

# Modeling Regulated Electricity Markets: Scalable Algorithms, Market Constraints, and Applications in Southeast Asia

PhD Defense (B-Exam)

Phumthep Bunnak

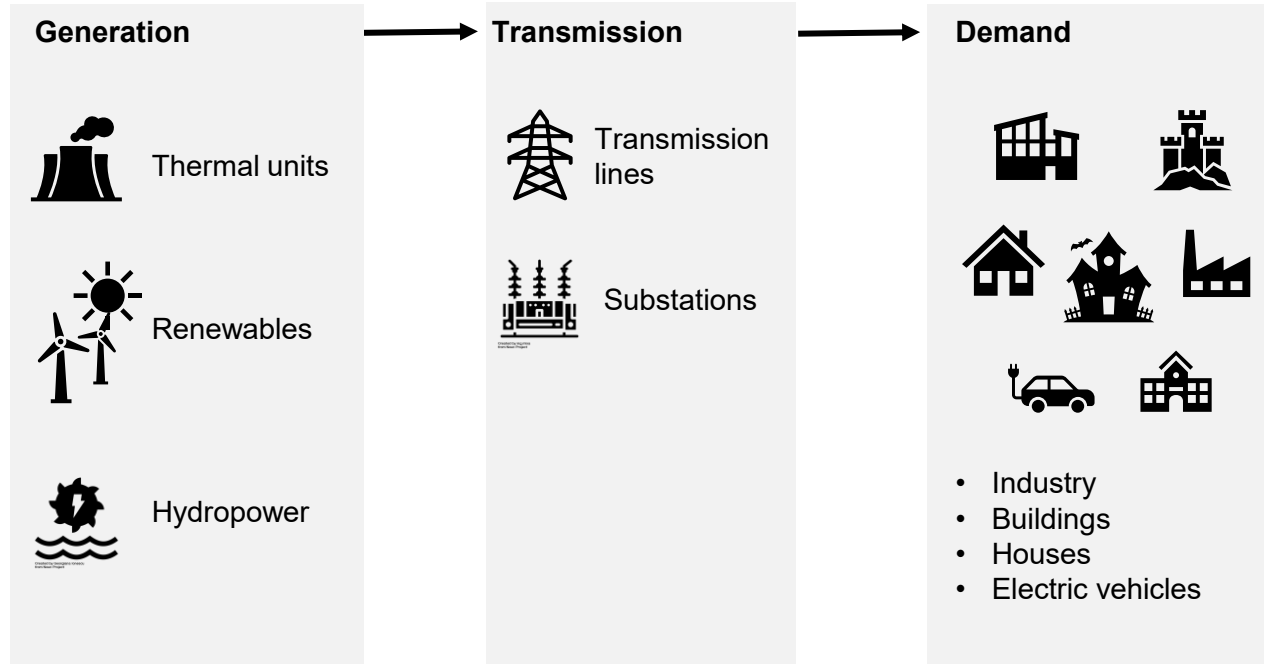
Committee Members: Stefano Galelli (Chair), Jacob Mays, Patrick Reed

School of Civil and Environmental Engineering

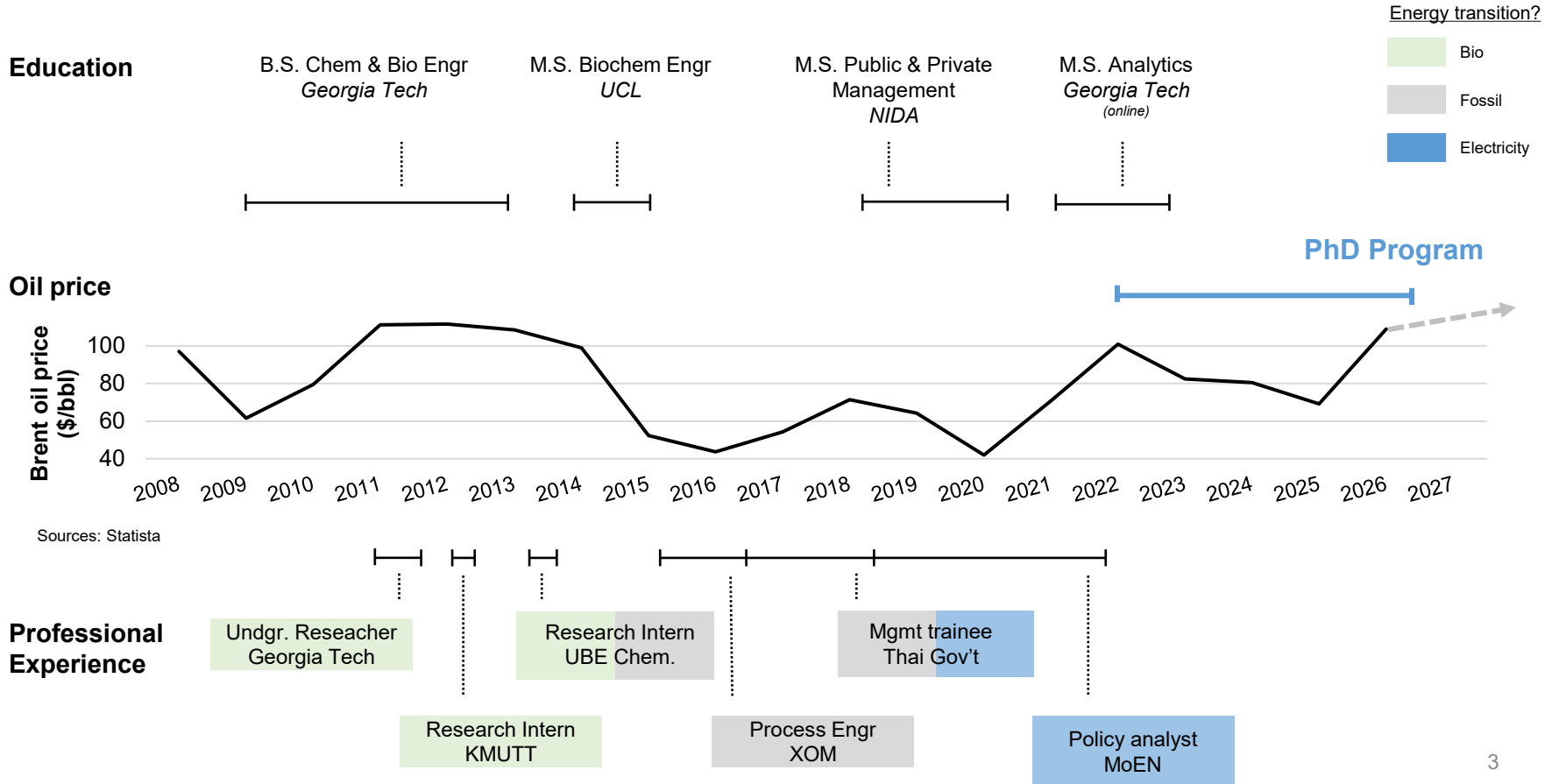
Cornell University

# Electricity flows from power stations to demand centers



## Main components of a power system



# I have gone through a few energy transitions



# My PhD journey covers two continents

	Funding	Teaching assistantships	Courses
 SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN  <b>Engineering Systems &amp; Design</b>	H.R.H. Princess Maha Chakri Sirindhorn & SUTD Scholarship	<ul style="list-style-type: none"><li>• Linear optimization (TA Award)</li><li>• Engineering Systems Architecture</li></ul>	<ul style="list-style-type: none"><li>• Linear optimization</li><li>• Stochastic modeling</li><li>• Metaheuristic optimization</li><li>• Machine Learning</li><li>• Research methods</li></ul>
 <b>Cornell University</b>  <b>Civil &amp; Environmental Engr</b> <ul style="list-style-type: none"><li>• <i>Computational Science and Engr</i></li><li>• <i>Mathematical Programming</i></li></ul>	GTA/GRA	<ul style="list-style-type: none"><li>• Decision Framing and Analytics</li><li>• Engineering Applications of Artificial Intelligence</li></ul>	<ul style="list-style-type: none"><li>• Decision Framing and Analytics</li><li>• Appl Parallel Computing</li><li>• Water-Resources Systems Engr</li><li>• Electric Power Systems I (Audit)</li><li>• Infrastructure Regulation and Policy</li><li>• Optimization Modeling in Finance (Audit)</li></ul>

# Research outputs during my PhD studies

## Mission

## Research outputs during my PhD

### Methodological innovation

Develop and maintain well-tested, open-source computational frameworks built on solid mathematical foundations to analyze energy policy challenges



- [Bunnak, P., Eldardiry, H., Pavičević, M., Feng, J. Z., & Galelli, S. \(2025\). PowNet 2.0: A production cost modeling framework for large-scale power systems. \*Journal of Open Source Software\*, 10\(111\), 8035.](#)
- [Bunnak, P., Coniglio, S., & Galelli, S. \(2025\). Bridging theory and practice: Efficiently solving the unit commitment problem in production cost models. \*Energy\*, 322, 135454.](#)
- [Bunnak, P., Pimsawan, J., & Galelli, S. \(Revised January 9, 2026; submitted April 21, 2025\). Beyond economic dispatch: Modeling renewable purchase agreements in production cost models, \*Renewable Energy\*.](#)

### Knowledge translation

Translate complex analytical insights on regional infrastructure governance, market reforms, and sustainability for stakeholders



- [Bunnak, P., Eldardiry, H., Reed, P., Sutabutr, T., & Galelli, S. \(Under review, submitted March 5, 2026\). Power purchase agreements are choke points for electricity trade in Southeast Asia, \*Joule\*.](#)
- [Bunnak, P., Song, N., Chen, X., & Thomson, R. \(2024\). A governance perspective on China's Belt and Road Initiative: a case study of the Sino-Thai railway project. \*Journal of Asian Public Policy\*, 1–20.](#)

# My thesis is built on the following papers



## Papers 1 + 2

*Advancing modeling techniques*

Fast algorithms and modeling frameworks for power system analysis

*How to improve the runtime while maintaining model fidelity?*



## Paper 3

*Advancing modeling techniques*

Integrating market constraints into a power system model

*How do we model contractual constraints?*



## Paper 4

*Knowledge translation*

Evaluate the opportunity costs of existing power purchase agreements in Mainland Southeast Asia

*Since contracts are conceived before physical infrastructure, were they designed to account for actual hydro-climate conditions?*

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- [Bunnak, P.](#), Eldardiry, H., Pavičević, M., Feng, J. Z., & Galelli, S. (2025). PowNet 2.0: A production cost modeling framework for large-scale power systems. *Journal of Open Source Software*, 10(111), 8035.



