Incorporating climate change in long-term planning models:

takeaways from current industry and academic practices

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Acknowledgements: PSERC Project S-99 Research Team and Advisory Board
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Students Gabriela Setyawan, University of Wisconsin - Madison

Agenda

1) Recent electric utility and industry reports

2) Incorporating climate in long-term planning

3) Synthesis and the way forward

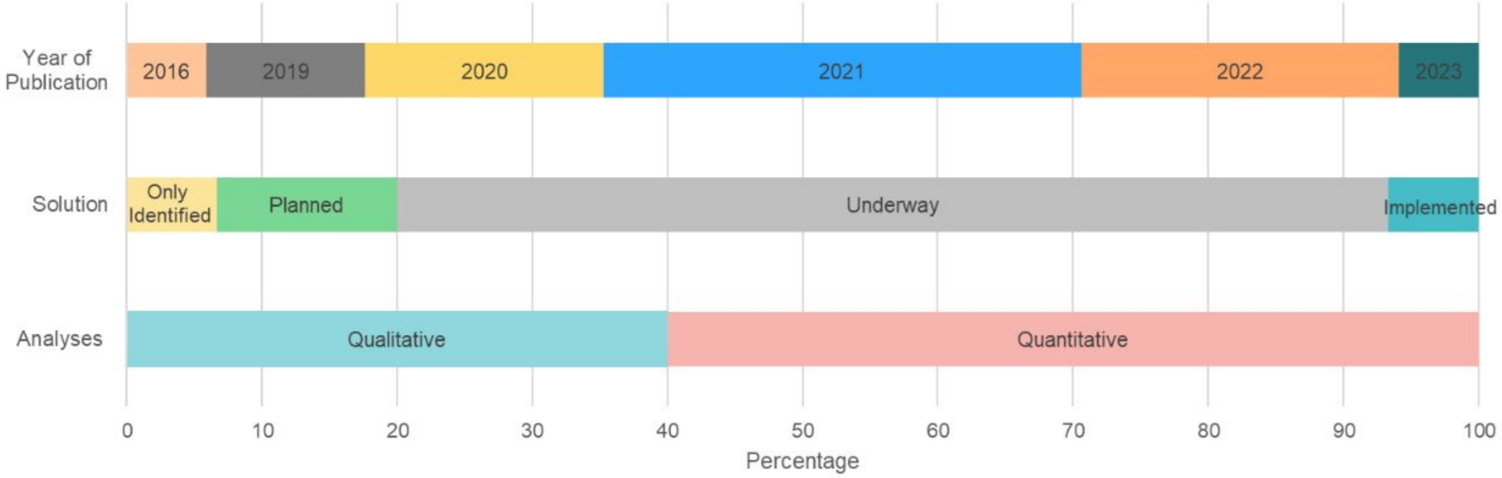
Recent electric utility and industry reports

Review of recent utility climate assessments

In 2015-2016, the U.S. DOE[1] partnered with 17 utilities to review their climate vulnerability assessments

- Type of stressors, actions planned and status, type of assessments, data inputs

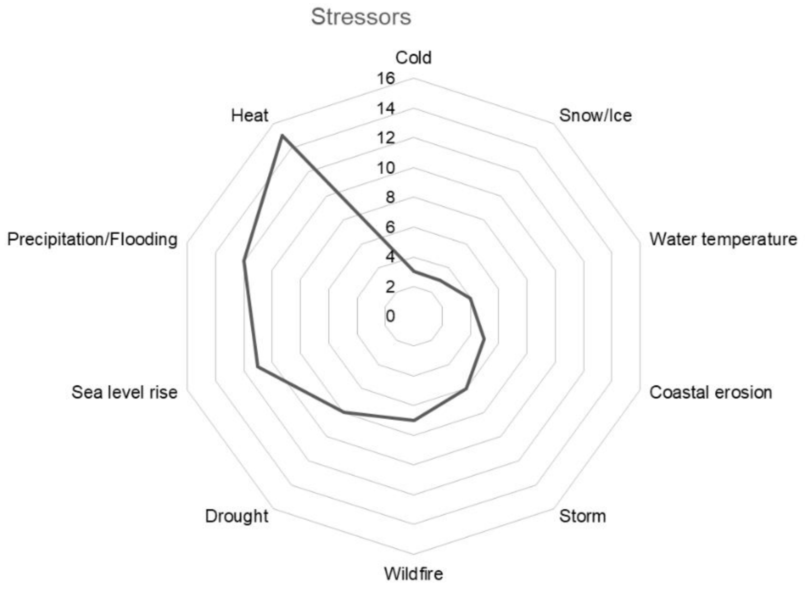
We pulled a sample of 16 recent (2016-2023) publicly available utility assessments:



[1]U.S. Department of Energy. (2016). *A Review of Climate Change Vulnerability Assessments Current Practices and Lessons Learned from DOEs Partnership for Energy Sector Climate Resilience*.

Review of recent utility climate assessments

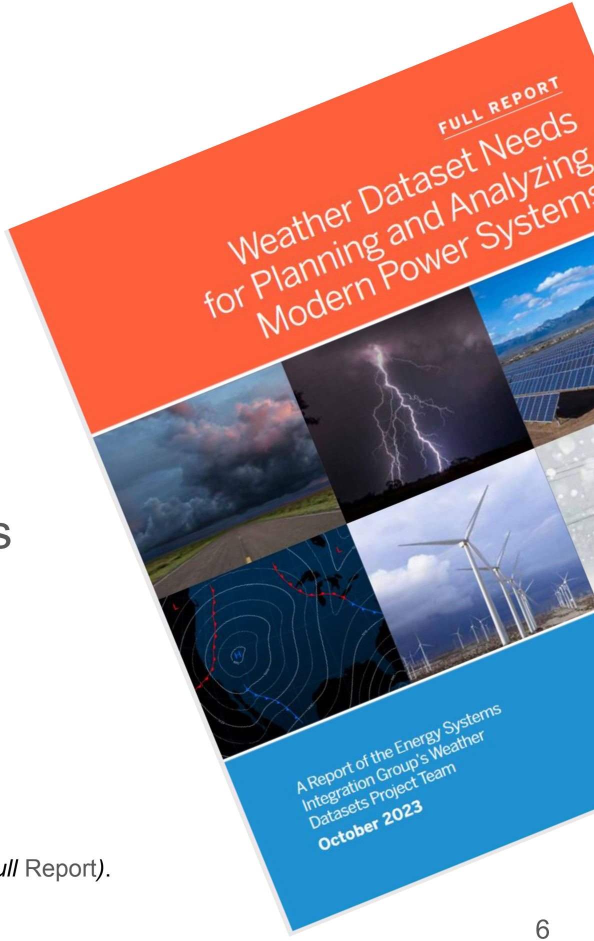
- Recent extreme events in a utility's experience influenced focus of stressors
- Studies covered generation, transmission, distribution, and load relatively equally
- Lighting was a new type of stressor mentioned in several recent climate assessments



