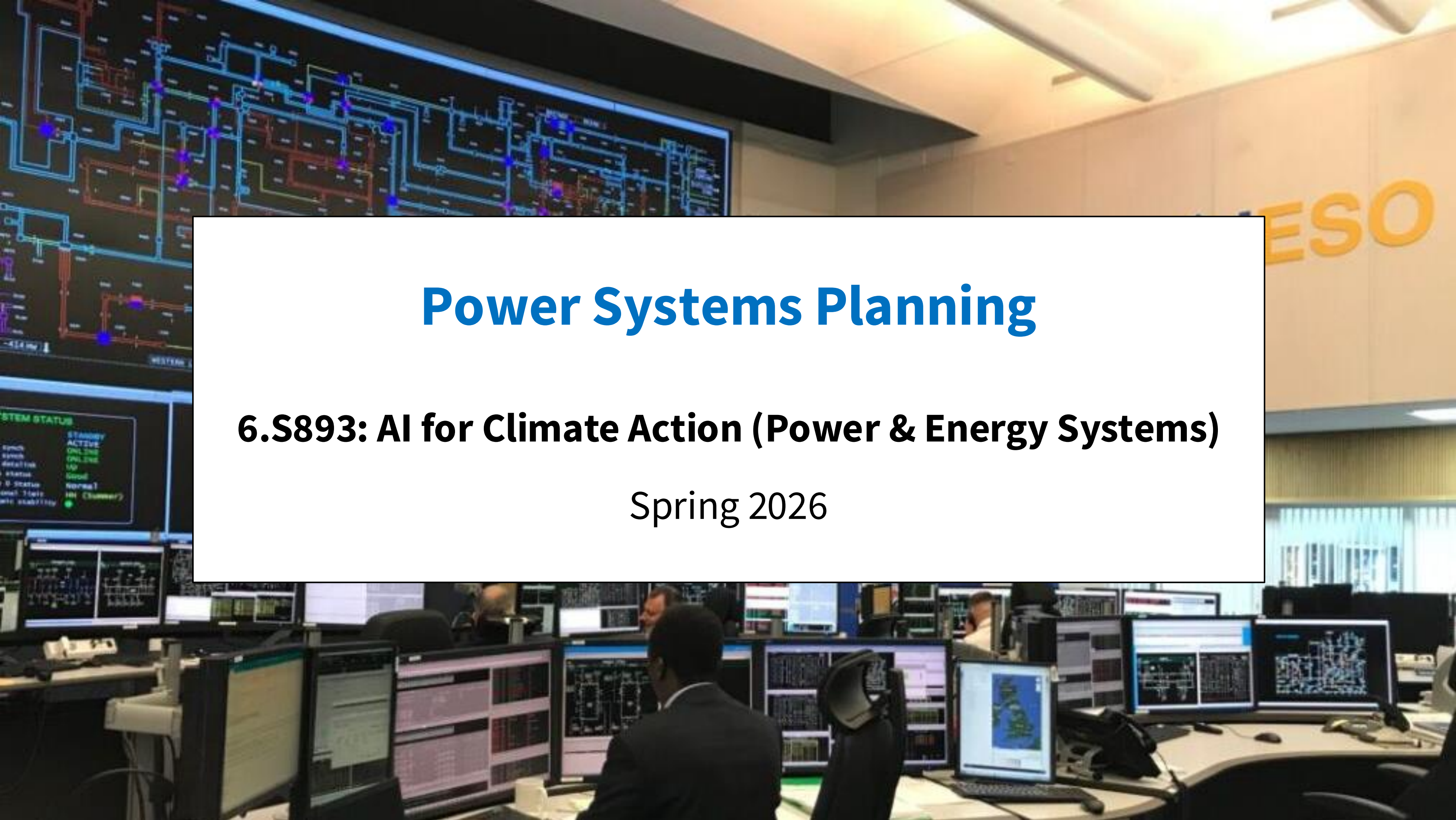

Power Systems Planning

6.S893: AI for Climate Action (Power & Energy Systems)

