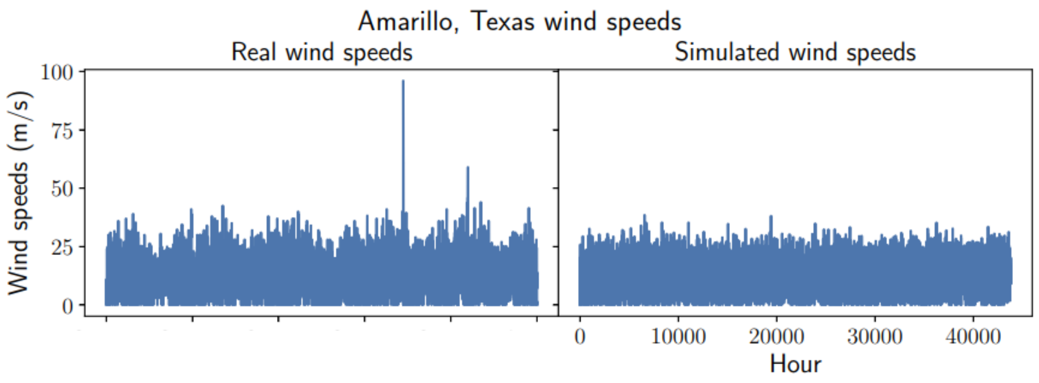


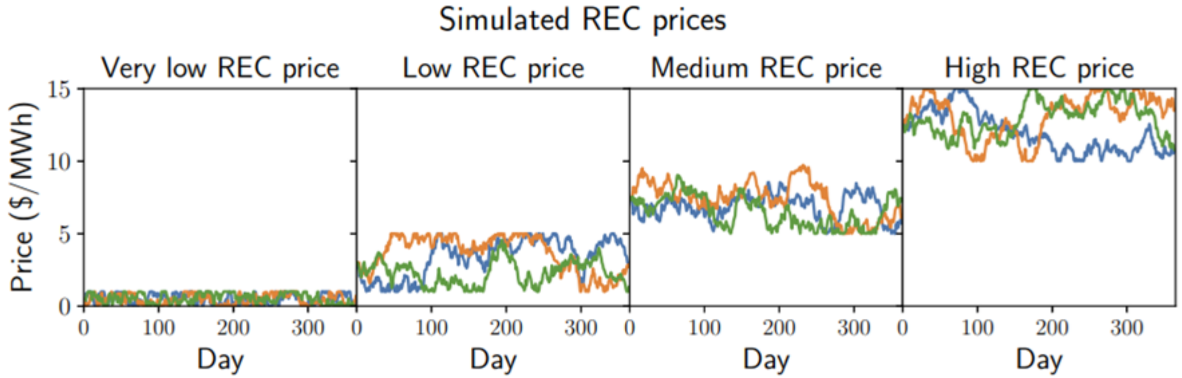
Coal and Natural Gas





Wind Speed and REC Prices





Supporting Data: Power Plants

Table 5.1: Power plant parameters

	CCGT	Coal-fired plant	Nuclear plant	Wind farm
Energy source	Gas	Coal	Uranium	Wind
Lifetime (years)[a]	30	40	60	25
Commissioning cost ($)[b]	1,000,000,000	2,100,000,000	5,000,000,000	1,390,000,000
Decommissioning cost ($)*	100,000,000	210,000,000	500,000,000	139,000,000
Renewal cost ($)*	300,000,000	630,000,000	1,500,000,000	417,000,000
Commissioning time (years)[c]	4	4	4	2
Renewal time (years)[†]	2	2	2	1
Fixed O&M cost ($)[a]	3,424.66	4,794.52	17,123.29	4,760.27
Variable O&M cost[a]	0.36 $/MMBtu	9.68 $/T	35,898.91 $/lb	10.00 $/MWh
MWh per unit[e,f]	0.156 MWh/MMBtu	2.715 MWh/T	1,196.630 MWh/lb	-
Minimal fuel usage[g]	1,929.00 MMBtu	147.33 T	0.42 lb	-
Maximal fuel usage[g]	6,430.00 MMBtu	368.33 T	0.84 lb	-
Efficiency loss (%/year)[h,i]	0.0	0.0	0.0	1.6
Mothball initiation cost ($)[j]	2,500,000	5,250,000	12,500,000	-
Mothball end cost ($)[j]	10,000,000	21,000,000	50,000,000	-
Mothball continuation cost ($)[j]	500,000	1,050,000	2,500,000	-