ESIG Weather Datasets Report

Assesses the state of current weather datasets for power system planning and future needs

- Describe available weather data
  - *Current* weather data is insufficient for modeling modern power systems; *climate change* is a further challenge
- Articulate data needs for modeling different grid assets
- Define characteristics of 'ideal' dataset



Energy Systems Integration Group. (2023). *Weather Dataset Needs for Planning and Analyzing Modern Power Systems (Full* Report*)*. https://www.esig.energy/weather-data-for-power-system-planning

Sharp, J. (2023). Meteorology 101 Meteorological Data Fundamentals for Power System Planning: Overview for Power System Planners and Engineers. ESIG.

EPRI Climate READi

Workstream 1

Physical Climate Data and Guidance

Workstream 2

Energy System and Asset Vulnerability Assessment

Workstream 3

Resilience and Adaptation Planning and Prioritization

www.epri.com/READi
EPRI. (2023). Climate Vulnerability Considerations for the Power Sector: Non-Nuclear Generation Assets. Technical Report.
EPRI. (2023). Climate-Informed Planning and Adaptation for Power Sector Resilience. Technical Report.

A few take-aways for long-term planning

- All weather variables should be based on one physically consistent model, to the extent possible
  - ESIG Chapter 3: Weather Inputs Needed for System Planning
- Currently, utility’s planning models do not often incorporate climate uncertainty rather emphasize on economic, technological, and policy uncertainty.
  - EPRI Workstream 3; bulk systems long-term planning
- Resource adequacy exercises are challenged to select and appropriately apply climate data
  - EPRI Workstream 3; bulk systems RA

Primer on climate uncertainty

Generally three types of variability and uncertainty are delineated:

1. Internal variability: Which years are selected?
2. Model uncertainty: Which climate models are selected?
3. Scenario uncertainty: Which climate projections are selected?

There are known gaps in climate modeling relevant to power systems:

1. Simulating the number of emission scenarios and timescales needed means that high-temporal resolution climate simulations are not typically prioritized
2. Downscaling climate data to spatial resolutions usable at a regional and power system scale is subject to its own set of limitations
3. Extremes are hard to model, we know that event recent extreme events were not expected based on climate scenarios

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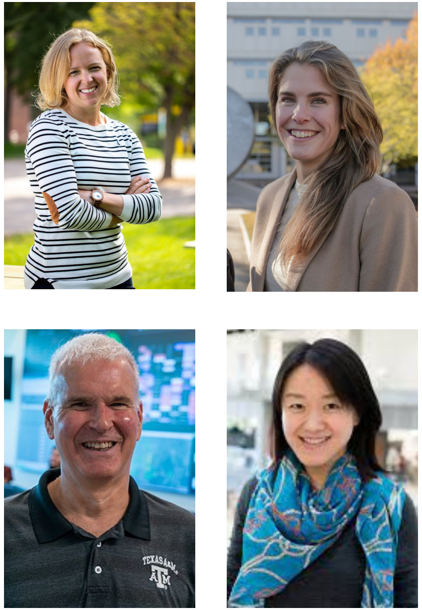
Incorporating climate in long-term planning

Overview of PSERC Project S-99 Incorporating climate impacts into electricity system planning models



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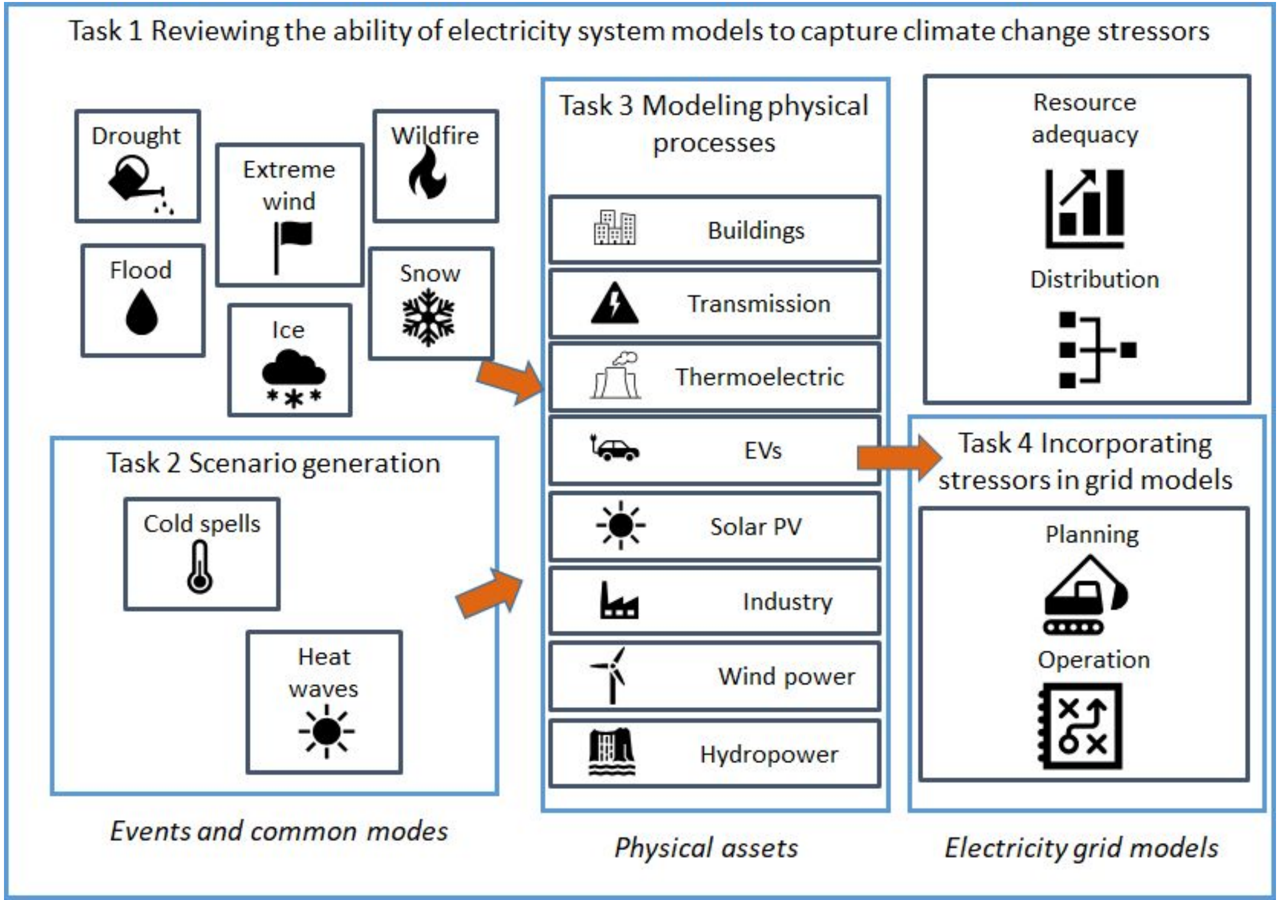


