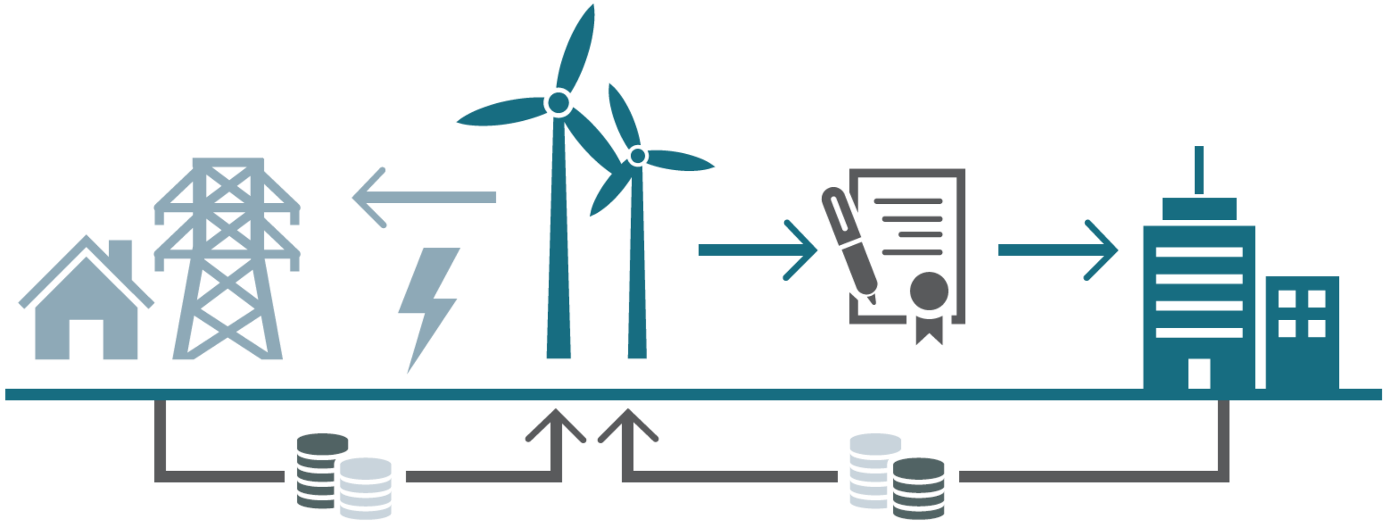

Meeting Corporate Renewable Power Targets

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Joint work with: Danial Mohseni-Taheri (UIC) and Selva Nadarajah (UIC)

Corporate Sustainability Goals

Over half of the Fortune 500 companies have committed to sustainability/climate targets (CDP et al. 2017):

- GHG emissions reduction
- Energy efficiency
- **Renewable energy procurement**

Corporate commitments to satisfy a percentage of energy demand via renewable sources

Target: α% of demand

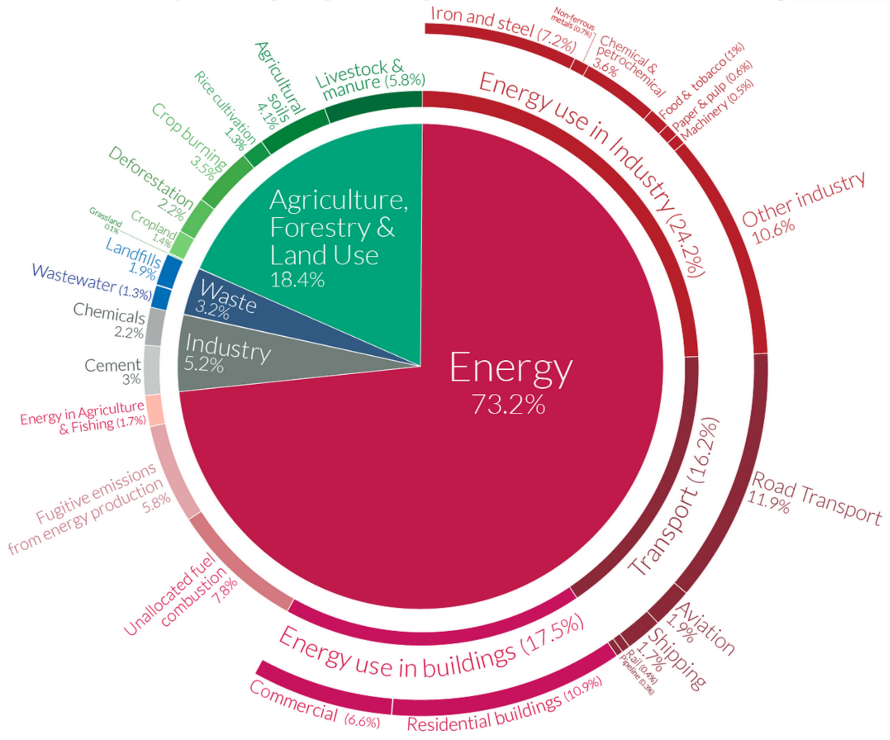
2021 — **Reach** — 2025 — **Sustain** — 2040