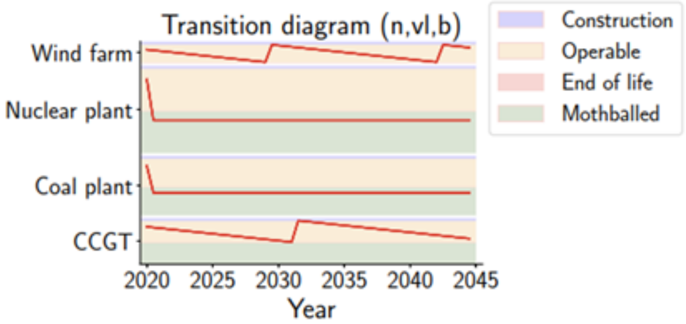
Sources: [a]Trinomics (2020), [b]International Energy Agency (2020), *these costs are set to fractions of the commissioning cost, [†]is set to 50% of the commissioning time, [c]International Energy Agency (2019), [d]Rand et al. (2022), [e]for the heat rate for the CCGT and coal-fired plant see Abadie (2015), [f]for the heat rate of a nuclear plant (2020 data) see U.S. Energy Information Administration (2024), [g]Sustainable Nuclear Energy Technology Platform (2024), [h]for the efficiency loss per year of a CCGT, coal-fired plant, and nuclear plant see Grubert (2020), [i]for the efficiency loss per year of a wind turbine see Staffell and Green (2014), [i]Sustainable Nuclear Energy Technology Platform (2024), [‡]determined from nameplate capacity, and [j]TenneT (2019).

Table 5.3: Non-immediate (no.) and immediate (im.) switching costs for power plants. The starting power plant is given on each row and the target power plant in each column.

		CCGT	Coal plant	Nuclear plant	Wind farm
CCGT	no. ($\cdot 10^6$ \$)	300 (2)	1,540 (2)	3,647 (2)	1,490 (2)
	im. ($\cdot 10^6$ \$)		1,050 (0)		
Coal plant	no. ($\cdot 10^6$ \$)	847 (2)	630 (2)	3,570 (2)	1,600 (2)
	im. ($\cdot 10^6$ \$)	500 (0)			
Nuclear plant	no. ($\cdot 10^6$ \$)	1,820 (2)	1,050 (2)	1,500 (2)	1,890 (2)
	im. ($\cdot 10^6$ \$)				
Wind farm	no. ($\cdot 10^6$ \$)	1,139 (4)	2,239 (4)	5,139 (4)	417 (1)
	im. ($\cdot 10^6$ \$)				