## Paper 3

*Advancing modeling techniques*

Integrating market constraints into a power system model

*How do we model contractual constraints?*



## Paper 4

*Knowledge translation*

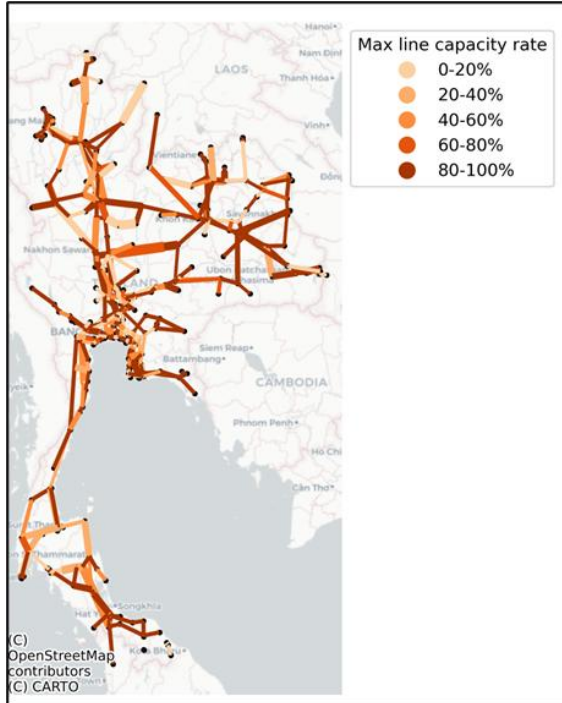
Evaluate the opportunity costs of existing power purchase agreements in Mainland Southeast Asia

*Since contracts are conceived before physical infrastructure, were they designed to account for actual hydro-climate conditions?*

# Use cases of a production cost model

## System-level analysis

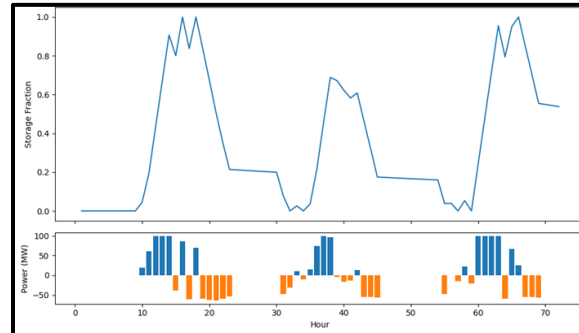
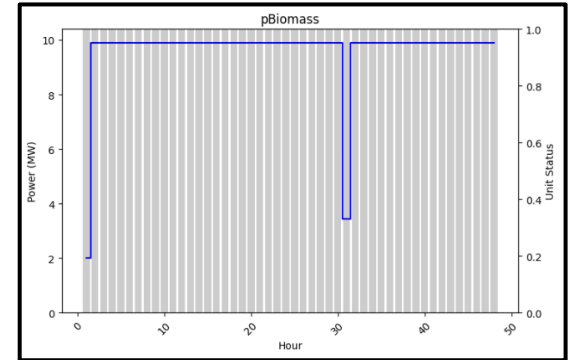
### Line congestion



## Unit-level analysis

### Thermal units

- Gray bands are periods when the unit is online
- Blue line is the power output



### Energy storage units

- Top graph shows the state of charge
- Bottom graph shows the charging/discharging rates

# A production cost model is an optimization problem

## Anatomy of the Unit Commitment Problem (mixed integer linear program)

### Example parameters

Minimize

**System costs  
+ penalties**

Fuel costs, O&M,  
Value of Loss load

**Binary variables make the math  
difficult to solve!**

---

Subject to

- **Electricity demand**

Load profile

- **Generators**

- **Energy storage units**

Location, capacity,  
technical parameters

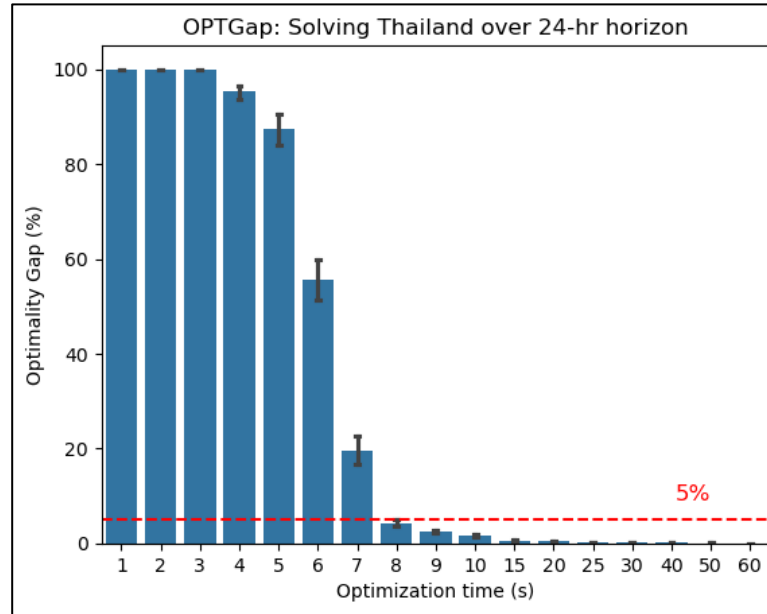
- **Transmission lines**

- **Regulatory requirements**

Spinning reserve,  
emission limits

# Modeling the Thai power system could require ~1,000 hours of compute

## Model error versus solver time



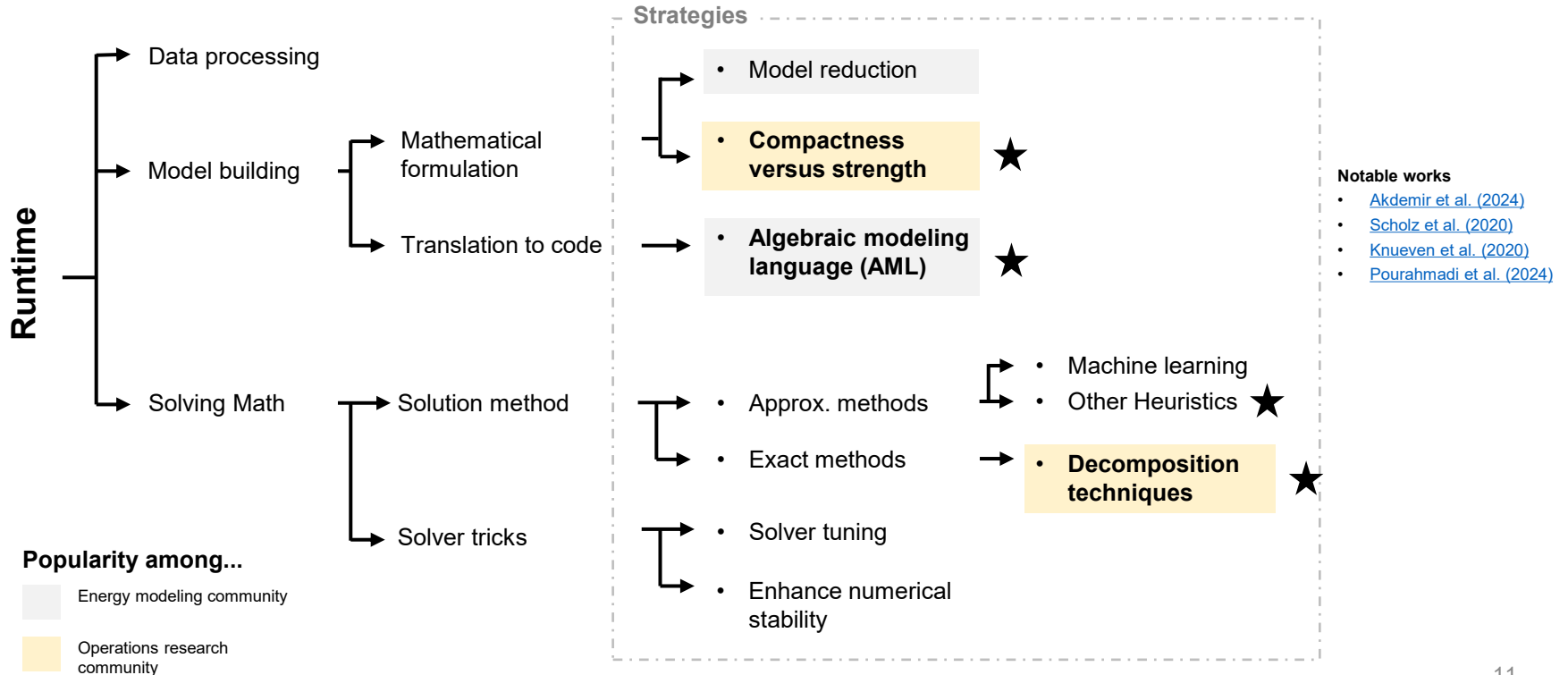
- The solver finds a good solution after 10s

Based on 10 seconds to solve x 365 days in a year x 1000 synthetic climate years = 36,500,000 seconds or 1000 hours or 40 days

# Let's take a more fundamental look at model runtime

★ Covered by Papers 1 and 2

## Breakdown of contributors to runtime



# Paper 1: How to improve the runtime while maintaining model fidelity?

## Research questions to address

- Which unit commitment problem formulation should be adopted?



- What is the performance of heuristics?
  - Solution quality
  - Runtime



- How robust are the performance of the heuristics to their parameterizations?



## Key activities

- Formulate a unit commitment problem with strong formulation

- Design two heuristics: iterative rounding and a column generation heuristic

- Evaluate the performance of these heuristics with country-scale unit commitment problems

# Mathematical formulation must balance compactness versus strength (1/2)

Formulation 1

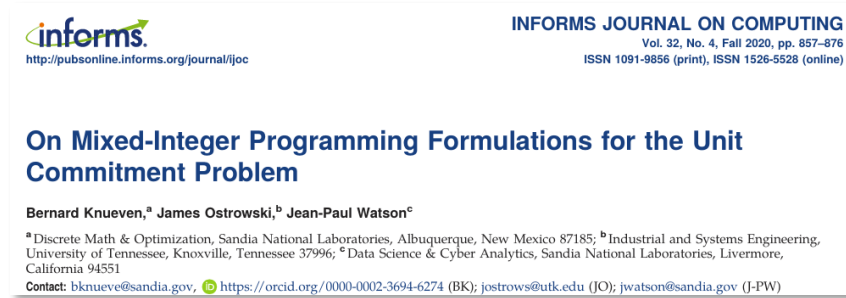
$$5 = 1 + 1 + 1 + 1 + 1$$

Formulation 2

$$5 = 2.5 \times 2$$

# Mathematical formulation must balance compactness versus strength (2/2)

The formulation of our unit commitment problem relies on these two works




**informs.**  
http://pubsonline.informs.org/journal/ijoc

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ISSN 1091-9856 (print), ISSN 1526-5528 (online)

## On Mixed-Integer Programming Formulations for the Unit Commitment Problem

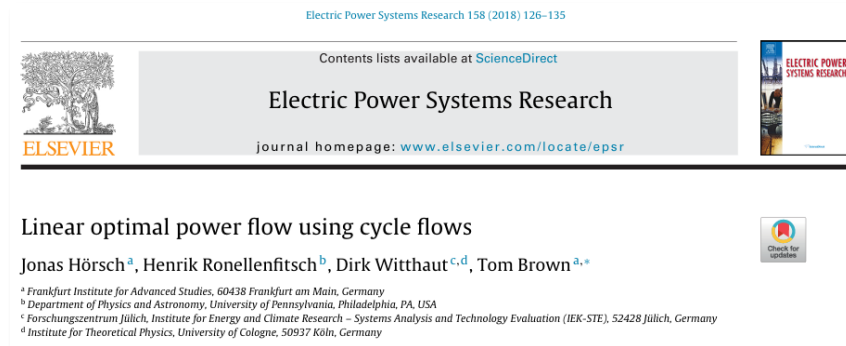
Bernard Knueven,<sup>a</sup> James Ostrowski,<sup>b</sup> Jean-Paul Watson<sup>c</sup>