Corporate Procurement and Climate Change

2/3 of all CO_2 emissions come from the energy sector	Almost 2/3 of global electricity demand is due to the commercial sector

Corporate renewable procurement can play a critical role to displace such CO_2 emissions but ….

"…..corporate sourcing is still in its infancy owing to its perceived complexity and the technical and financial risks associated with changing existing patterns of energy consumption"
(International Renewable Energy Agency 2018)



Global GHG emissions by sector
(Climate Watch 2020)

Meeting a Renewable Power Target

Two dominant approaches:

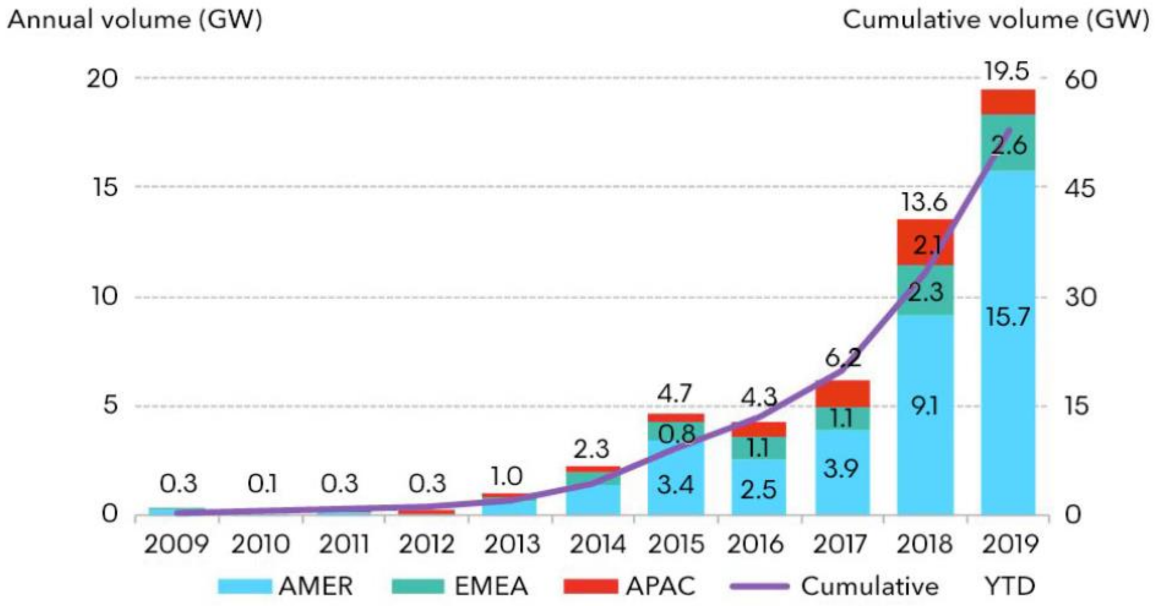
1. Short-term strategy
   - → Purchase electricity from the utility
   - → Purchase unbundled renewable energy certificates (**RECs**) when needed

2. Enter into **corporate power purchase agreements (PPAs)**
   - → Long-term contracts between company and generator
   - → Deliver both energy and RECs at fixed strike price

(from IRENA 2018)

We focus on the most-common virtual (or synthetic) PPAs

Corporate Power Purchase Agreements



- Global PPA volumes are rising sharply (BloombergNEF 2018, 2020)
- Despite encouraging trends, the majority of corporations have not signed PPAs yet

Goal of our work is understanding:

1. When a PPA is an effective procurement vehicle for renewable power
2. How a firm can reduce procurement costs while meeting a renewable energy target, potentially using a portfolio with multiple PPAs

Summary of Contributions

1. **Framework**: Propose a Markov decision process (MDP) that accounts for **timing flexibility**, **sourcing flexibility**, and **uncertainty**, and provides a framework to compare PPA-based policies

2. **Procurement tools:**
   - Consider forecast-based reoptimization heuristics and simple benchmarks (they sacrifice some MDP properties)
   - Develop a novel dual reoptimization heuristic that is consistent with the MDP policy properties, and has desirable theoretical support