Modeling climate impacts on generation (examples)

e.g. Thermal models to represent how daily maximum dry bulb and wet bulb temperatures affect the available capacity of different types of thermal generators with different cooling systems.

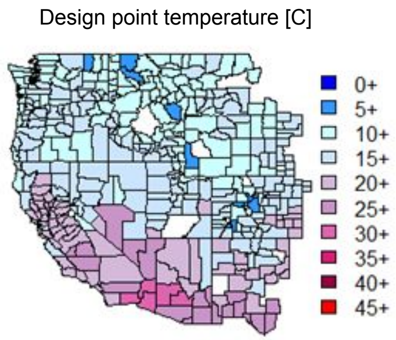
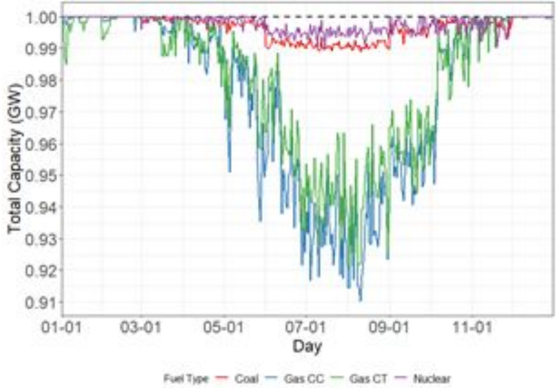


Table: Temperature sensitivities of thermoelectric power plants above design point temperature.

Slope and range	Coal	CC	Nuclear
Air-cooled	-0.36%/C	-0.74%/C	NA
Cooling tower	-0.14%/C	-0.72%/C	-0.18%/C



Dyreson, A., Devineni, N., Turner, S. W. d., De Silva M, T., Miara, A., Voisin, N., Cohen, S., & Macknick, J. (2022). The Role of Regional Connections in Planning for Future Power System Operations under Climate Extremes. Earth's *Future*, *10*(6), e2021EF002554. https://doi.org/10.1029/2021EF002554.
Photo credit: Michigan Tech
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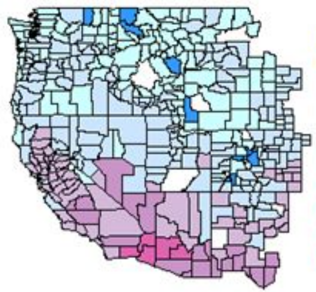

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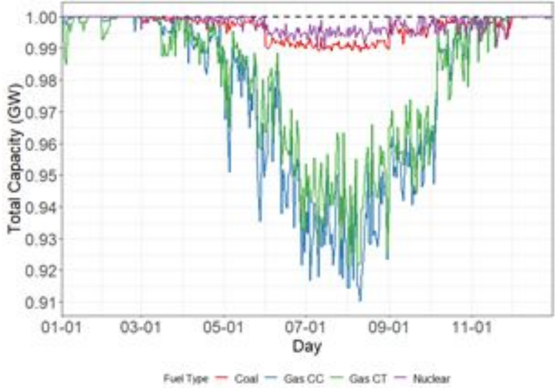

e.g. Empirical models to represent how long snow stays on solar PV panels and reduces their output.

Sliding if: $T_a > I_{POA} / (-80\ W/m^2C)$

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Modeling climate impacts on generation and load

Identify modalities by which climate change affects gen. & load

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U.S. DOE, 2015
Allen-Dumas et al. 2019
Craig et al. 2021
ESIG, 2023

Fuel transport	Reduction in river levels	Disruption of barge transport of crude oil, petroleum products, and coal
	Increasing intensity and frequency of flooding	Disruption of rail and barge transport of crude oil, petroleum products, and coal
Thermoelectric power generation (Coal, natural gas, nuclear, geothermal, and solar CSP)	Increasing air temperatures	Reduction in plant efficiencies and available generation capacity
	Increasing water temperatures	Reduction in plant efficiencies and available generation capacity; increased risk of exceeding thermal discharge limits
	Decreasing water availability	Reduction in available generation capacity; impacts on coal, natural gas, and nuclear fuel supply chains
	Increasing frequency of intense hurricanes, and increasing sea level rise and storm surge	Increased risk of physical damage and disruption to coastal facilities
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Hydropower	Increasing temperatures and evaporative losses	Reduction in available generation capacity and changes in operations
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	Extended growing season	Increased production
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Wind energy	Potential variation in wind patterns	Uncertain impact on resource potential
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Electric grid	Increasing air temperatures	Reduction in transmission efficiency and available transmission capacity
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Compile stress response functions