Spring 2026

Outline

Background: Power systems planning

Overview of ML for power systems planning

Discussion: Considerations and enablers for ML in power systems

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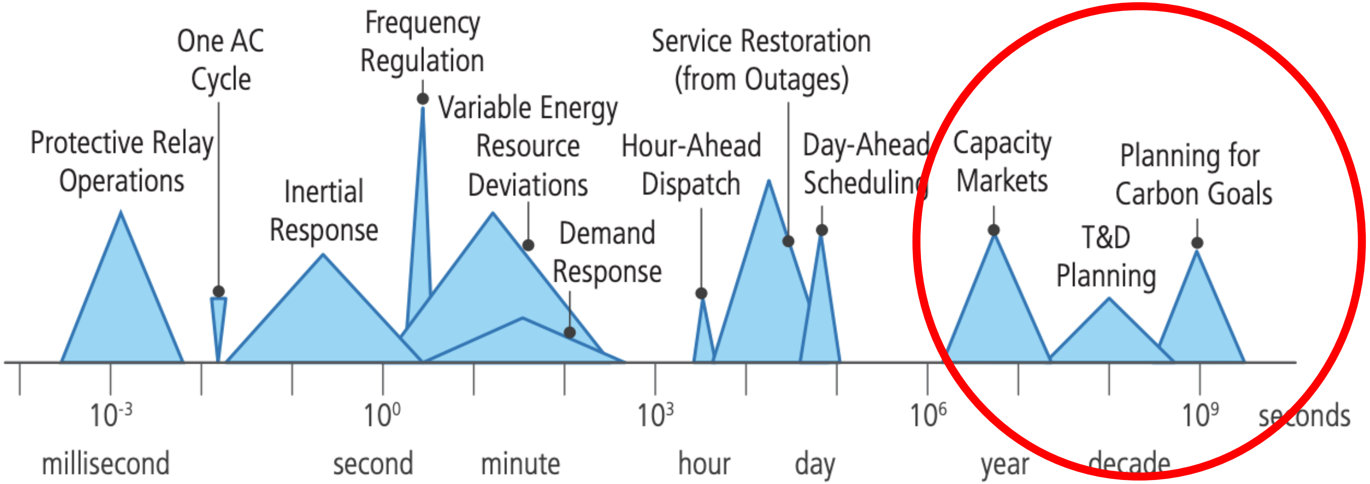
Figure S-5. System Reliability Depends on Managing Multiple Event Speeds



Capacity markets, day-ahead scheduling, and hour-ahead dispatch are well-understood tools for managing supply variability (mid-right axis). Beyond capacity contracts, traditional transmission and distribution (T&D) system long-term planning methods work to map and price investment requirements to ensure grid reliability (right end of axis). However, the widespread integration of variable energy resources significantly expands the time dimensions in which grid operators must function, ranging from hourly to minute to second intervals (mid-left axis). And, in a world of subsecond decision making (i.e., inertial response, one alternating current (AC) cycle, and protective relay operations), dispatch effectiveness will require the integration of automated grid management (left end of axis).

Figure source: US Department of Energy Quadrennial Energy Review (January 2017)

Importance of power grid planning

Necessary for ensuring that power grids can continue to serve demand in an economically efficient and reliable manner

Important for facilitating the transition to more sustainable energy

Considers actions such as:

- Building new generation and transmission
- Enhancing existing grid assets
- Retiring existing generation

Generation project development

Several steps

- **Siting:** Where to put it? Consider the grid, land/property, and fuel availability
- **Permitting:** Receiving authority to construct & operate from regulatory agencies (state-level utility commission, local zoning agencies, environmental agencies)
- **Grid assessment:** System impact assessment (e.g., power flows) and recommendation of remedial actions (e.g., transformer upgrades)
- **Fuel delivery assessment** (if applicable)**:** Is there an adequate system for fuel delivery? E.g., for natural gas plant, understand impact on local gas pipeline flows
- **Financing**
- **Construction**

In the US, overall process can take several years

Example overview of development process

Timeline		
Activity	Start time beginning of month	Completion time end of month
Siting	0	6
Gas pipeline impact study	5	6
System impact study grid	5	6
Permitting process	6	18
Financing	12	18
Construction	18	28
Testing	28	29
On line	29	On line 20 to 30 years