3. **Computation and insights:** Define new PPA strike price model, calibrate stochastic models of uncertainty to real data, perform a comparison of procurement policies to meet a renewable target using PPAs, and understand what makes such policies effective

*The paper also includes an analysis of a stylized model

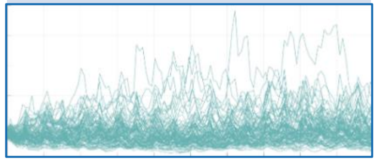
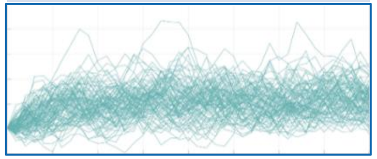
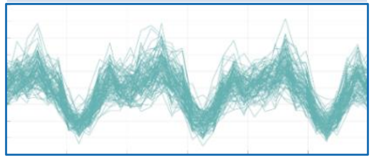
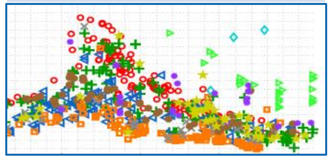
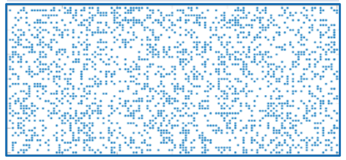
Challenges for Decision Making

Ideally, a company wants to fulfill the target at minimum cost, but:

1. Long-term planning horizon (e.g., 40 years)
2. PPAs are fairly new and “non-traditional” procurement instruments
3. Different decisions to make:

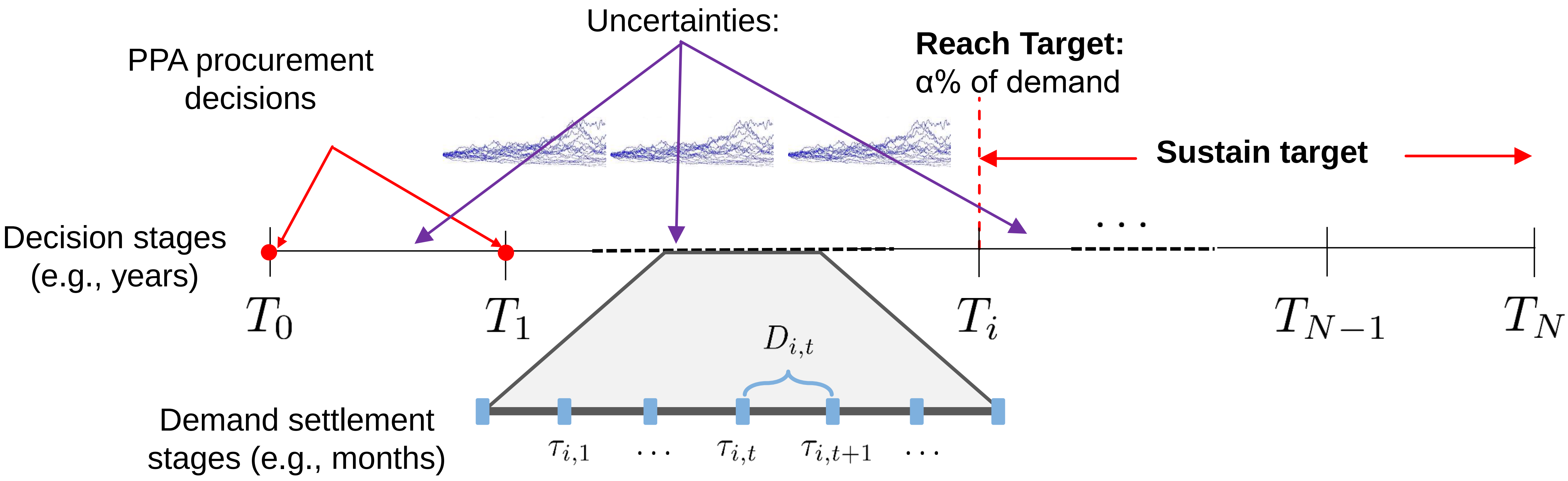
PPA length	PPA size (MW)	Timing
		

4. Multiple uncertainties:

Electricity price	REC price	Renewable supply	PPA strike price	PPA availability
				

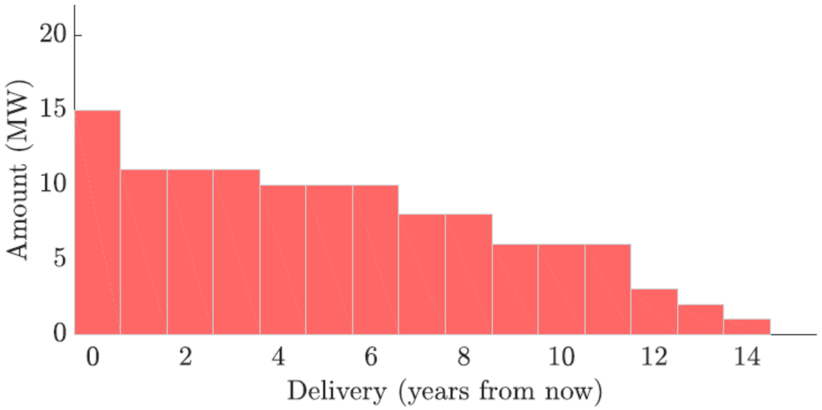
Overcoming these challenges entails solving a complex problem

Markov Decision Process

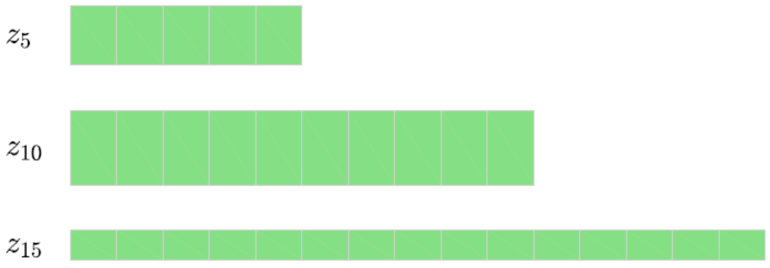


- Cost function: PPA settlements, cost of short-term electricity, cost of unbundled RECs if shortfall
- Constraints: target has to be met, min/max procurement quantities (non-convex action space)

Endogenous States, Actions, Transitions



(a) Current stage i state x_i



(b) PPA investment decision at state i

(c) Power delivery profile from new PPAs

(d) New state x_{i+1}

Procurement Analytics

- The optimal MDP policy is challenging to compute: MDP is intractable to solve when using realistic models of uncertainty and incorporating contract minima

Current practice

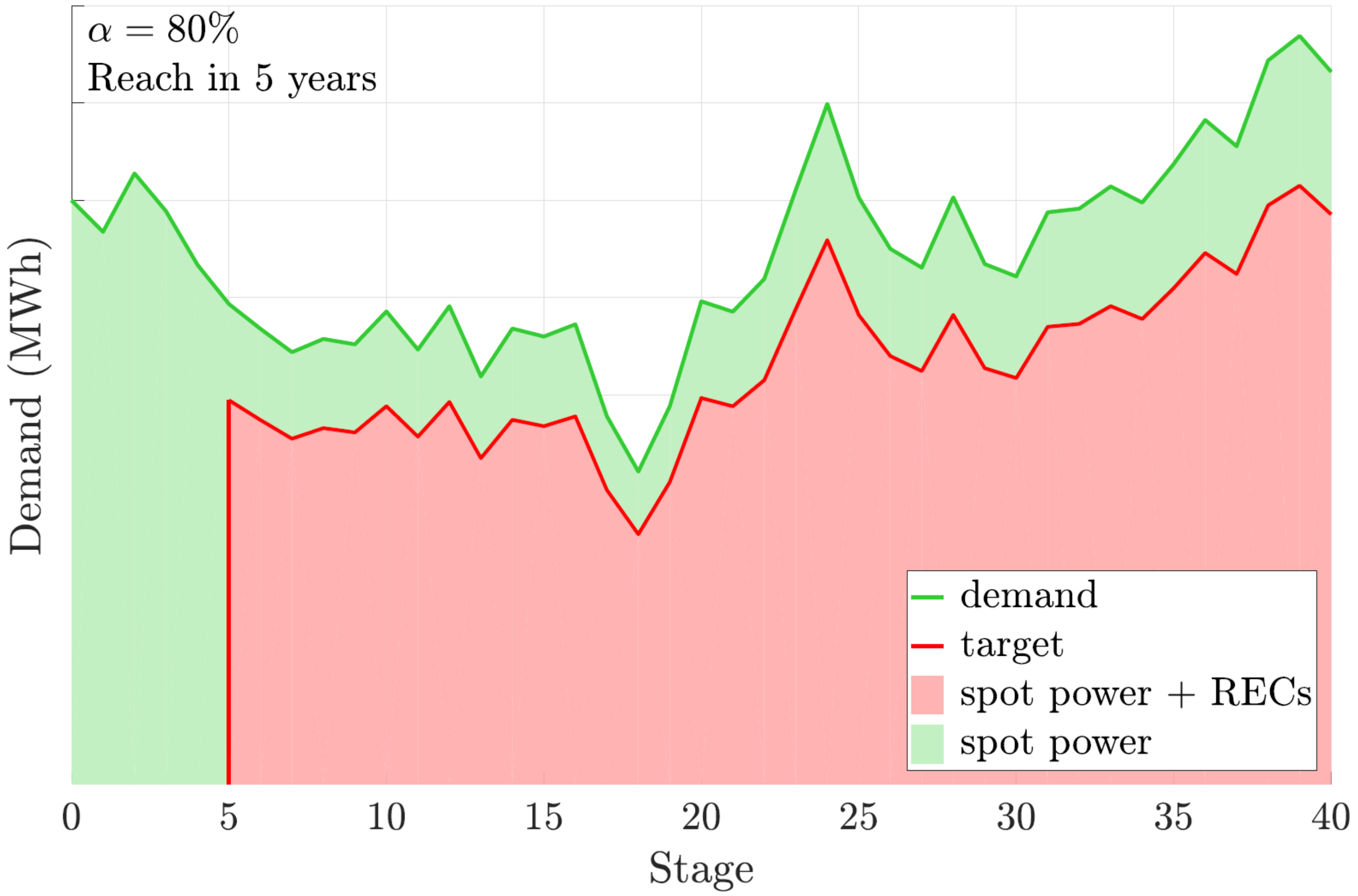
- Short-term procurement or simple algorithms
- Typically rolling horizon strategies based on forecasts
- Also known as model predictive control