<sup>a</sup> Discrete Math & Optimization, Sandia National Laboratories, Albuquerque, New Mexico 87185; <sup>b</sup> Industrial and Systems Engineering, University of Tennessee, Knoxville, Tennessee 37996; <sup>c</sup> Data Science & Cyber Analytics, Sandia National Laboratories, Livermore, California 94551

Contact: bknueve@sandia.gov,  <https://orcid.org/0000-0002-3694-6274> (BK); jostrows@utk.edu (JO); jwatson@sandia.gov (J-PW)



- 3-bin formulation
- Use  $\bar{p} = p + u_t \underline{p}$  to get a continuous variable



Electric Power Systems Research 158 (2018) 126–135

Contents lists available at ScienceDirect


## Electric Power Systems Research

journal homepage: [www.elsevier.com/locate/epsr](http://www.elsevier.com/locate/epsr)

### Linear optimal power flow using cycle flows

Jonas Hörsch<sup>a</sup>, Henrik Ronellenfitsch<sup>b</sup>, Dirk Witthaut<sup>c,d</sup>, Tom Brown<sup>a,\*</sup>

<sup>a</sup> Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany  
<sup>b</sup> Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA, USA  
<sup>c</sup> Forschungszentrum Jülich, Institute for Energy and Climate Research – Systems Analysis and Technology Evaluation (IEK-S TE), 52428 Jülich, Germany  
<sup>d</sup> Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany



- Switch from angle-based flow formulation to Kirchhoff's formulation (based on KVL)

# What is the iterative rounding heuristic?

**Iterative rounding:** If binary variables are difficult to solve, then treat them as continuous variables and round them later

## Which variables to round?

- **generator's status**
- indicator of start up
- indicator of shut down

## What is the rounding threshold?

- Anything fractional values above zero

## What parameters do we need to tune?

- Only need to select from two rounding strategies
  - Slow rounding
  - Fast rounding

# What is the best way to round variables? (1/2)

## Strategy 1: SLOW rounding >> to ensure feasibility

Optimal solution when all variables are continuous.

$u$  is the unit status.

Variable	LP solution
$u_{pGas,7}$	0.404
$u_{pGas,8}$	0.493
$u_{pGas,9}$	<b>0.539</b>
$u_{pGas,10}$	<b>0.539</b>
$u_{pGas,11}$	<b>0.539</b>
$u_{pGas,12}$	<b>0.539</b>
$u_{pGas,13}$	<b>0.539</b>
$u_{pGas,14}$	<b>0.559</b>
$u_{pGas,15}$	0.533
$u_{pGas,16}$	0.503
$u_{pGas,17}$	0.478
$u_{pGas,18}$	0.478
$u_{pGas,19}$	0.478




1. Select a variable(s) with the largest fraction
2. If the fraction is larger than a pre-specified threshold, then round to one. Else, round down to zero.
3. Re-optimize
4. Repeat (1) to (3) till there is no fraction left

# What is the best way to round variables? (2/2)

## Strategy 2: FAST rounding >> to quickly solve

Optimal solution when all variables are continuous.  
 $u$  is the unit status.

Variable	LP solution
$u_{pGas,7}$	0.404
$u_{pGas,8}$	0.493
$u_{pGas,9}$	0.539
$u_{pGas,10}$	0.539
$u_{pGas,11}$	0.539
$u_{pGas,12}$	0.539
$u_{pGas,13}$	0.539
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$u_{pGas,15}$	0.533
$u_{pGas,16}$	0.503
$u_{pGas,17}$	0.478
$u_{pGas,18}$	0.478
$u_{pGas,19}$	0.478

- 
1. Select all variables with fractional values
  2. If the fraction is larger than a pre-specified threshold, then round to one. Else, round down to zero.
  3. Re-optimize
  4. Repeat (1) to (3) till there is no fraction left

# Experimental set-up: Iterative rounding

## Key steps

### 1. Select three power systems

- Laos (8,040 variables and 4,204 constraints)
- Cambodia (5,232 variables and 5,118 constraints)
- Thailand (48,000 variables and 44,556 constraints)

### 2. Run the models across 365 days with Gurobi

- Outputs represent the “true” solutions

### 3. Solve the problem with iterative rounding

- Evaluate FAST and SLOW across several rounding thresholds

### 4. Calculate the optimality gap (OPTGap)

### 5. Solve the problem like (2) but set MIPGap equal to the OPTGap from (4)

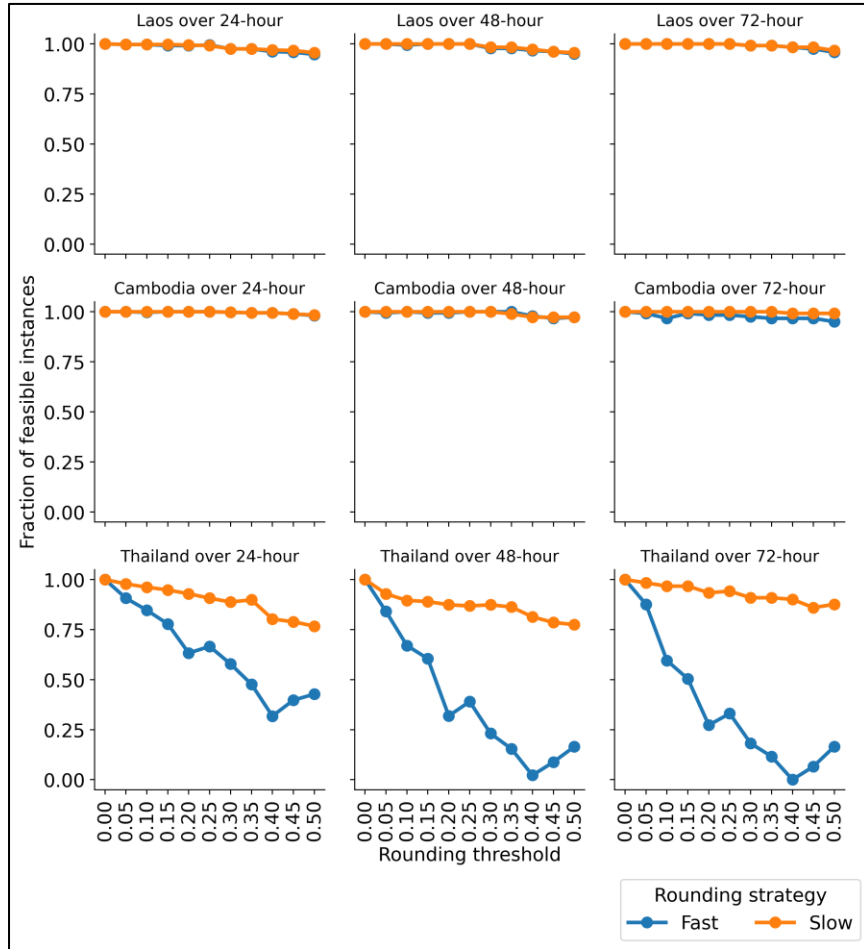
## Hardware

- Hopper Cluster (@Cornell CAC)
- Dual 20-core Intel Xeon Gold 5218R CPUs @ 2.1 GHz, 192 GB of RAM

## Software

- Python 3.10
- OpenHPC 2.3 with Rocky Linux 8.4
- Gurobi 3.9

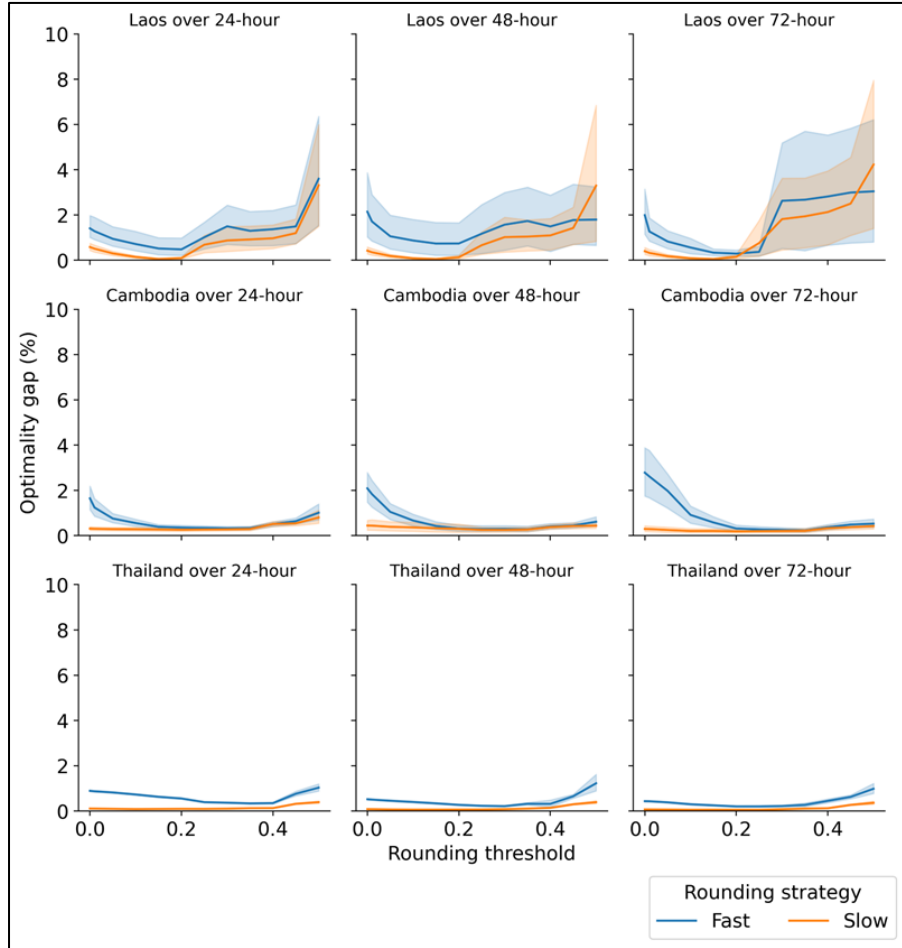
## Feasibility versus rounding threshold



## Findings on Iterative rounding

1. Low rounding thresholds can reduce infeasibility to zero

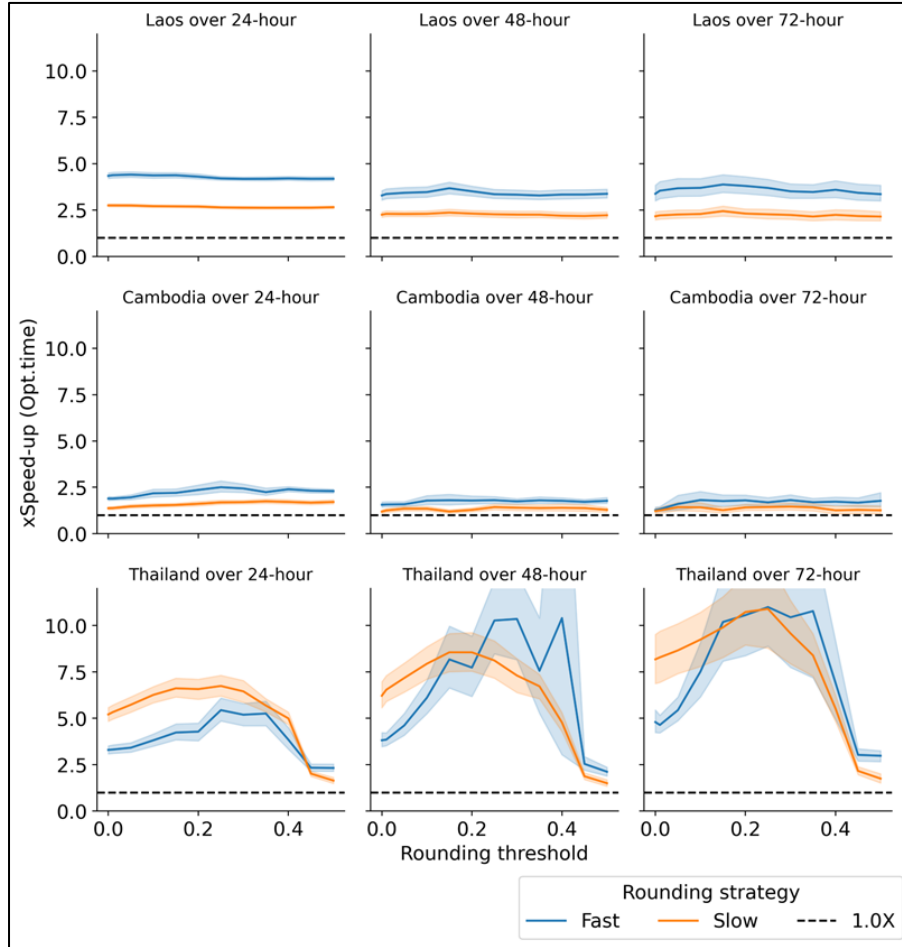
## Optimality gap vs. rounding thresholds