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Table 2. Environmental Sensitivity Quantification and Sources

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Modeling climate impacts on generation and load

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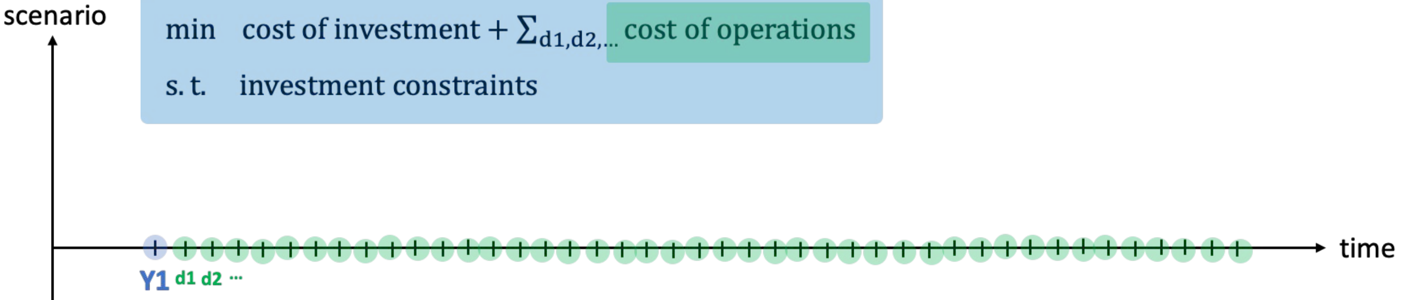
Long-term planning models

Long-term planning is about making decisions **NOW** that will impact system operations for a **LONG TIME**

$$\begin{aligned} &\min \quad \text{cost of investment} + \textstyle\sum_{d1,d2,\dots} \text{cost of operations} \\ &\text{s.t.} \quad \text{investment constraints} \end{aligned}$$



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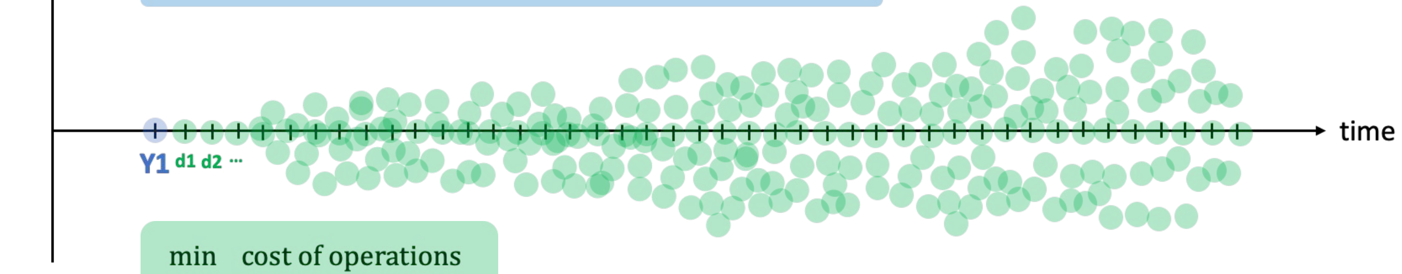

$$\min \quad \text{cost of operations}$$
$$\text{s.t.} \quad \text{generation limits}$$
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$$\text{power flow}$$
$$\text{transmission limits}$$

Problem: We don't know the future!
Solution: Consider many possible future scenarios

Demand
Renewables

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Measuring uncertain future costs!

min cost of investment + $\sum_{d1,d2,\ldots}$ cost of operations
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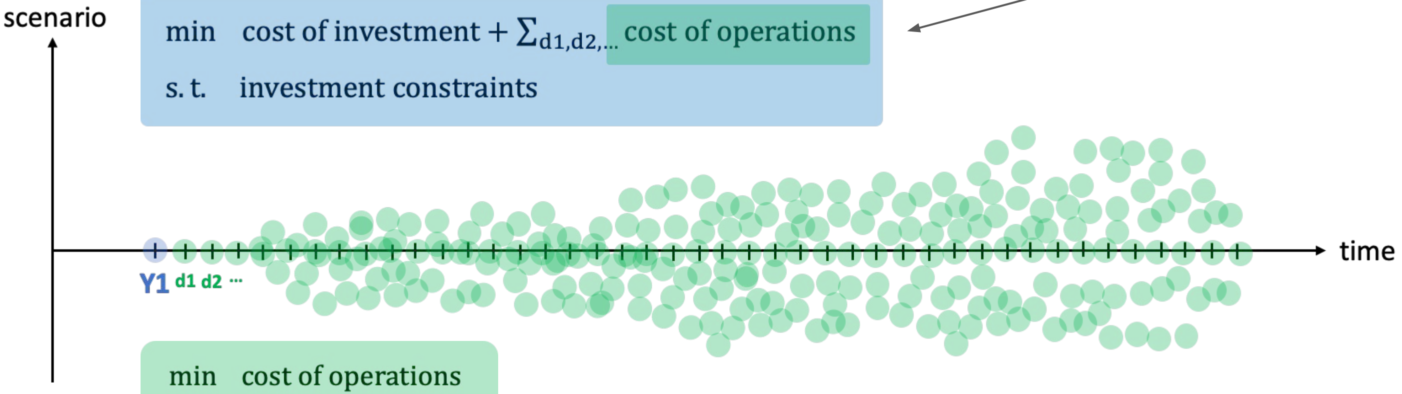

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s. t. generation limits
power balance
power flow
transmission limits

Problem: We don't know the future!
Solution: Consider many possible future scenarios

Demand
Renewables

Long-term planning models

Long-term planning is about making decisions **NOW** that will impact system operations for a **LONG TIME**

scenario

$$\begin{aligned} \min \quad & \text{cost of investment} + \textstyle\sum_{d1,d2,\ldots} \text{cost of operations} \\ \text{s.t.} \quad & \text{investment constraints} \end{aligned}$$

Measuring uncertain future costs!