Our approach

- New ADP method
- Based on the information relaxation and duality approach
- Decisions explicitly account for the unfolding of future uncertainty

Simplest Benchmark: short-term/spot

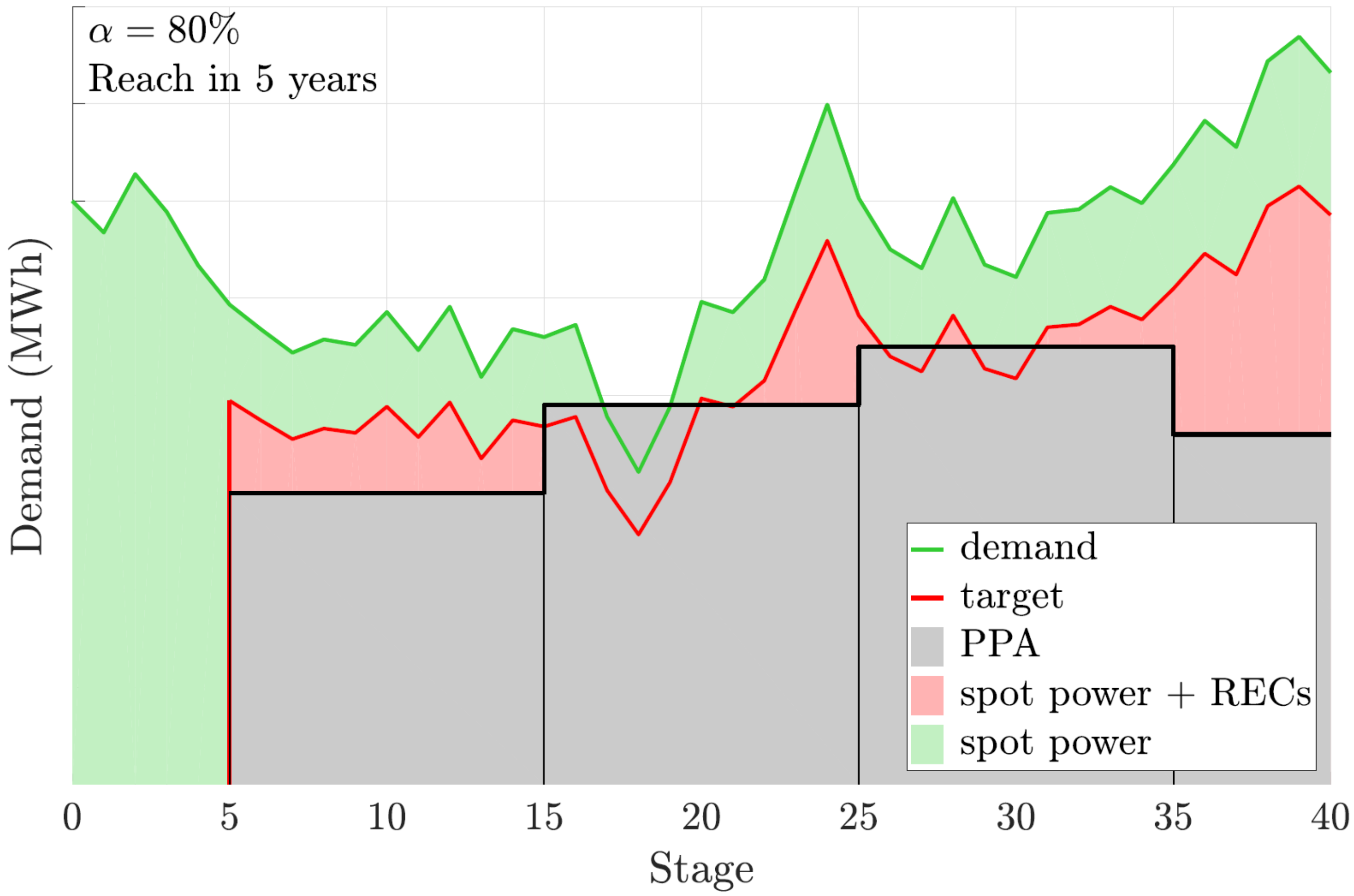
Electricity and unbundled RECs are purchased from the short-term market/utility