## Findings on Iterative rounding

1. Low rounding thresholds can reduce infeasibility to zero
2. Iterating rounding consistently achieves less than 2% error

## Speed-up (Optimization time) vs. rounding thresholds



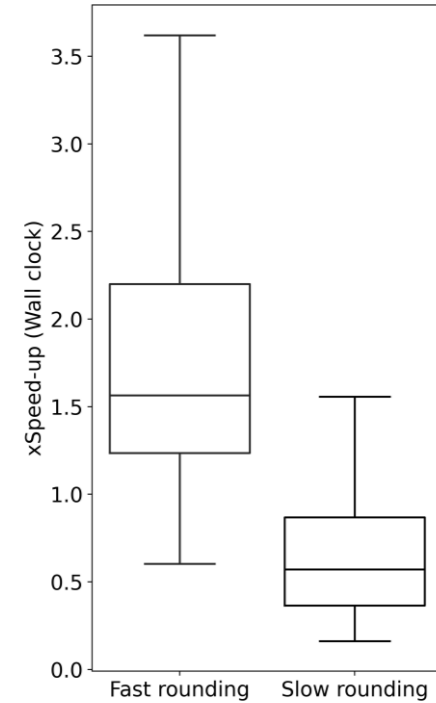
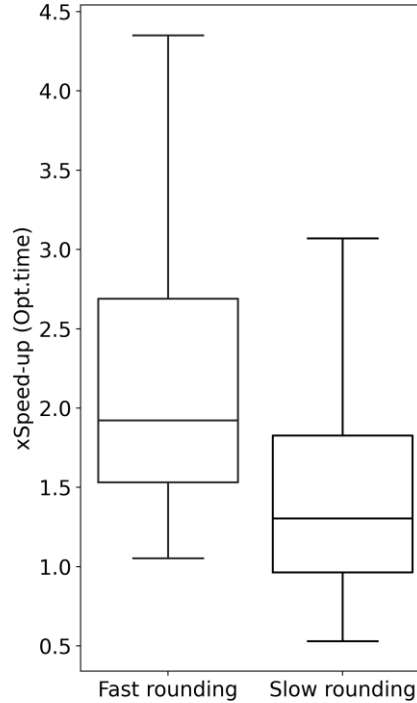
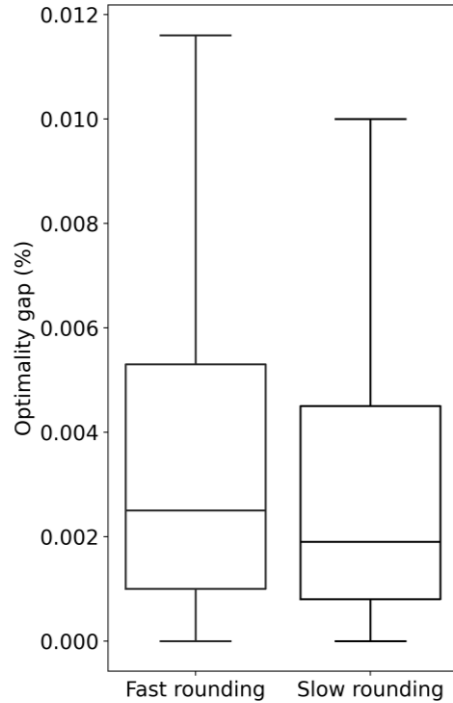
## Findings on Iterative rounding

1. Low rounding thresholds can reduce infeasibility to zero
2. Iterating rounding consistently achieves less than 2% error
3. The solution process achieves 5x speed-up

# Iterative rounding scales very well with large problem instances

Tested case6468rte system (1,262 thermal units and 6,468 buses)

The performance of iterative rounding in terms of optimality gap and speed-ups



*Thank you Reviewer 2.....*

# Software contributions from this work



## Paper 2: Power system modeling framework

- Python package for production cost modeling – PowNet 2.0
- Development of the reservoir module was supported by the US Department of Energy (DOE) Water Power Technologies Office as a part of the HydroWIRES “HydroCHiPPs” project (53165).



## Decomposition-technique(s) framework

- Python package to implement Dantzig-Wolfe Decomposition



# Conclusions from Papers 1 and 2

- We can take the first principles approach to tackling model runtime
- The iterative rounding heuristic can work well for large-scale systems with limited transmission bottlenecks (fast rounding)
- Everyone is welcome to join the PowNet community and contribute
- Please take the Decomposition package out of my hands

# My thesis is built on the following papers



## Papers 1 + 2

*Advancing modeling techniques*

Fast algorithms and modeling frameworks for power system analysis

*How to improve the runtime while maintaining model fidelity?*



## Paper 3

*Advancing modeling techniques*

Integrating market constraints into a power system model

*How do we model contractual constraints?*



## Paper 4

*Knowledge translation*

Evaluate the opportunity costs of existing power purchase agreements in Mainland Southeast Asia

*Since contracts are conceived before physical infrastructure, were they designed to account for actual hydro-climate conditions?*

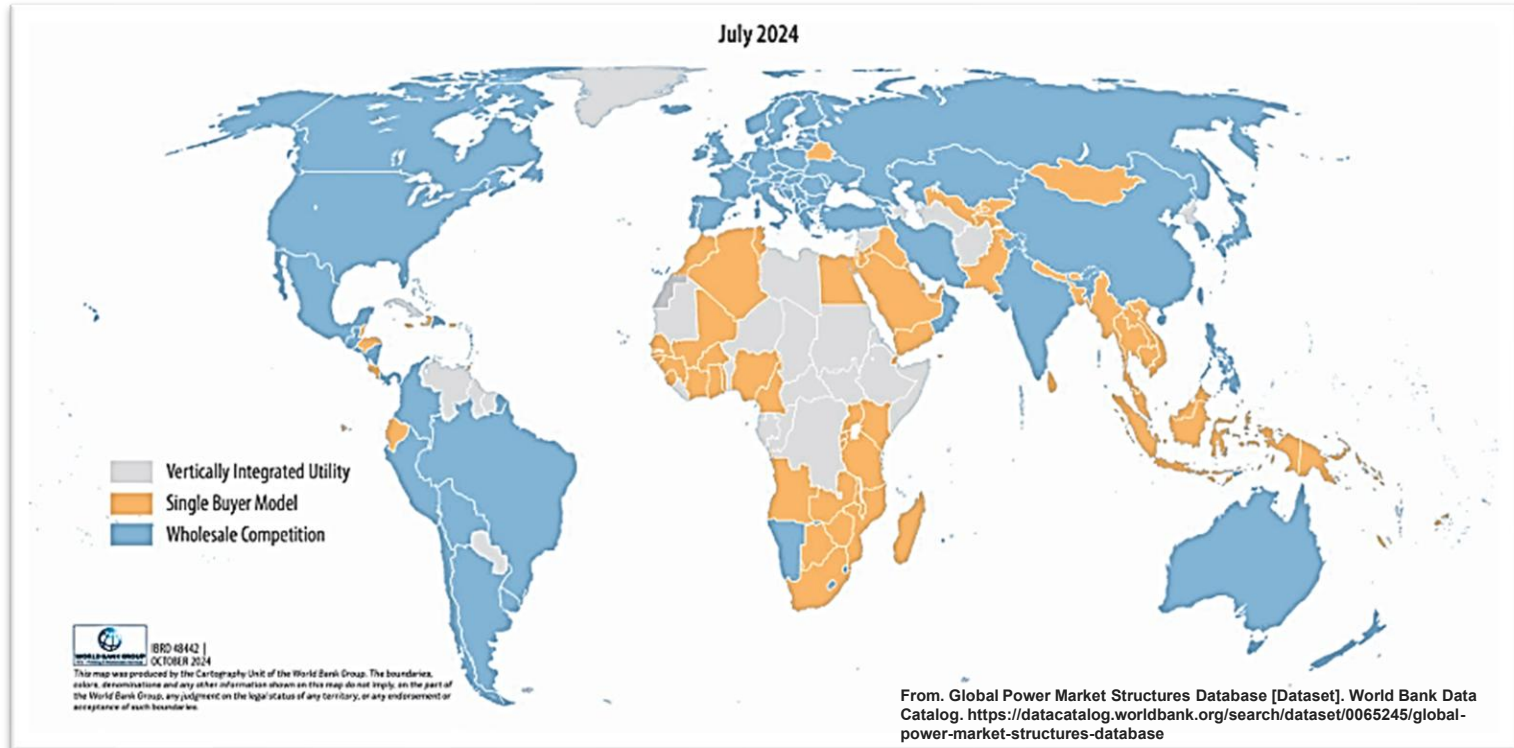
- [Bunnak, P.](#), Pimsawan, J., & Galelli, S. (Revised January 9, 2026; submitted April 21, 2025). Beyond economic dispatch: Modeling renewable purchase agreements in production cost models, Renewable Energy.