$\min \quad \text{cost of expected operations}$

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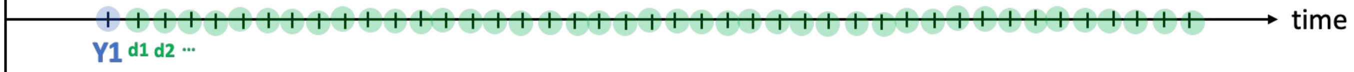
$\min \quad \text{worst} - \text{case cost}$



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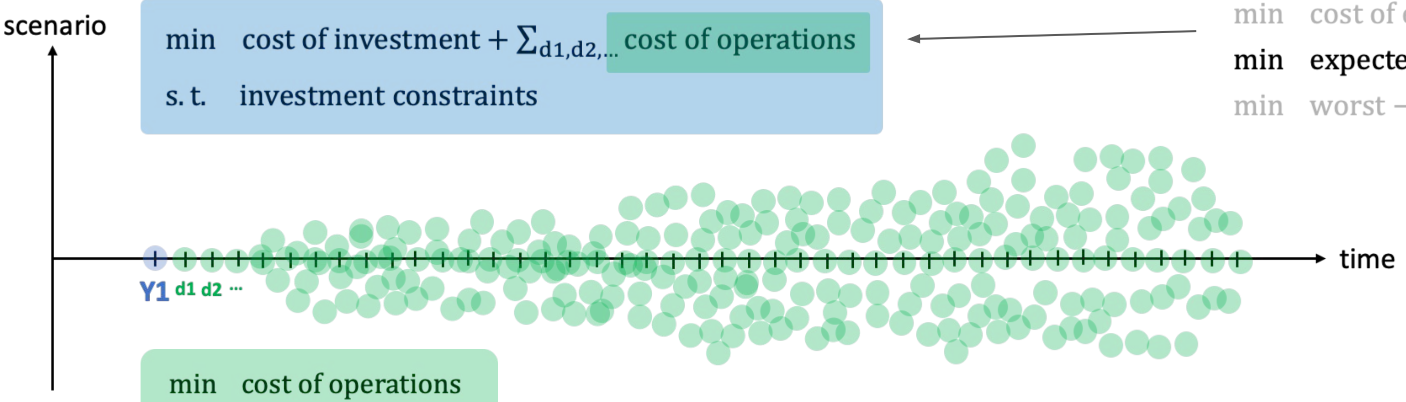

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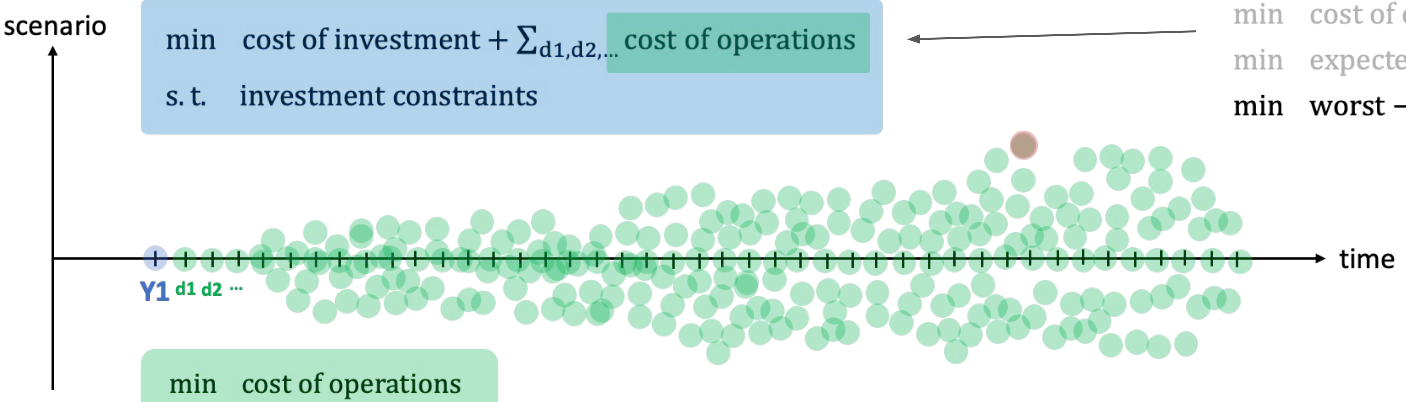

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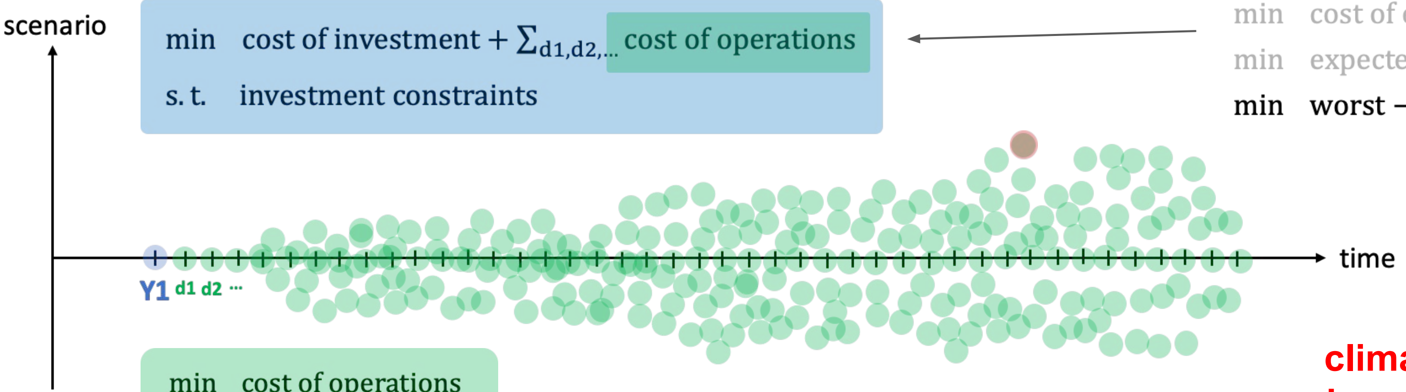


$$\min \quad \text{cost of operations}$$
$$\text{s.t.} \quad \text{generation limits}$$
$$\text{power balance}$$
$$\text{power flow}$$
$$\text{transmission limits}$$