Permitting process	
Agency	Responsibility
California Energy Commission	State land use
Air Pollution Control District	Emissions permitting
Regional Water Control Board	Waste water discharge
California Coastal Commission	Coastal development planning
US Environmental Protection Agency	Emissions permitting
California Department of Fish and Game	Reviews impact on fish and wildlife, endangered species Consultation
State Land Commission	Approves use of state lands
California Public Utilities Commission	Approves cost recovery through regulated rates

For a combustion turbine (CT) within California

Example from a 2007 textbook (timelines have changed since then)

Example from (Mazer, 2007)

Transmission project development

Transmission upgrades can be:

- Standalone projects
- In association with addition of new generation unit

Can include:

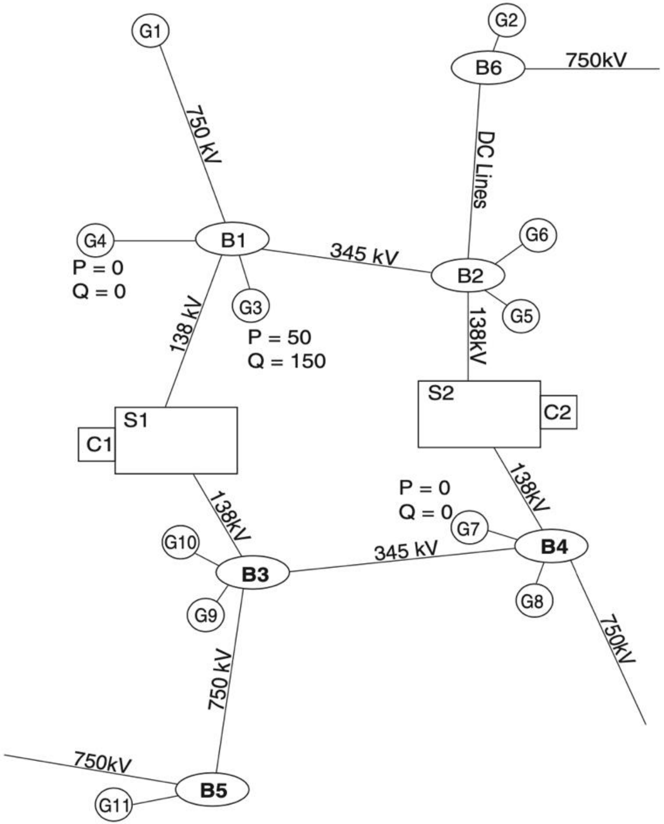
- Building new lines and transformers
- Enhancing existing equipment

Several steps: Siting, permitting, financing, and construction

Major cost (and headache) includes acquisition of land along the proposed transmission line’s pathway

In the US, often a (much) longer process than generation project development

Generation interconnection studies



Example: Suppose G10 is proposed plant with interconnection bus B3

Do a power flow study to determine impact on grid

- Suppose adding G10 would cause additional 100MW of power flow from B3 → B4

Determine remedial actions if needed

- Suppose B3 → B4 only has 70MW additional capacity beyond its current use
- Upgrade line by at least 30MW (likely by several hundreds of MW in anticipation of future needs)

Overall, interconnection studies need to consider the impact of multiple simultaneous projects

Example from (Mazer, 2007)