# Electricity markets are categorized into three archetypes



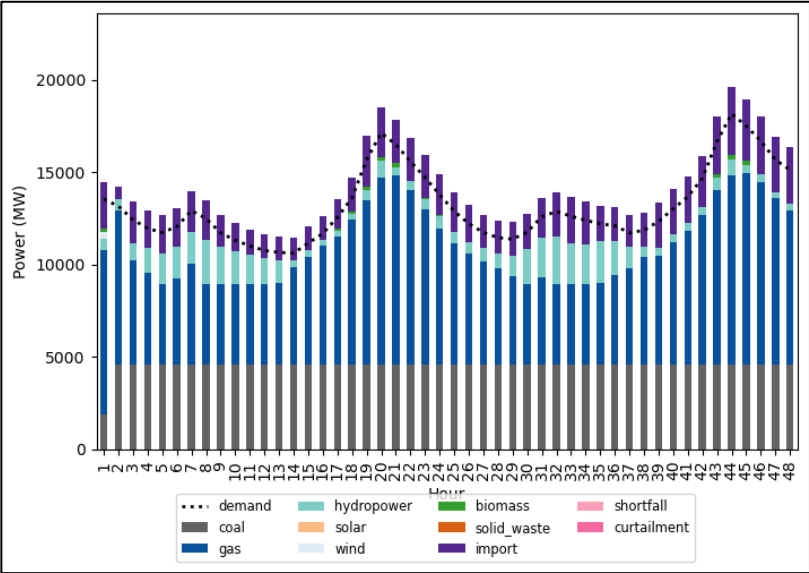
# Regulated electricity markets are found in 161 countries

Worldwide distribution of electricity markets as of July 2024



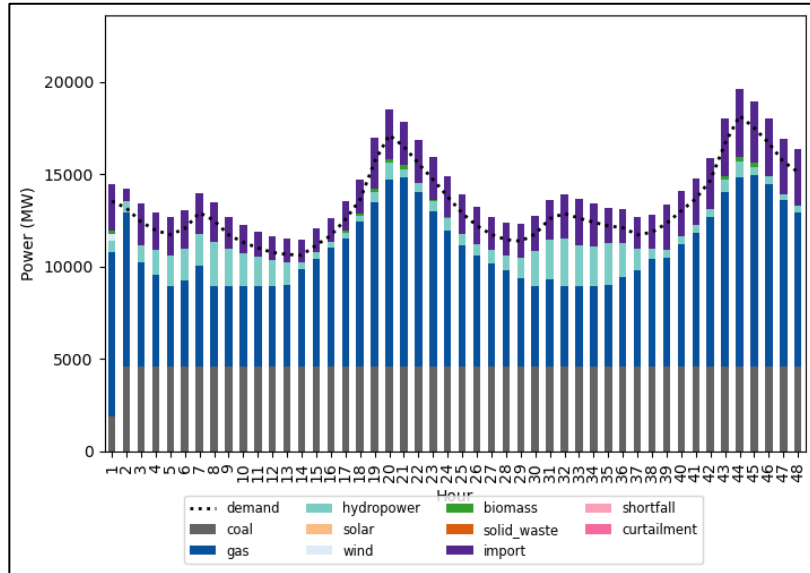
# Production cost models are validated by comparing their fuel mixes to the reported values

Simulated fuel mix (Thailand)

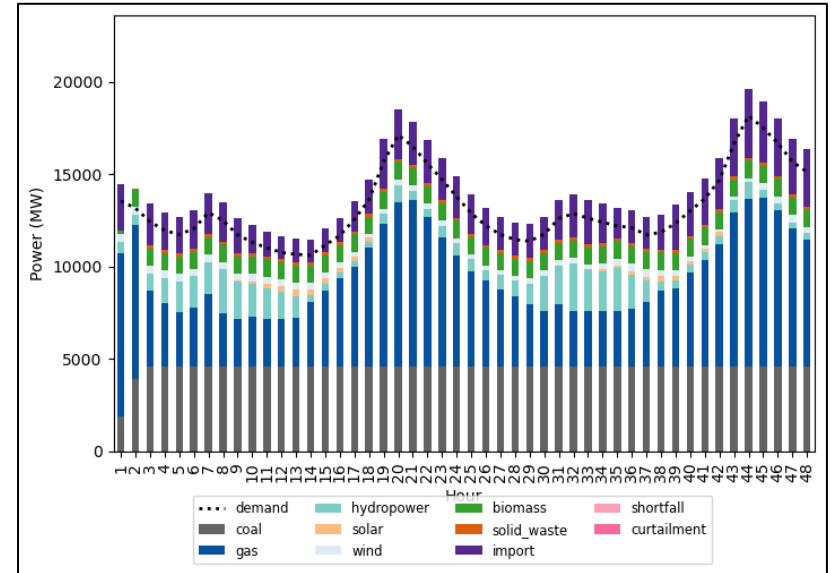


# Despite sufficiently accurate model parameters ...

## Simulated fuel mix (Thailand)



## Reported values (Thailand)



VS

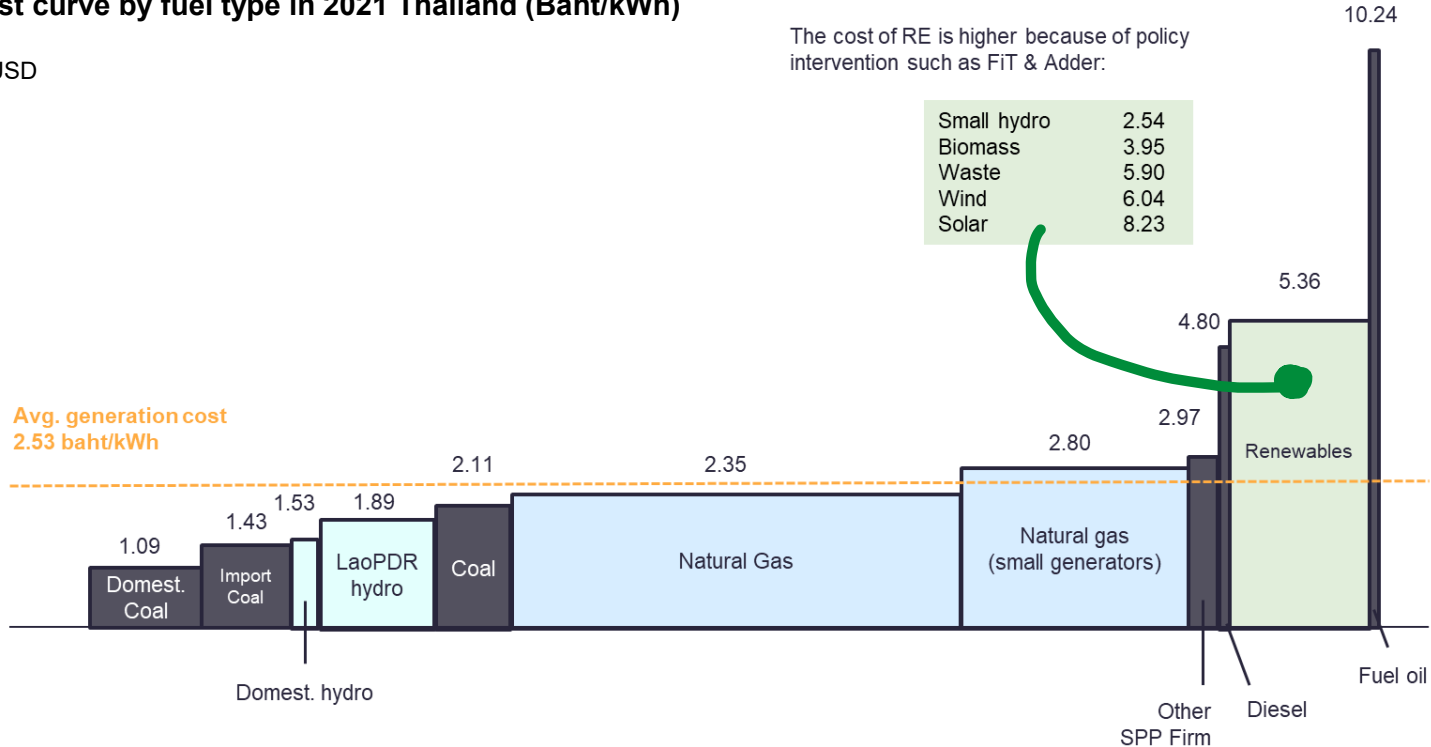
Why does the model produce unrealistic results?

# Reasons the model does not dispatch renewables (1/2)

## Renewables are not the cheapest source of electricity

### Supply-cost curve by fuel type in 2021 Thailand (Baht/kWh)

35 baht = 1 USD



# Reasons the model does not dispatch renewables (2/2)

The “market” is a set of long-term bilateral contracts

## Contents of a power purchase agreements (PPAs)

### Project finance

#### **Credit support**

financial guarantees (like letters of credit or parent company guarantees) provided by one or both parties to secure their payment obligations under the PPA.

#### **Tariff structure**

the price the buyer will pay for the electricity generated

#### **Invoicing and payments**

procedures for billing and payment terms

#### **Exchange rate**

specifics of handling foreign exchange rates

### Construction and operations

#### **Interconnection infrastructure**

the responsibilities and costs associated with building and maintaining the physical connection

#### **Testing and commissioning**

procedures to verify that the power plant meets the performance standards and specifications before commercial operation begins

#### **Operations and maintenance**

the responsibilities for operating and maintaining the power generation facility according to specific standards

### Risk management

#### **Force majeure**

clause excuses parties from fulfilling their contractual obligations due to unforeseeable events beyond their control

#### **Insurance**

types and levels of insurance coverage each party must maintain

### Administration

#### **PPA Expiration**

what happens upon PPA's conclusion

#### **Default and termination**

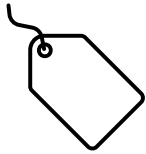
the conditions under which a party is considered in breach of the agreement

#### **Resolving disputes**

establishes the mechanism for handling disagreements between the parties

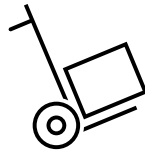
# PPAs impose multi-decade, rigid contractual obligations to the system

## Specific contract terms of note



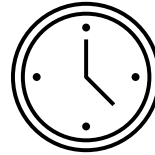
### Pricing structure

Renewables are contracted with financial incentives like feed-in tariffs



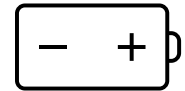
### Purchase obligation (Minimum offtake)

An obligation to purchase a certain amount of energy from “must-take” units



### Timing of delivery

Allowed window of energy delivery (hours in a day, days in a week)



### Firm energy

Required amount of energy over specific periods often with energy storage

# Paper 3: Integrating market constraints into a production cost model

## Research questions to address

- What are the strengths and weaknesses of existing strategies to model power purchase agreements?
- How do these modeling strategies affect PCM modeling outcomes?



## Key activities

- Review current approaches to model power purchase agreements
- Compare the model outputs in terms of economic and reliability dimensions

# Most studies model the purchase obligation in isolation

## Overview of strategies to model the minimum offtake

	<b>Min capacity constraint [most popular]</b>	<b>Zero-cost renewables</b>	<b>Penalized curtailment [our proposed strategy]</b>
<b>Rationale</b>	Set a min generation level for must-take units	Set the energy costs of must-take units to zero	Apply penalty for curtailing must-take units
<b>Model formulation</b>	Set the min offtake as the lower bound	Set coefficients in the objective function to zero	Add a penalty term to the objective function
<b>Considers economic curtailment?</b>	No	Misleading	Yes

# Computational experiment: Comparing strategies to model the purchase obligation

## Key steps

1. Set-up and run the following modeling scenarios using the Thai power system

Strategy	Non-dispatchable units	Dispatchable units
No must-take units (NoMT)	<ul style="list-style-type: none"><li>• Uses actual costs</li></ul>	<ul style="list-style-type: none"><li>• Uses actual costs</li></ul>
Zero-cost renewables (ZCR)	<ul style="list-style-type: none"><li>• Sets costs to zero</li></ul>	<ul style="list-style-type: none"><li>• Sets fuel costs to zero while keeping startup and shutdown costs</li></ul>
Minimum-capacity (MinCap)	<ul style="list-style-type: none"><li>• Sets the lower bound of power generation to the hourly availability</li><li>• Uses actual costs</li></ul>	<ul style="list-style-type: none"><li>• Forces units to be online</li><li>• Uses actual costs</li></ul>
Penalized curtailment (proposed)	<ul style="list-style-type: none"><li>• Penalizes curtailment in the objective function</li><li>• Uses actual costs</li></ul>	<ul style="list-style-type: none"><li>• Penalizes curtailment in the objective function</li><li>• Requires ramp rates to reach full capacity within one hour</li><li>• Uses actual costs</li></ul>