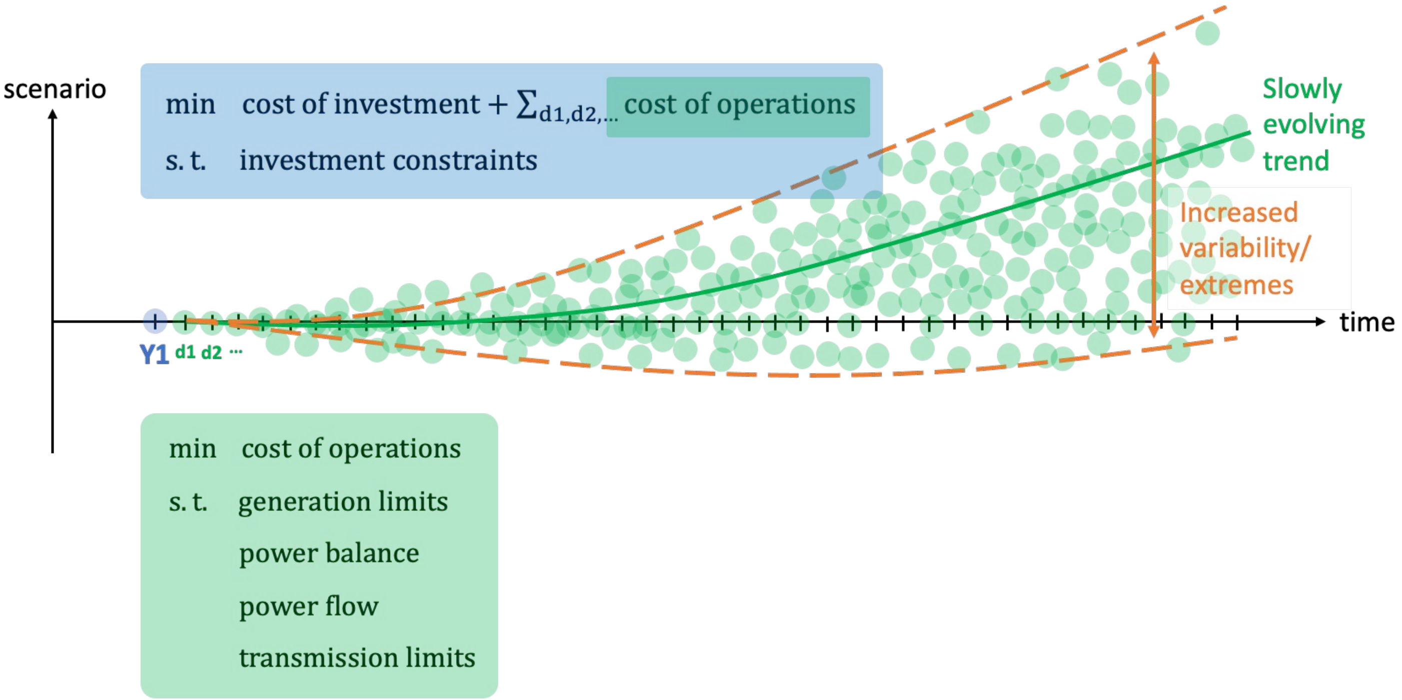
Considering climate change further increases uncertainty!

Problem: We don't know the future!
Solution: Consider many possible future scenarios

Demand
Renewables

How about climate change??

Long-term planning is about making decisions **NOW** that will impact system operations for a **LONG TIME**



Climate change will cause slowly evolving trends

Climate change will increase both weather variability and frequency of extreme weather

How about climate change??

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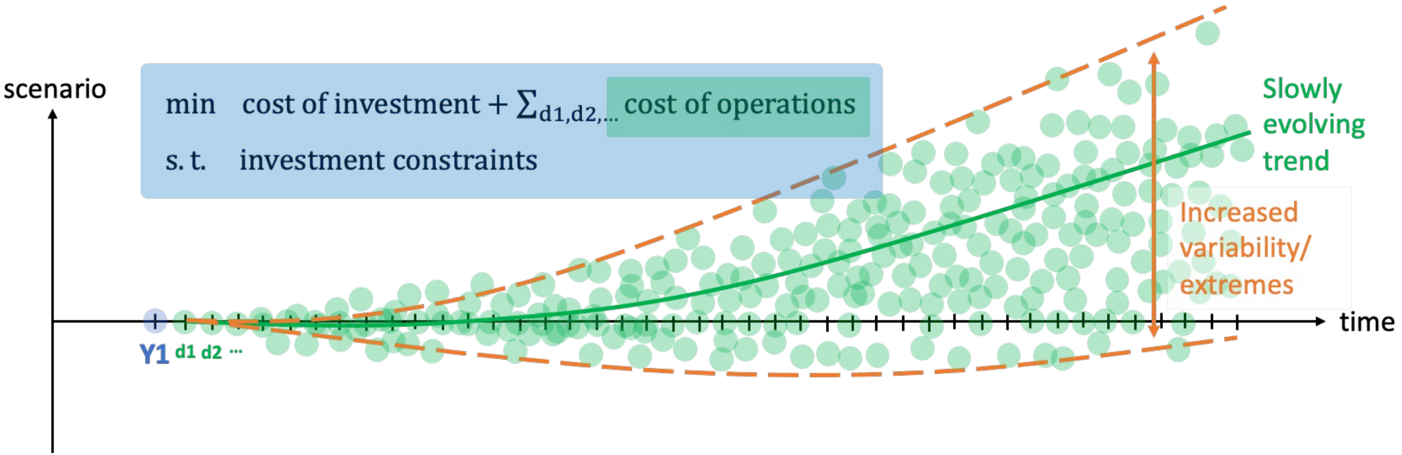