Generation interconnection queues in the US

Plot shows capacity in interconnection queues as of the end of 2024

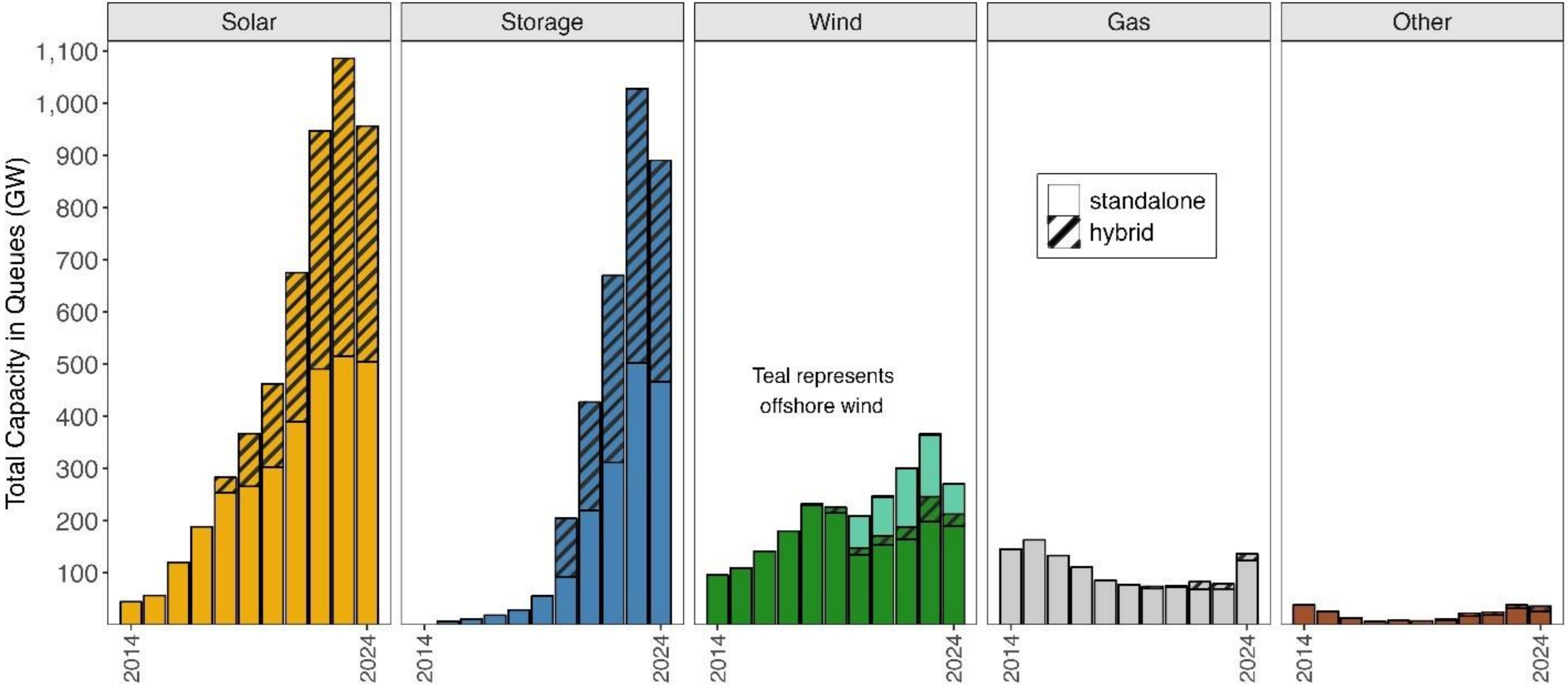


Figure source: https://emp.lbl.gov/queues

Capacity expansion models

Optimization-based tools that simulate generation and transmission capacity investment, given assumptions about future electricity demand, fuel prices, technology cost and performance, and policy and regulation

Inputs/assumptions:

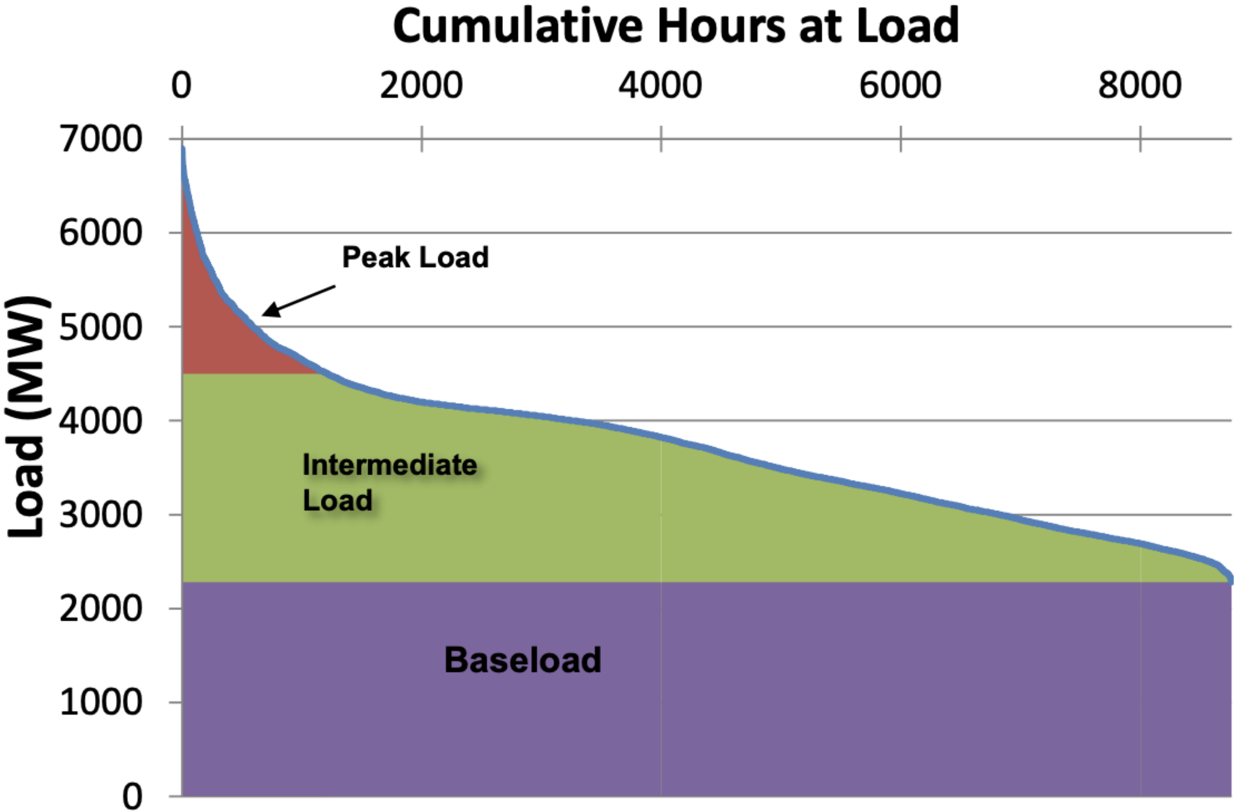
- Future electricity demand
- Fuel prices
- Renewables production patterns
- Technology cost and performance (capital cost, operations & maintenance, capacity factors, emissions factors)
- Policy and regulation
- …

Typical outputs:

- Annual power generation
- Generation and transmission capacity builds/retirements
- Emissions
- Fuel consumption
- Electricity prices
- Credit/allowance prices