2. Process the model outputs

## Hardware

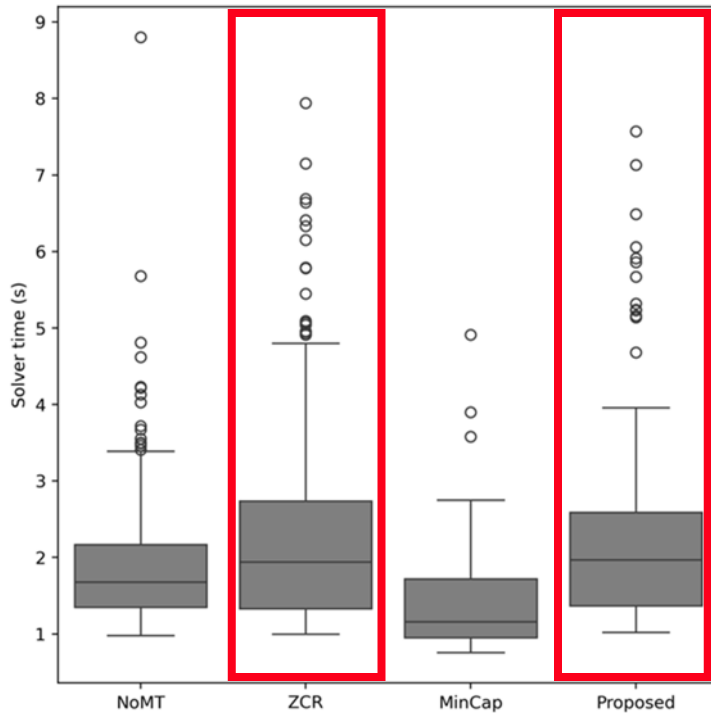
- Hopper Cluster (@Cornell CAC)
- Dual 20-core Intel Xeon Gold 5218R CPUs @ 2.1 GHz, 192 GB of RAM

## Software

- Python 3.10
- PowNet 2.0
- Gurobi 3.9

# Finding 1: The proposed strategy sees a marginal increase in model size while remaining tractable

Generation mix of different strategies



Model characteristics

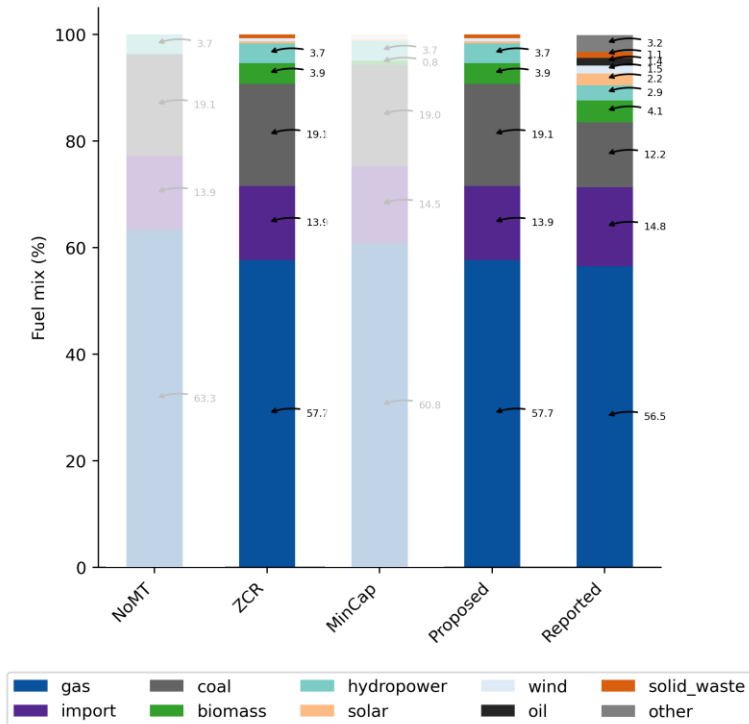
	NoMT	ZCR	MinCap	Proposed
No. continuous variables	56,688	56,688	56,688	56,688
No. binary variables	13,656	13,656	13,656	13,656
No. constraints	50,575	50,575	52,831	51,775
No. non-zero coefficients in the constraint matrix	178,885	178,885	181,141	181,285

## Findings

- The median solver time for our proposed strategy appears within the general range as other strategies
- The spread is also comparable

# Finding 2: The proposed strategy produces a realistic fuel mix

## Generation mix of different strategies



## Findings

- Our approach produces accurate generation mix
- Incurs comparable computational cost as ZCR with a smaller model size

# Conclusions from Paper 3

- Academic modeling studies often neglect the presence of power purchase agreements or model individual contractual terms in isolation
- This study provides the first comparative analysis of various strategies for modeling renewable purchase obligations in production cost models
- Our proposed modeling strategy is capable with all key PPA clauses

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Fast algorithms and modeling frameworks for power system analysis

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*Knowledge translation*

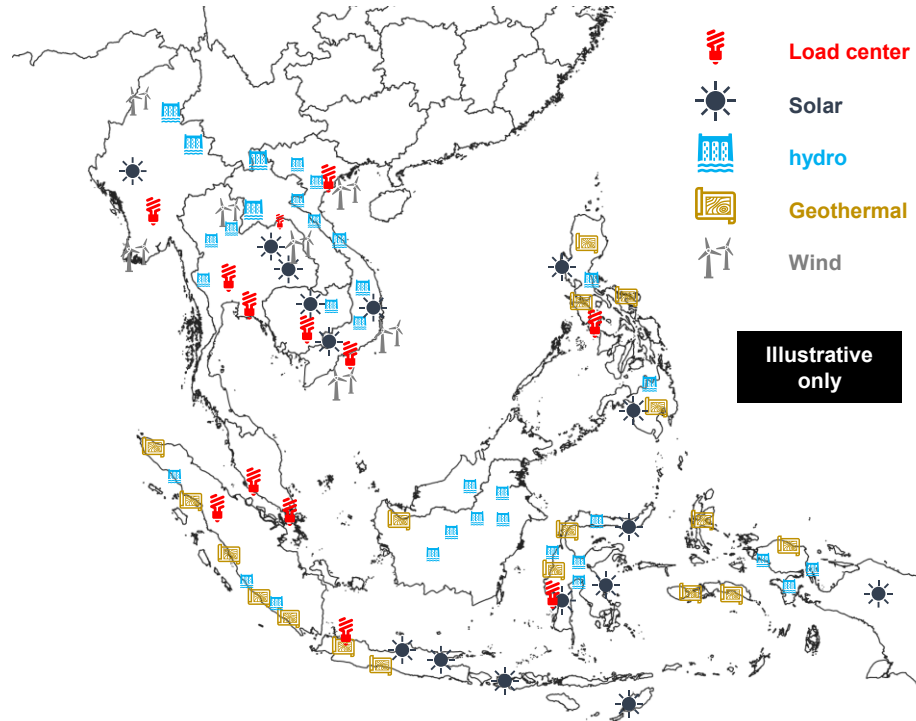
Evaluate the opportunity costs of existing power purchase agreements in Mainland Southeast Asia

*Since contracts are conceived before physical infrastructure, were they designed to account for actual hydro-climate conditions?*

- Bunnak, P., Eldardiry, H., Reed, P., Sutabutr, T., & Galelli, S. (Under review, submitted March 5, 2026). Power purchase agreements are choke points for electricity trade in Southeast Asia, Joule.

# ASEAN Power Grid is the leading priority of regional cooperation

Map of major demand centers and renewable sources



SOURCE: Compiled from various sources, such as national reports

# **Paper 4: Since contracts are conceived before physical infrastructure, were they designed to account for actual hydro-climate conditions?**

**Most cross-border trade (5600+ MW) happens in the Laos-Cambodia-Thailand-Vietnam corridor under long-term bilateral agreements**

- 1** To what extent do existing PPAs suppress the utilization of built physical infrastructure assets?
- 2** Does removing cross-border PPA constraints yield uniform economic and environmental benefits across all countries?
- 3** How effectively does transitioning to more flexible electricity trade mitigate hydro-climate-induced price shocks?

# Two types of cross-border electricity trade

## 1. Generator-to-Grid Trading

- Countries buy hydropower directly from projects in Laos
- Hydropower purchase agreements are structured after large baseload generators (coal, gas)
- *Agreements limit the maximum dispatch from a power station*

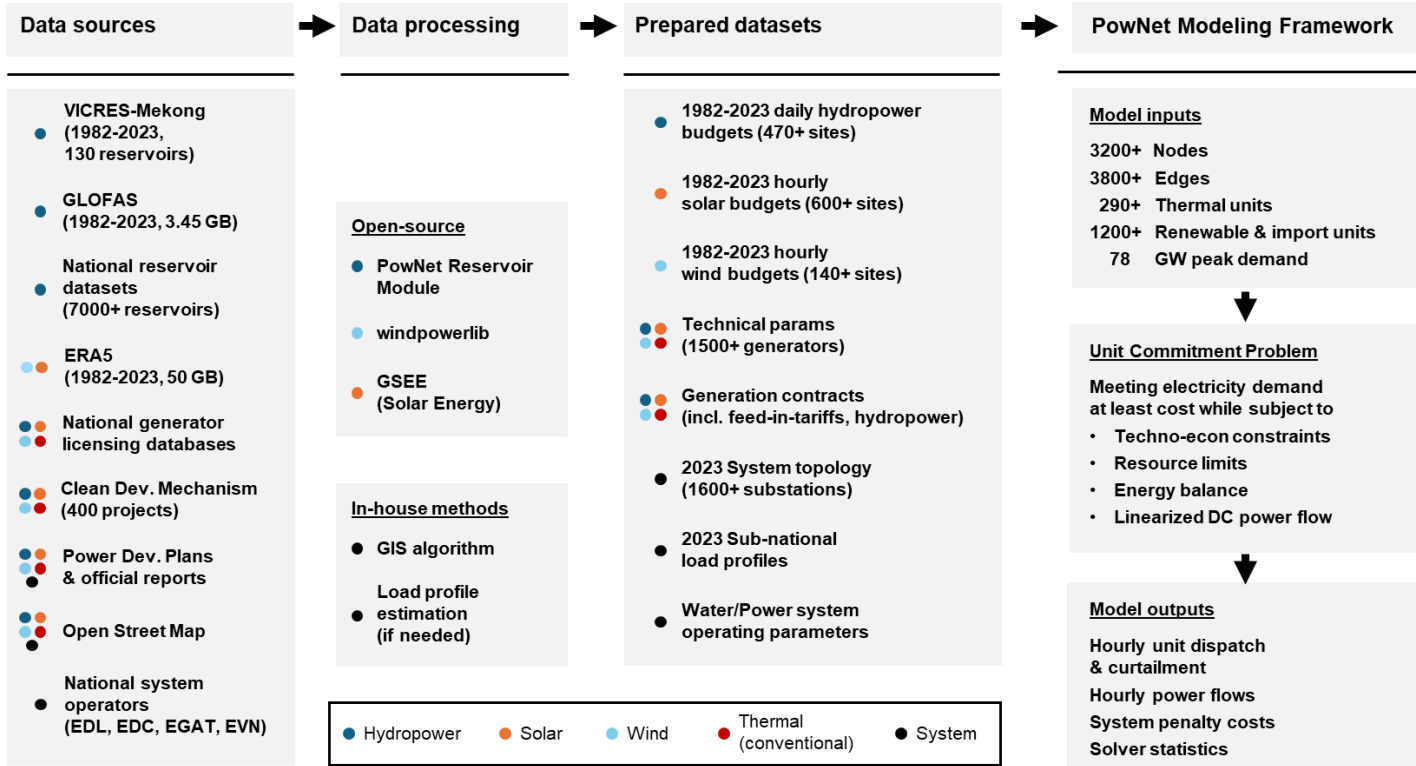
## 2. Grid-to-Grid Trading

- *Agreements limit the magnitude and direction of electricity flow*
- 18 cross-border interconnections