Climate change will cause slowly evolving trends

Climate change will increase both weather variability and frequency of extreme weather

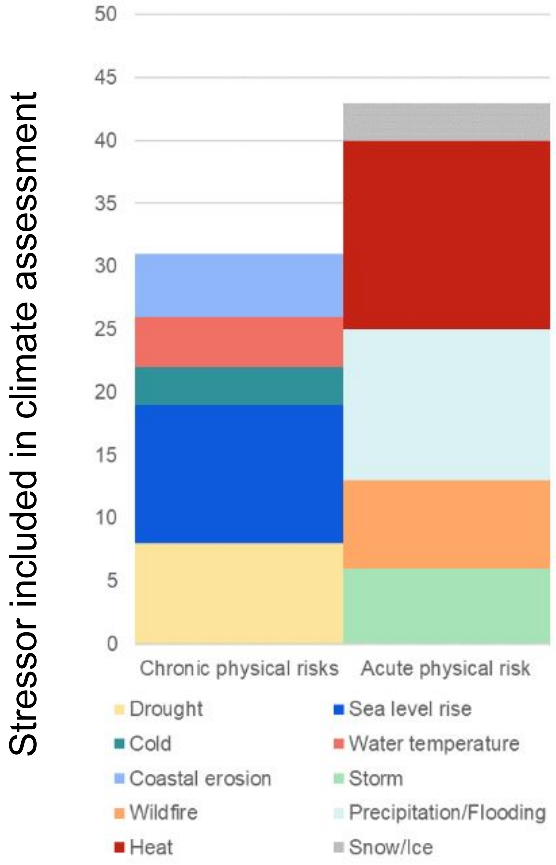
Exact impacts are hard to estimate (recall internal variability, model uncertainty, scenario uncertainty)
Also compounds with effects not covered in climate models, e.g. changes driven **climate change mitigation** (renewable energy, electrification), **climate migration**, policy impacts, etc

Chronic vs acute events

- **Chronic impacts** (also referred to as high-probability, low-impact events) [ESIG 2023, Perera et al 2020]: Slowly evolving impacts that become permanent such as higher temperatures (leading to, e.g. increased cooling demand), sea level rise (causing permanent flooding in coastal areas), changing ecosystems (e.g. more days with high wildfire risk) or climate migration

- **Event-driven/acute impacts** (also referred to as low-probability, high-impact events) [ESIG 2023, Perera et al 2020]: Sudden impacts from major events, such as hurricanes, wildfires, particularly severe heat waves, winter storms …

Perera, A.T.D., Nik, V.M., Chen, D. *et al.* Quantifying the impacts of climate change and extreme climate events on energy systems. *Nat Energy* **5**, 150–159 (2020).



From review of utility reports

Relationship with reliability and resiliency

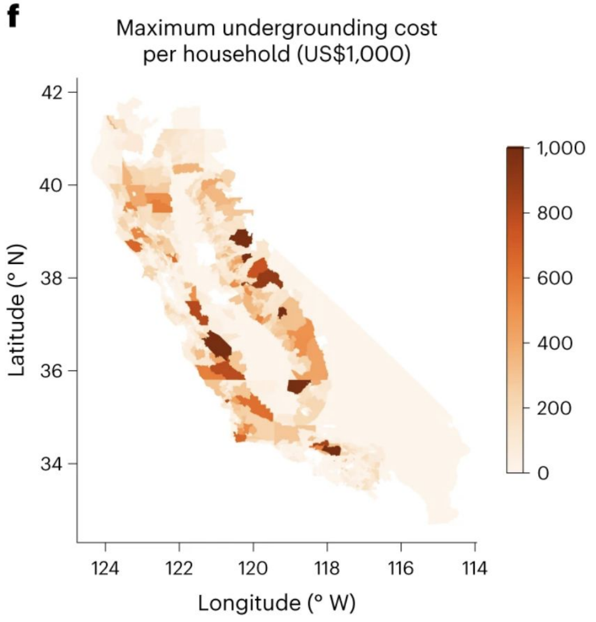
Power systems operate under two different operational paradigms:

- **Reliability** (i.e., electricity should always be available) in "normal" situations
- **Resiliency** (i.e., the grid may fail, but should recover as quickly as possible) during "extreme" events

Reliability vs resiliency map well to chronic vs acute climate change impacts:

- **Chronic impacts** are common enough to require **reliability**
- **Acute impacts** from extreme events can be handled in a **resilient** manner

It is necessary to carefully consider the cost of achieving reliability and resiliency benefits. Investing too much in reliability and resiliency can make electricity unaffordable (Wang et al, 2023).



Per household cost of undergrounding wildfire-prone power lines (Wang et al 2023)

Wang, Z., Wara, M., Majumdar, A. *et al.* Local and utility-wide cost allocations for a more equitable wildfire-resilient distribution grid. *Nat Energy* **8**, 1097–1108 (2023).

Power systems review - a very brief summary

Significant literature focused on improving modeling of **day-to-day grid operations** using stochastic optimization, and in particular more accurately capture e.g. load and renewable generation, to improve **system economics and reliability**.

Significant power system literature focused on planning measures such as system hardening, microgrids, … as well as operational models to improve **resiliency** of system operations during **extreme events**.