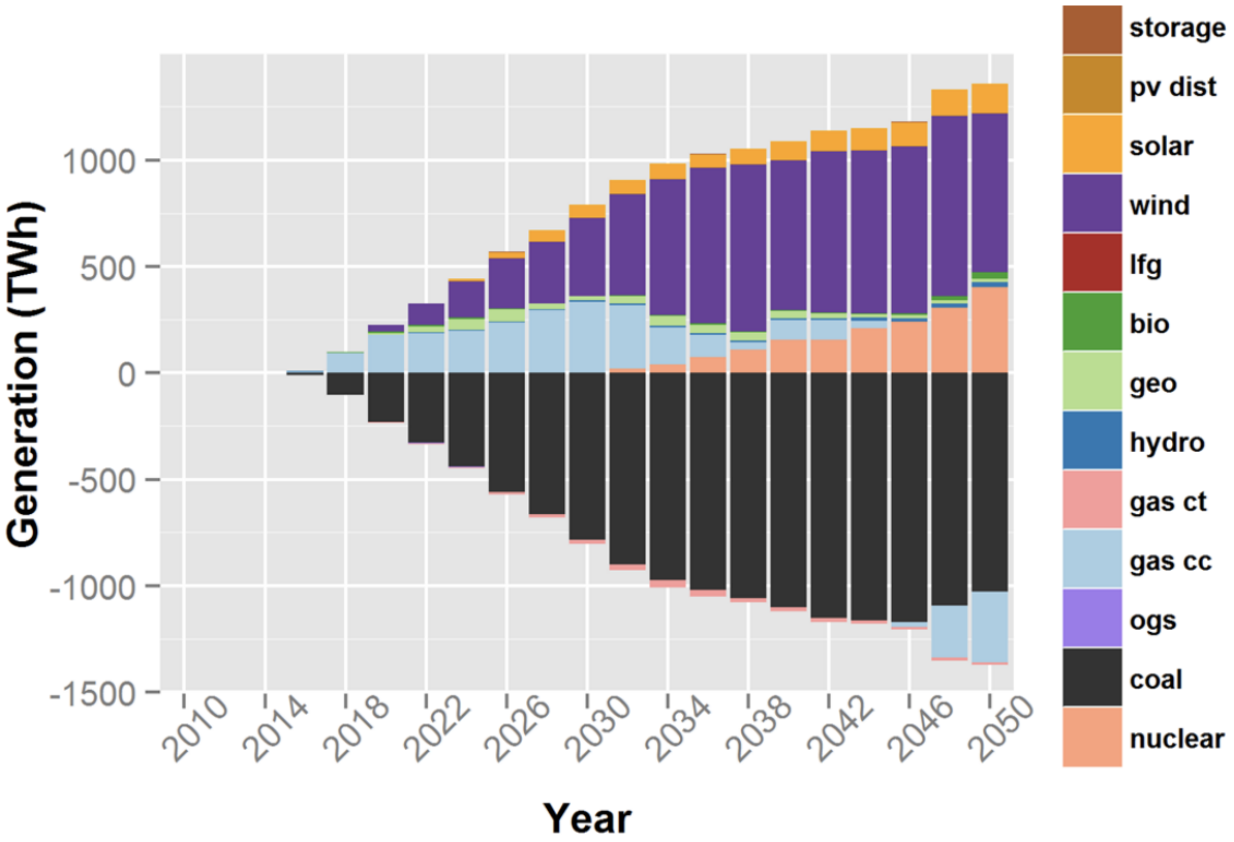
Adapted from: Power Sector Modeling 101 (https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf)

Long-term load forecasting: Load-duration curve



From: Power Sector Modeling 101 (https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf)

Example output: Power generation per year



From: Power Sector Modeling 101 (https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf)

Capacity expansion model formulation (high-level)

Decision variables: Investments in generation, transmission, and storage (potentially location-specific, potentially aggregate)

Objective: Minimize sum of capital costs and operation costs over the time horizon

- May involve weighting costs at different times differently (e.g., via discounting)

Constraints:

- Generator constraints – e.g., min/max output, ramp rates, min up/down time
- Storage constraints – e.g., limits on power dispatch/uptake and total energy stored
- Network constraints – e.g., power balance, flow limits
- Other operational constraints/requirements – e.g., reserves
- "Global" constraints – e.g., CO_2 emissions cap, transmission volume expansion limit, technology capacity expansion limit, growth limit per carrier

For more detailed formulations, see documentation of leading capacity expansion models – e.g., PyPSA and GenX

Many variations across capacity expansion models

Regionality
- Geographic scope (state, regional, national)
- Vertically-integrated vs. market regions

Temporal resolution
- Time of day, seasons
- Raw or representative periods

Time steps
- Building new capacity, dispatch

Time horizon
- Near-term: 2015-2020, Long-term: 2015-2050

Representation of generating units
- Individual Plants or Model Plants
- Representation of capital costs and other production costs