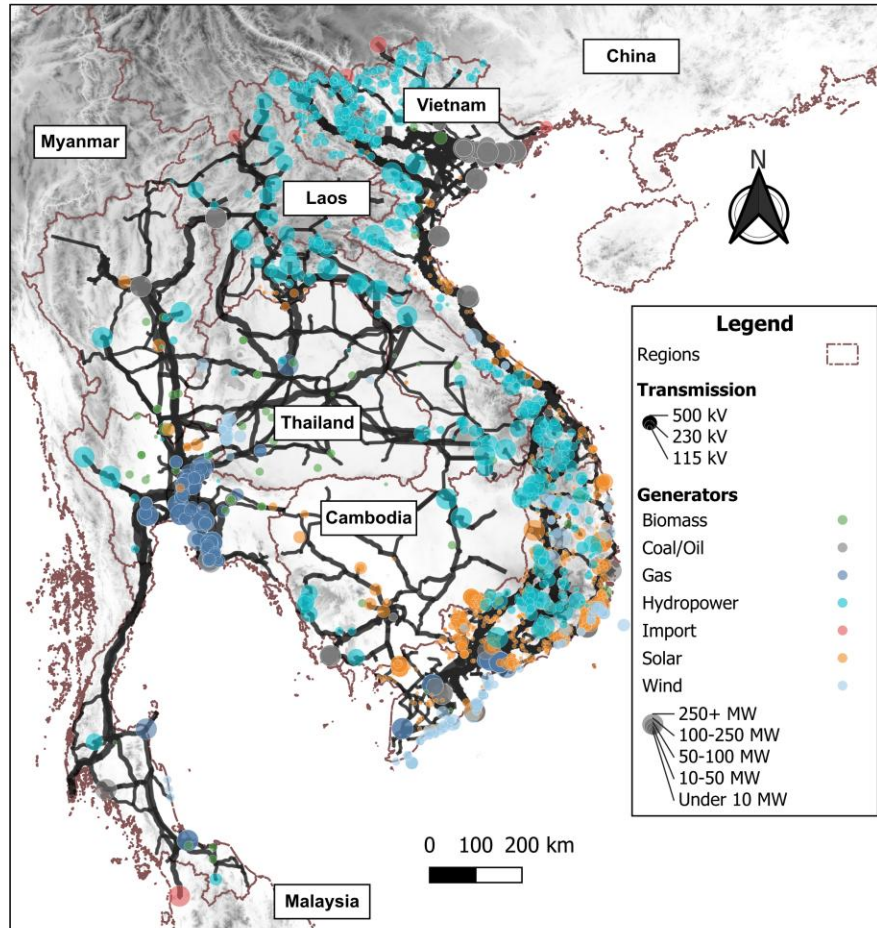
Source	Sink	Source region	Sink region	Capacity (MW)
LAO_busDongMeng	LAO_busNamo1	CHN	LAO	60
VNM_busXinqiao	VNM_busLaoCai	VNM	CHN	145
VNM_busWenshanCHN	VNM_busHaGiang	VNM	CHN	145
VNM_busDongxing	VNM_busMongCai	VNM	CHN	75
LAO_busThaLi	LAO_busPakLay	LAO	THA	100
THA_busKenThao	THA_busThali	LAO	THA	100
busNongKai	busPhonThong	LAO	THA	100
busNongKai	busThaNaLaeng	LAO	THA	100
busBungKan	busPakSan	THA	LAO	100
busNaKhonPaNom2	busThaKhaek2	THA	LAO	100
busNaKhonPaNom	busThaKhaek	THA	LAO	100
busMukDaHan	busPakBo	THA	LAO	100
busSirindhorn	busBangYo	THA	LAO	150
busSirindhorn2	busBangYo	THA	LAO	150
busWathanaNakhon	GSIndustrialEstate	THA	KHM	100
busChauDoc	busTakeo	KHM	VNM	250
busBanHat	busPreahVihear	KHM	LAO	70
THA_busGurun	THA_bus43	MYS	THA	300

# Preparing inputs for high-resolution, multi-sector modeling framework

## Overview of the workflow



## Power systems in Laos, Cambodia, Thailand, and Vietnam



# Computational experiment: Quantifying the impact of PPAs on cross-border trade and system performance

## Operating regime of the power systems

### Key steps

1. Create PowNet inputs
2. Run two policy scenarios of cross-border electricity trade
  - Business-as-Usual (BAU)
  - Flexible trade (FXT)
3. Extract performance metrics from model outputs
  - Sales revenue from export-oriented hydropower projects
  - Weighted cost of energy (WCOE)
  - Carbon emission

### Hardware

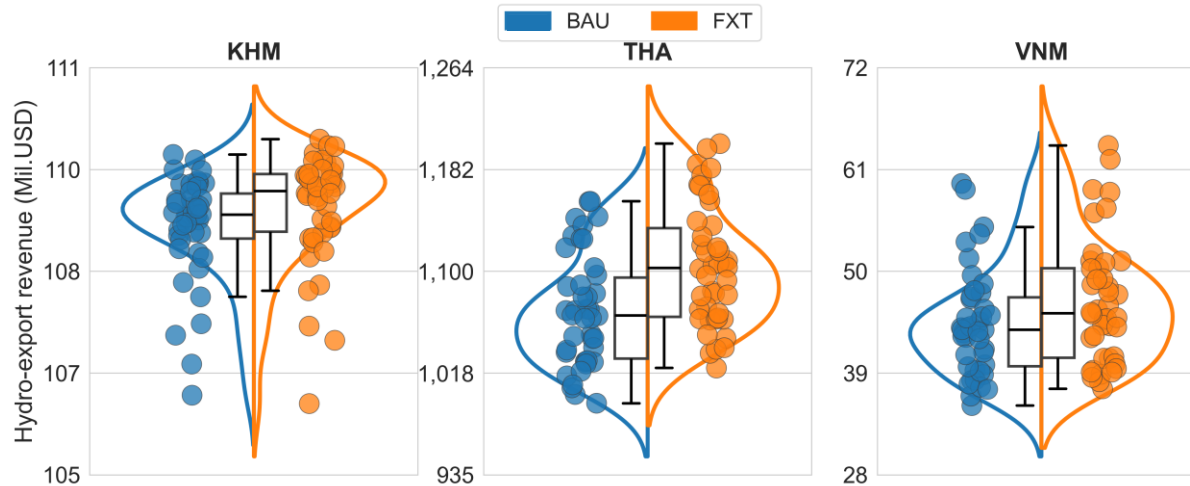
- Hopper Cluster (@Cornell CAC)
- Dual 20-core Intel Xeon Gold 5218R CPUs @ 2.1 GHz, 192 GB of RAM

### Software

- Python 3.10
- PowNet 2.1
- Gurobi 3.11

# Finding 1: Inflexible PPAs cost Laos millions of dollars in lost hydropower-export revenue (Generator-to-Grid)

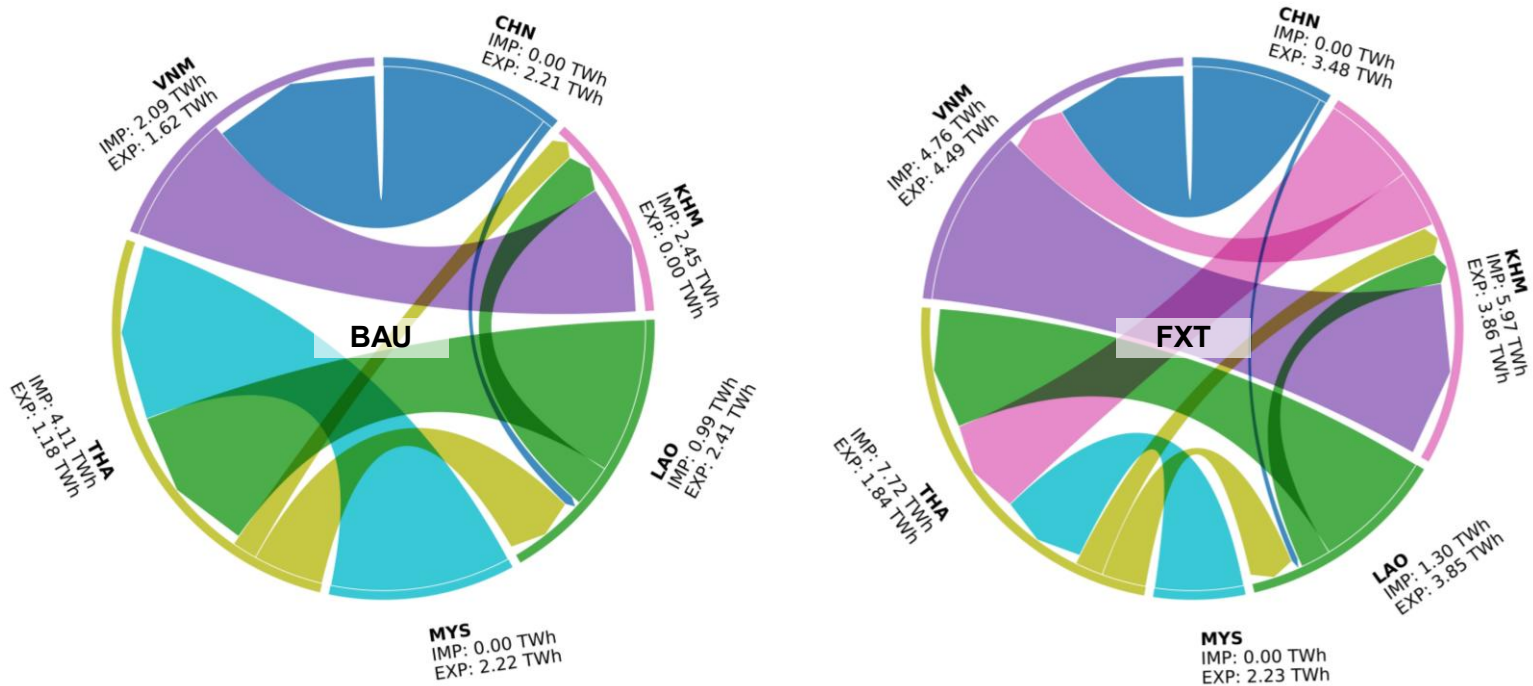
Distribution of Lao's hydropower revenue over 1982-2023 hydro-climate conditions



- The revenue gap between the BAU and FXT scenarios stems from the contractual design that prioritizes firm hydropower production over flexibility
- Contractual flexibility hedges against drought by providing a financial buffer during the driest year, increasing revenue by US\$ 28 million