- No analytics needed
- Fully exposed to price risk

Forecast-based Block Heuristic (FBH)

Traditional use of PPAs renewed in a rolling fashion (WBCSD 2018)



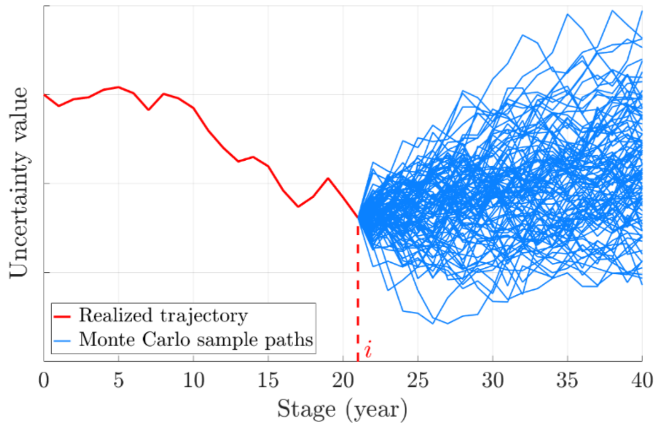
- Hold a single PPA at any time
- Renew it when needed

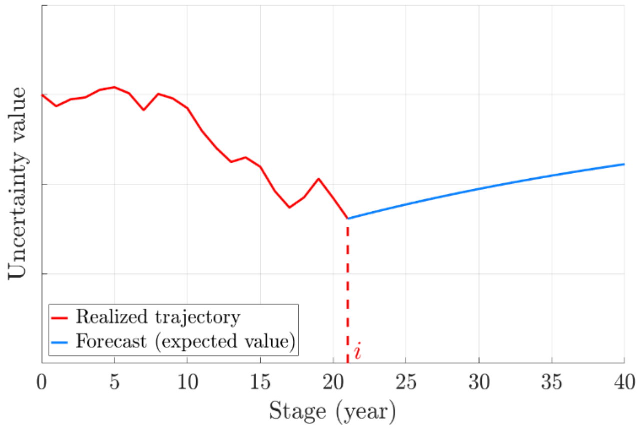
Forecast-based Reoptimization Heuristic (FRH)

Popular in operations management problems under uncertainty (Sethi and Sorger 1991, Chand et al. 2002, Sethi et al 2004, Bertsekas 2005, Balakrishnan and Cheng 2009, Lian et al. 2009)

At a stage i:

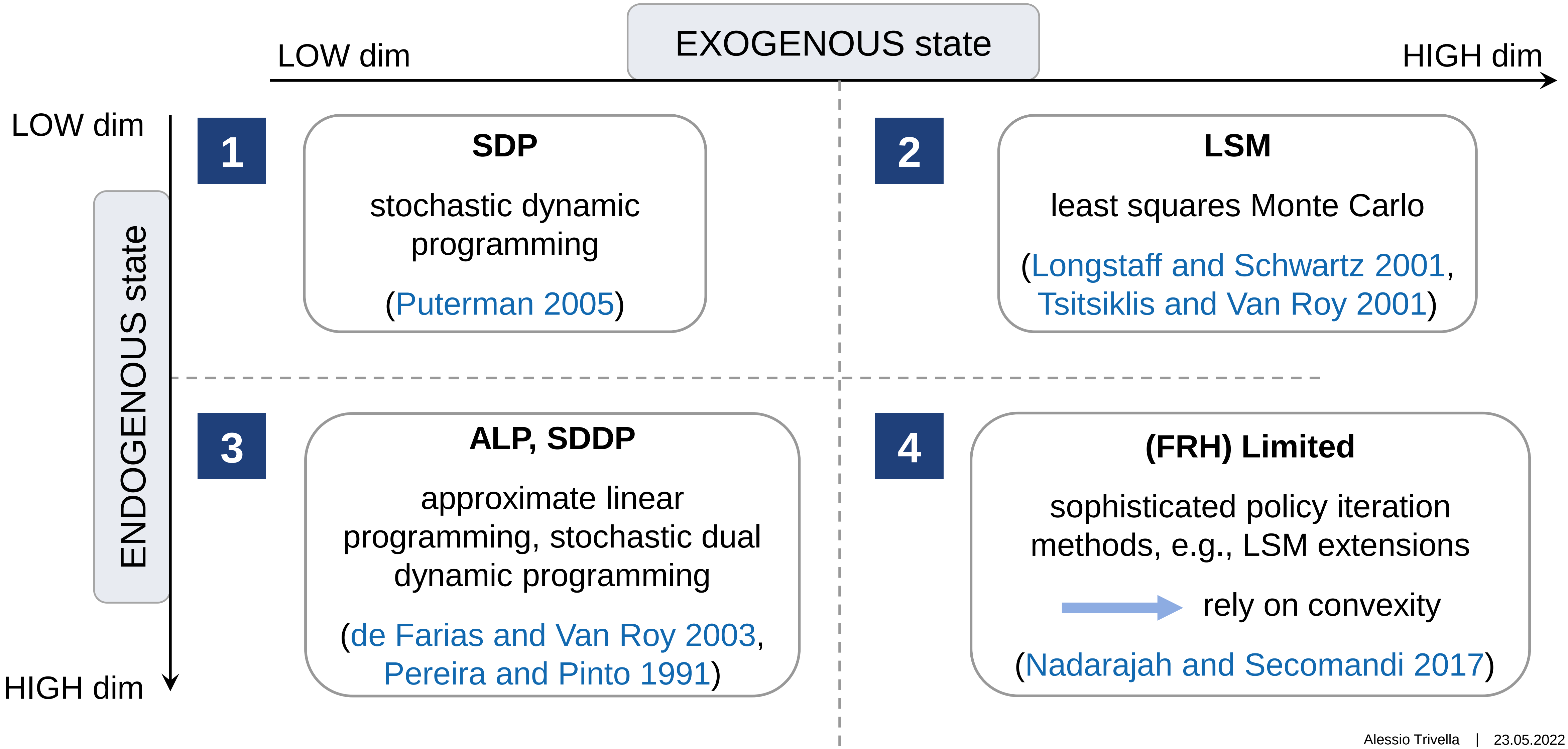
1. Replace future uncertainty by forecasts
2. Solve deterministic optimization model
3. Implement current decision only
4. Move to $i+1$ and repeat





- We can vary the **sourcing** and **timing flexibility**
- FRH does not **directly account** for the unfolding of uncertainty (based on a static model)
- FRH provides a policy but no **lower (dual) bound** to assess its quality

Need for a New Method?



Information Relaxation and Duality

- Dual bounds based on perfect information are often loose

- Information relaxation and duality is a more general approach (Brown et al. 2010, 2014, Brown and Haugh 2017, Nadarajah and Secomandi 2018, Ye et al. 2018)
  1. Penalize knowledge of future information using a dual penalty function
  2. Solve a deterministic problem with rewards corrected by the dual penalty

- There are different ways of defining dual penalties, e.g.:
  1. Standard procedure given an MDP value function approximation
  2. Linear penalties in the action or state

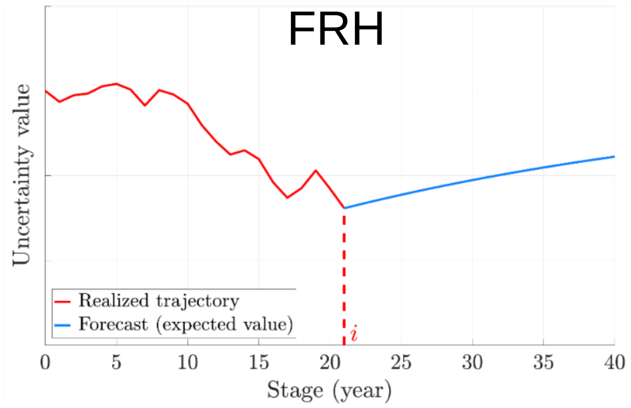
Information-relaxation based Reoptimization Heuristic (IRH)