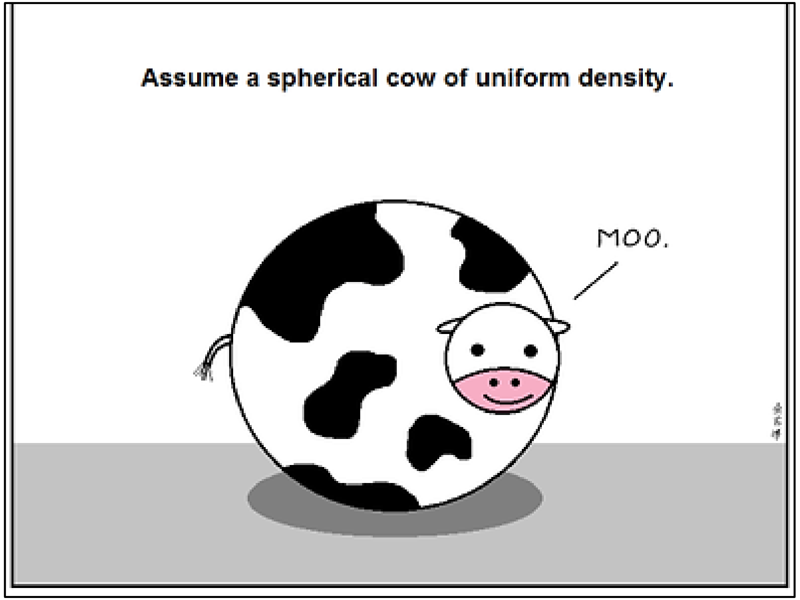
Representation of transmission and associated constraints
- Pipe-flow or DC power flow
- Individual transmission lines or aggregated

Representation of renewable energy (RE)
- Which RE technologies are represented in the model
- Underlying resource dataset – spatial and temporal resolution
- Accounting for variability and uncertainty in generation (e.g., representation and treatment of curtailments and capacity value of RE technologies)

Consideration of other parameters (e.g., electric power sector model vs. economy wide model, representation of environmental constraints)

Adapted from: Power Sector Modeling 101 (https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf)

Models vs. reality



Comic by [Abstruse Goose]

Cost recovery

Regulator determines revenue the transmission company can collect, based on regulated rate of return

Transmission company must decide how that revenue is collected from producers & consumers

Common allocation methods:

- Postage stamp: All users must pay a "use of system charge" to gain access to network (can vary across users based on, e.g., peak demand, annual energy usage, voltage level)
- Contract path: Pay a wheeling charge along the "assumed path of travel" of electricity, in cases of bilateral agreement between producer and consumer
- MW-mile: Use power flow calculations to determine "actual" path of travel of electricity, and assess charges along that path

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Long-term forecasting and projection

Question: What are the long-term trajectories of demand, supply, & technology costs?

Approach for macro-scale projections: Econometric models, climate models

Potential role for ML: Creating more granular predictions

- Pure data-driven ML unlikely to be a good fit *(distribution shift, large discrete events)*
- More likely approach: Hybrid approaches combining traditional models with ML

Example: Climate model downscaling

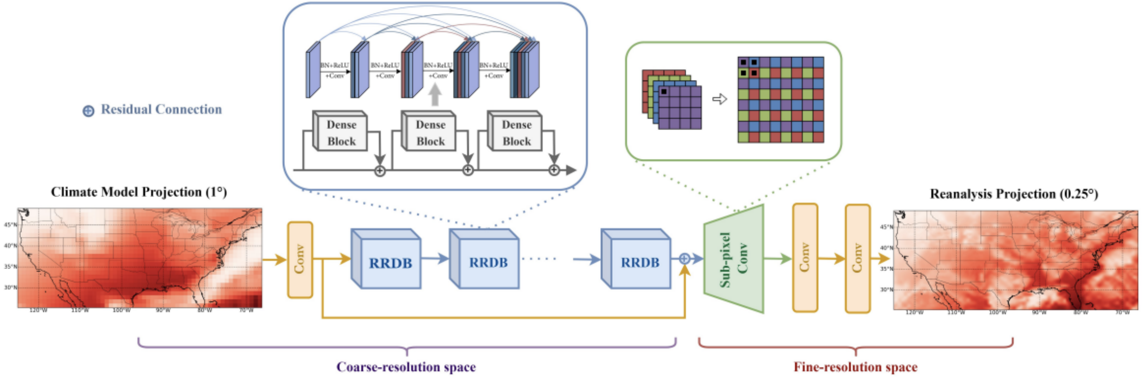

Figure source: Harilal, Hodge, Monteleoni, Subramanian (2022)

Scenario generation

Can we generate scenarios that are representative or otherwise useful to optimize over?