# Finding 2: Grid-to-Grid agreements under utilize existing physical assets

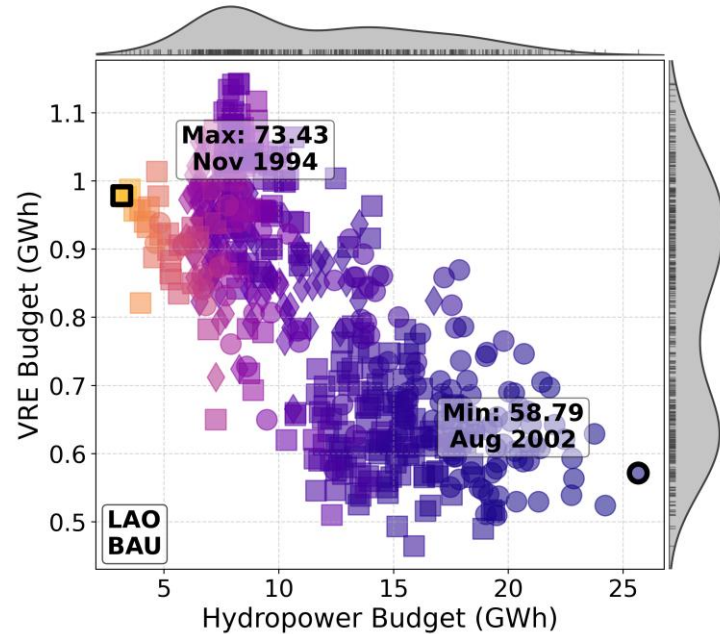
Average annual volume of grid-to-grid exchange under trading scenarios



Flexible exchanges transform Cambodia into the LCTV corridor's central trading hub

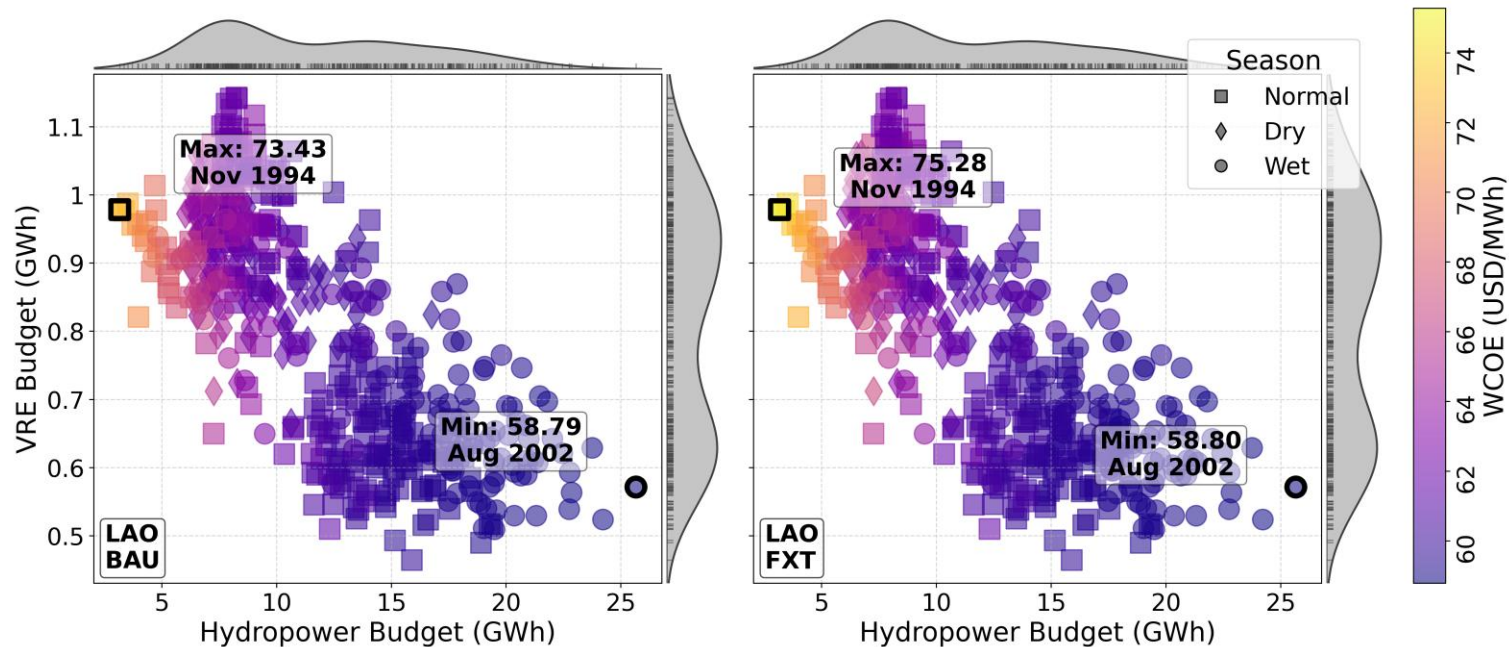
# Finding 3: Laos is seeing a hydro-climate-induced price shocks of 25%

Influence of hydro-climatic variability on the monthly weighted cost of energy (WCOE)



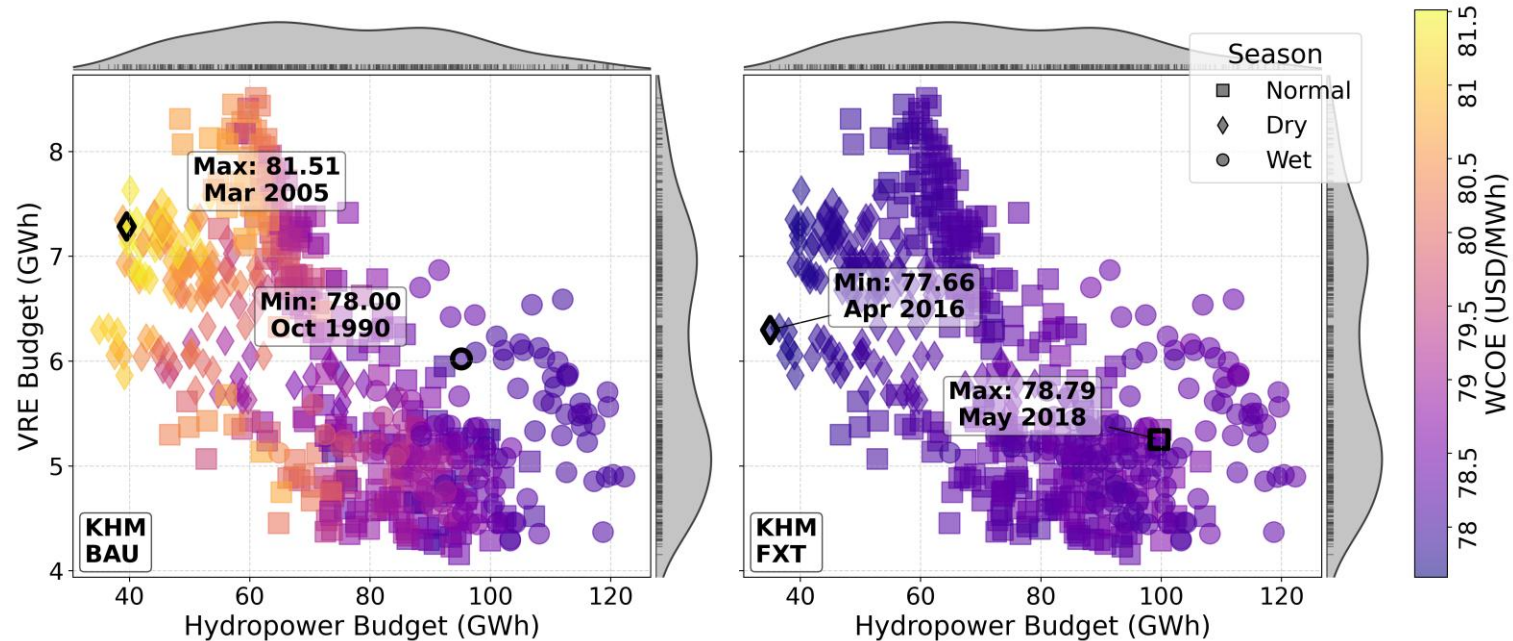
# Finding 4: Flexible trade could worsen the peak electricity cost in Laos

Influence of hydro-climatic variability on the monthly weighted cost of energy (WCOE)



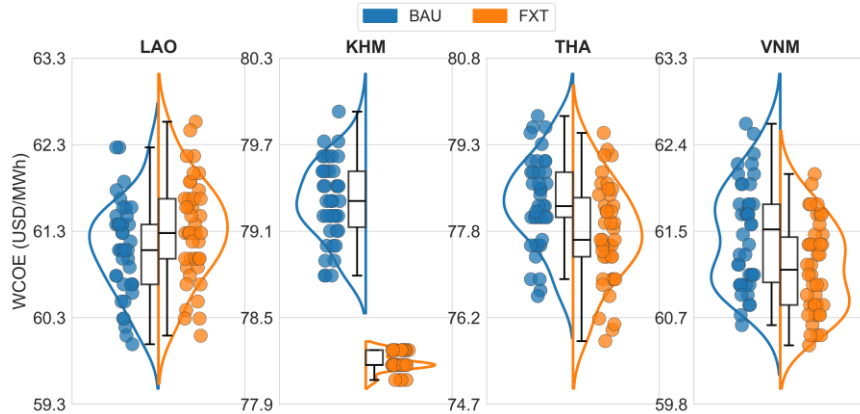
# Finding 5: Cambodia could eliminate hydro-climate induced price shocks through flexible trade

Influence of hydro-climatic variability on the monthly weighted cost of energy (WCOE)



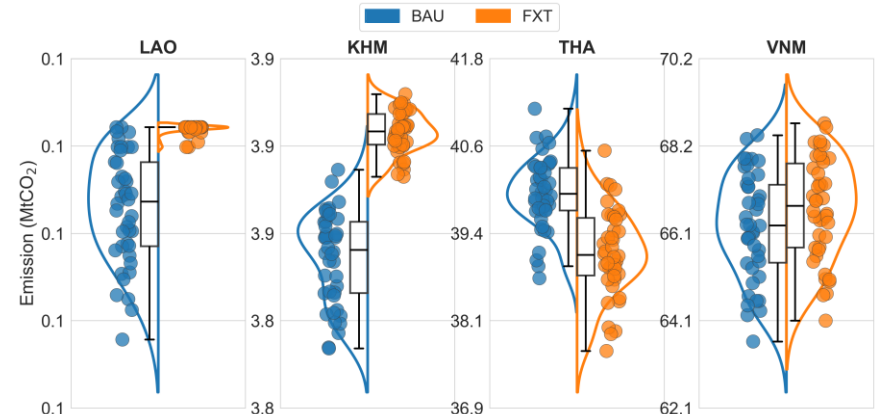
# Finding 6: More flexible cross-border trading does not benefit countries equally

Annual weighted cost of energy (WCOE)



Cambodia achieves the largest cost reduction by reducing its reliance on high-cost oil generators

Annual carbon emission



- While regional average annual carbon emission decreases by 0.31%
- For every unit of carbon Thailand saves, nearly 0.6 units are leaked to its neighbors

## Conclusions from Paper 4

- The flows of electrons are choked by ink and paper rather than physical infrastructure
- While PPAs have been the historical building blocks for cross-border electricity trade, once established, they may impose a path dependence that locks countries into sub-optimal operations for decades
- Hydro-climate-induced price shocks could create an interesting policy discussion

# Thank you

Let me know if you have questions

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