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Reducing the Impact of Public Safety Power Shutoffs

Input data: Combine wildfire ignition risk, location of power lines

Operational goal: Minimize wildfire ignition risk, minimize load shed (Rhodes et al 2020) while considering capacity to inspect and restore lines (Rhodes and Roald 2023)

Planning goal: Determine which lines to underground to reduce risk and load shed in operations (Kody et al 2022)

N. Rhodes, L. Ntaimo and L. Roald, "Balancing Wildfire Risk and Power Outages Through Optimized Power Shut-Offs," in *IEEE Trans. on Power Systems*, July 2021.
N. Rhodes and L. A. Roald, "Co-Optimization of Power Line Shutoff and Restoration Under High Wildfire Ignition Risk," *2023 IEEE Belgrade PowerTech*, Belgrade, Serbia, 2023
Kody, A., Piansky, R., and Molzahn, D. K., “Optimizing Transmission Infrastructure Investments to Support Line De-energization for Mitigating Wildfire Ignition Risk”, IREP 2022

Power systems review - a very brief summary

Significant literature focused on improving modeling of **day-to-day grid operations** using stochastic optimization, and in particular more accurately capture e.g. load and renewable generation, to improve **system economics and reliability**.
There are few works that use climate projected data, and those that exist tend to not include detailed grid modeling.

Significant power system literature focused on planning measures such as system hardening, microgrids, … as well as operational models to improve **resiliency** of system operations during **extreme events**.
While the focus on resiliency is inspired by more frequent extreme weather (and the expectation that it will increase with climate change), this literature rarely makes use of climate projections to quantitatively assess future risks

D. Chattopadhyay, E. Spyrou, N. Mukhi, M. Bazilian, A. Vogt-Schilb, “Building climate resilience into power systems plans: Reflections on potential ways forward for Bangladesh”, The Electricity Journal, Volume 29, Issue 7, 2016, Pages 32-41,ISSN 1040-6190

Mathaios Panteli, Pierluigi Mancarella, “Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies”, Electric Power Systems Research, Volume 127, 2015, Pages 259-270, ISSN 0378-7796

How to integrate all this in the model?

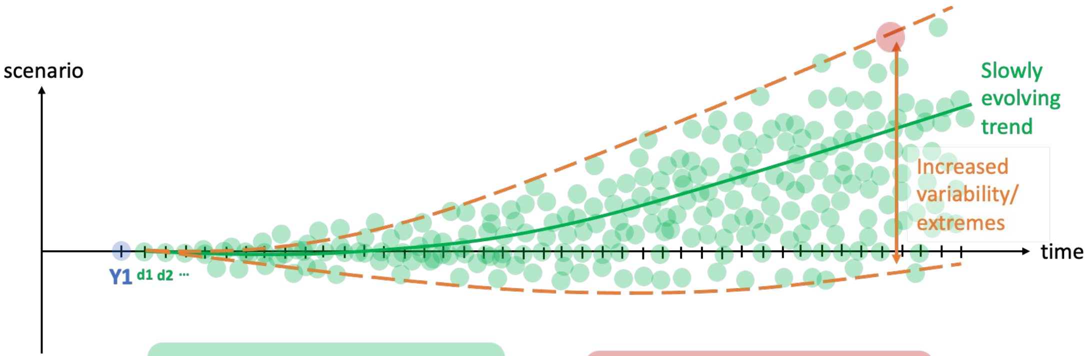
Models should plan for **both** reliability in normal operations and resiliency to extremes, while taking into account climate projected data!

Defining what is considered “extreme” vs “normal” is an unsolved challenge

Models should also consider multi-scale uncertainties (i.e. both uncertainty in long-term trends and short term variability)

Alexandre Moreira, David Pozo, Alexandre Street, Enzo Sauma, Goran Strbac, “Climate-aware generation and transmission expansion planning: A three-stage robust optimization approach”, European Journal of Operational Research, Volume 295, Issue 3, 2021, Pages 1099-1118, ISSN 0377-2217

$$\begin{aligned} \min \quad & \text{cost of investment} + \mathbb{E}[\text{cost of operations}] + \text{worst} - \text{case energy not served} \\ \text{s.t.} \quad & \text{investment constraints} \end{aligned}$$



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Synthesis
and the way forward

Some worthwhile insights and gaps

The necessary input data is still evolving!

Climate projections with spatial and temporal resolution that are adequate for power system modeling is not commonly available

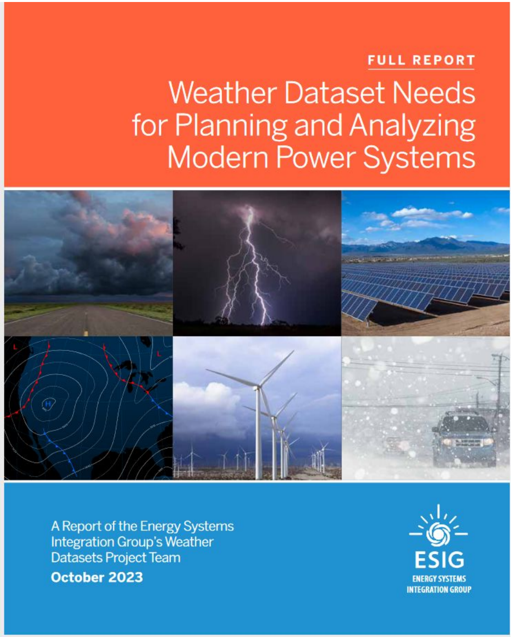
-Even for contemporary climate, data is lacking

Uncertainty affects modeling of both normal conditions and extreme events, but extreme event modeling is particularly challenging

Addressing interactions between sectors and systems through complementary multi-sector modeling approaches can shed light on other items like climate migration, gas-electricity dynamics, land-use changes.

Action items:

- **Uncertainty propagation from climate drivers to physical impacts** on generation, load and grid assets should be quantified (and integrated in long-term planning models!)
- Need to consider **short-term variability (in weather)** and **long-term uncertainty (in climate)**
- Need to capture both **reliability in normal operations** and **resiliency during extreme events**



"How can power system modelers incorporate possible climate scenarios and articulate their uncertainty? How can energy meteorologists monitor these impacts and trends going forward? **These questions are beyond the scope of this report,** but power system modelers and atmospheric scientists must be thinking about them and working together to make sure that the right problems are being addressed."

Review is still ongoing!

If we missed something, or you have any insights to share, please let us know!

If you would like access to our full bibliography, we are happy to share!

You can request access here (requires Zotero account):

https://www.zotero.org/groups/4387114/electricity_and_climate

Discussion

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