Often based on generative methods that fit a distribution over historical data or uncertainty sets, and then strategically sample from them

Representative scenarios: Can we generate scenarios that "look like" real scenarios, and are sufficiently representative of the span of scenarios we may face?

- Includes *conditional* scenario generation ("give me a scenario conditioned on…")

Optimization-cognizant scenarios: Can we generate scenarios that are specifically geared towards improving outcomes of the planning model's optimization process (e.g., adversarial scenarios)?

Speeding up solvers

Can we enable faster, more scalable solution of the planning problem?

More efficient solution search: Can we more effectively characterize the search space and/or more efficiently search through it?

- E.g., Multi-objective optimization: Characterize the Pareto frontier
- E.g., Mixed-integer optimization: More efficient search over discrete variables (e.g., improving branch-and-bound)

Surrogate modeling: Can we learn approximations to parts of the models and then integrate these approximations into the broader solver?

- E.g., ML surrogates for the operational subproblem (AC-OPF)

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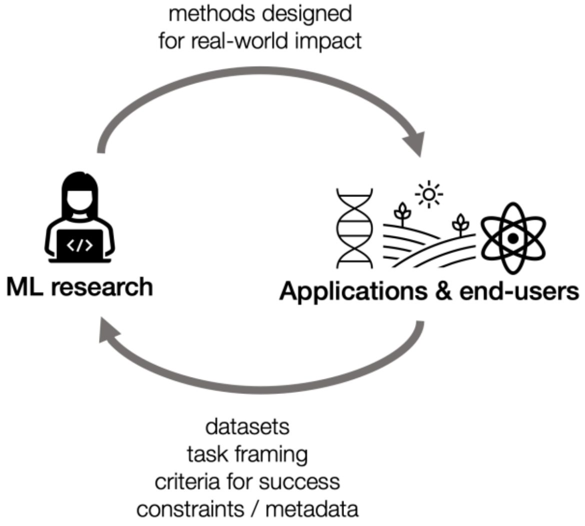
Considerations for ML in power & energy systems

Different requirements for ML models and their outputs, depending on the context

- Accuracy/solution quality (better than SOTA)
- Safety & physical feasibility
- Robustness
- Interpretability, explainability, & auditability
- Uncertainty quantification
- Fast running time
- Hardware integration
- Data efficiency
- Generalizability
- Multi-agent and human-in-the-loop
- Privacy preservation
- Usability and accessibility
- Meeting regulatory standards



David Rolnick, Alan Aspuru-Guzik, Sara Beery, Bistra Dilkina, Priya L. Donti, Marzyeh Ghassemi, Hannah Kerner, Claire Monteleoni, Esther Rolf, Milind Tambe, Adam White. "Position: Application-driven innovation in machine learning." *ICML 2024.*

Enablers for advancing ML in energy systems

More openness in data (incl. synthetic data), beyond bilateral agreements and limited access

Simulators and test beds, with realistic/diverse scenarios and easy-to-use interfaces

- Incl. digital twins, but also simpler frameworks (e.g., Grid2Op)
- Need for *progression pathways* from basic to advanced simulators/test beds

Evaluation metrics / benchmarks: What does it mean for a method to succeed (or fail)?

Mathematical formulations and transparent writeups of important "challenge problems"

Modular, "open-source" software, enabling integration & evaluation of new methods

Translational research exchange: Enhanced collaboration between academia, national labs, solutions providers, and energy industry players (power system operators, utilities)

Note: None of these enablers are solely about ML!

Takeaways

⚡ **Power systems planning**

- Generation & transmission project development: Siting, permitting, interconnection
- Capacity expansion models (optimization-based tools)
- Mechanisms for cost recovery

🔎 **ML for planning:**

- Long-term forecasting and projection (via hybrid models!)
- Scenario generation (representative and optimization-cognizant)
- Speeding up solvers (solution search, surrogates)

💪 **Considerations & enablers for ML in power systems:** Methodological & broader