Case Study: ERCOT Baseline

- Baseline electricity price, very-low REC price, no transitions



Matches current situation well

- Baseline electricity price, very-low REC price, plant transitions allowed

Case Study: Increased Electricity Price

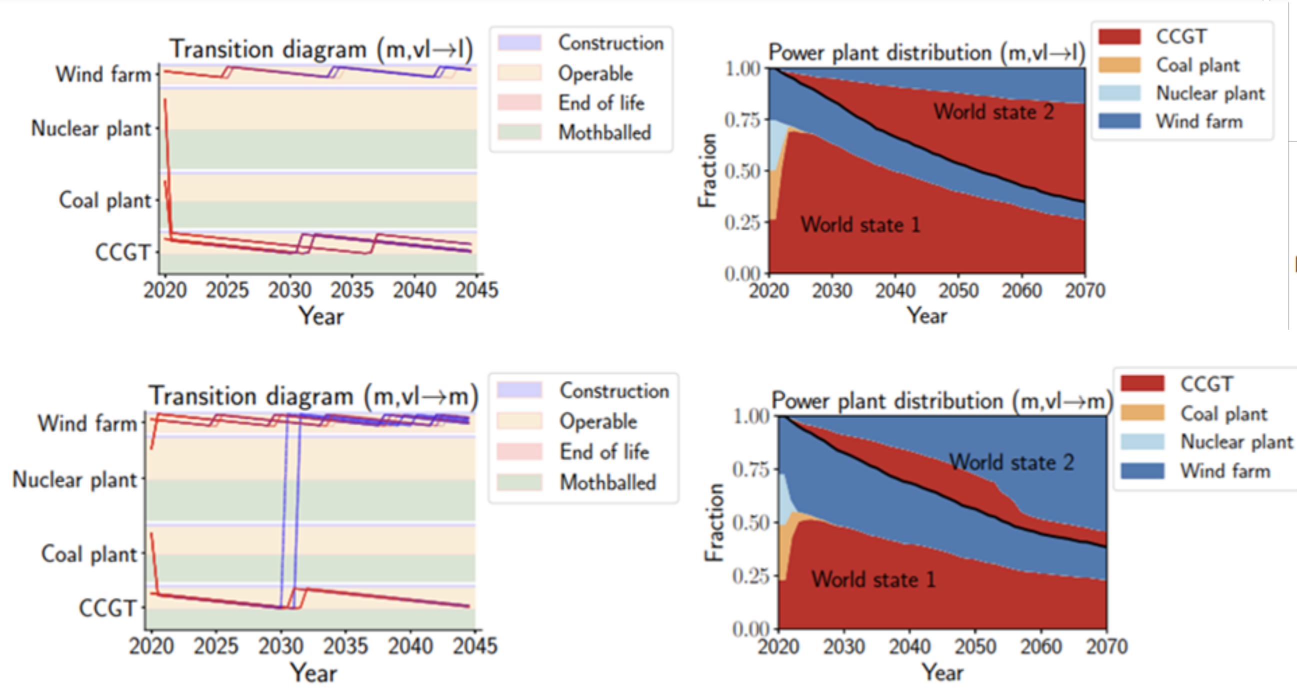
- Increased electricity price, different REC prices, plant transitions

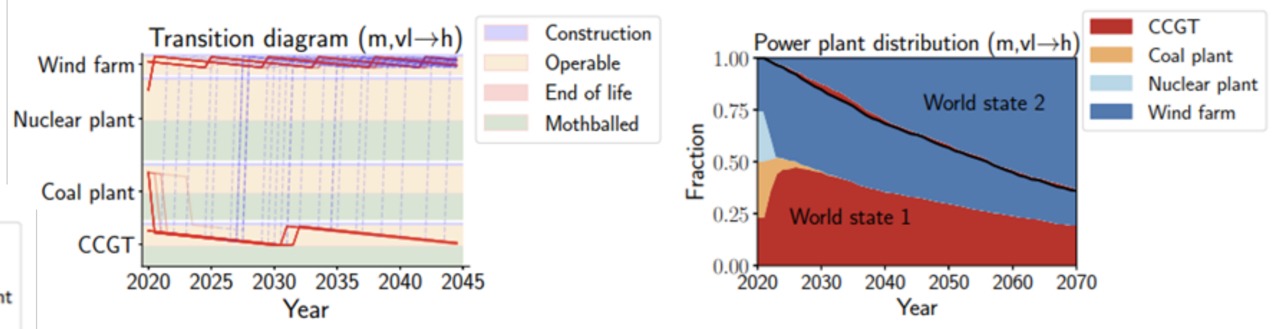
Technology Trapping

Temporal Trapping

Case Study: REC Transitions

- Increased electricity price, REC price transitions, plant transitions





(e) Transition diagram.

(f) Distribution diagram.

Insights (I)

- **Technology Trapping** is a real concern
  - CCGT may be a *bridge to nowhere*
  - Imposing higher REC prices sooner can mitigate this
    - Caution: Is this feasible? Is it a good idea?
  - Future experiments:
    - Test what role REC price certainty will play
    - Test what different REC transition matrices induce

Insights (II)

- **Temporal Trapping** can delay the technology transition
  - This might not always be a bad thing!
    - People are retiring plants early…
    - Is *wasting* useful lifetime sustainable?
  - Incentives to facilitate faster transitions may mitigate this
  - Future experiments:
    - Test what role REC price certainty will play
    - Test what different REC transition matrices induce

Conclusions & Future Work

- Strategic + Operational model to evaluate technology paths
- MDP framework to prove policy structure and solve numerically
- Fit empirical models to data
- Case study for ERCOT:
  - Under current prices transition to wind seems likely
  - As prices increase, technology and temporal trapping are potential concerns
- Future Work:
  - Evaluate other REC price scenarios
  - Evaluate other regions (like PJM)
  - Evaluate two-way REC price transitions
  - Other thoughts?

Thank you!

Any questions?