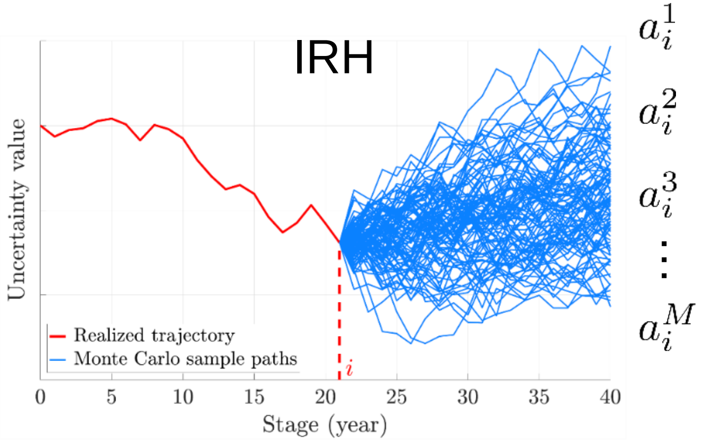
Combine FRH with information relaxation and duality

1. Solve deterministic hindsight optimization on sample paths

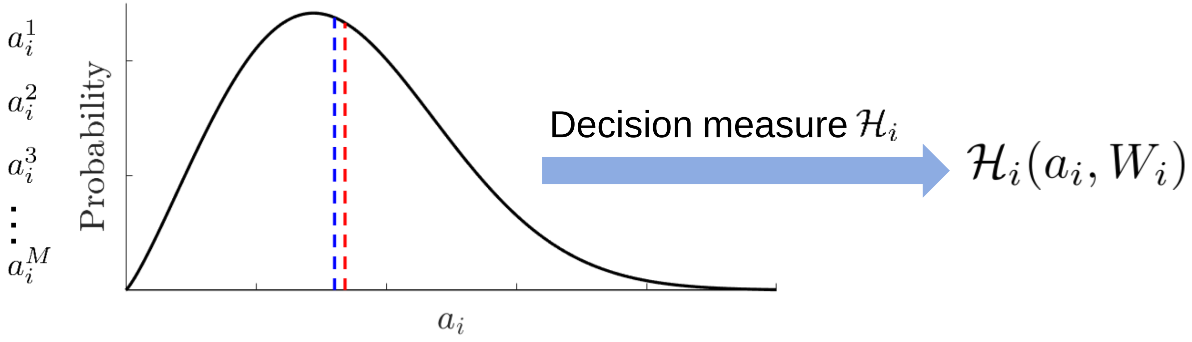
   ↓

   Distribution of optimal actions





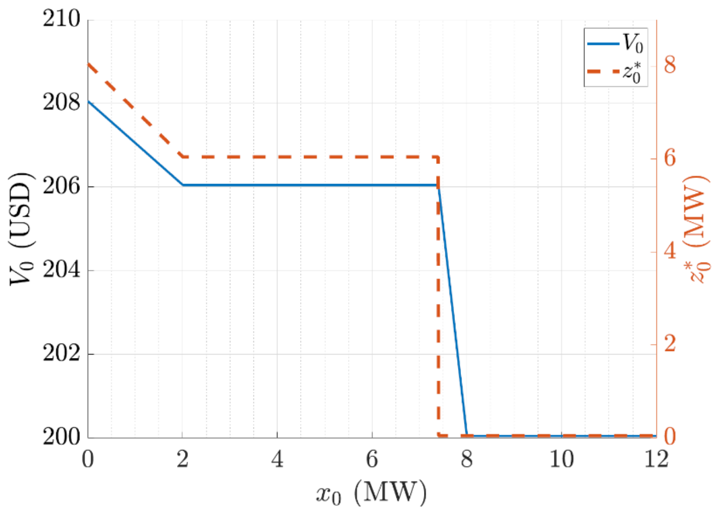
2. Extract a non-anticipative decision from the action distribution (mean, median, …)



3. We obtain at the same time a dual bound

Theory

- We show that our model (MDP value function) is
  - Non-convex, in general
  - Convex when we relax some assumptions



- We characterize when the IRH decision measure leads to a feasible action, e.g.
  - The mean is feasible under some assumptions
  - The component-wise median leads to a feasible action also in the presence of non-convexities

- We show that our IRH method is optimal (on every sample) when using an “ideal” penalty

Numerical Study

1 Procurement and operational parameters

- Instances based on two large data centres
- 40 years (stages) with reach period of 5 years
- Contract lengths: 5, 10, 15, 20, 25 years based on Google's portfolio
- Discount factors, min/max PPA size, premia,etc.

2 Stochastic models of the uncertainty calibrated on market data and practitioner literature

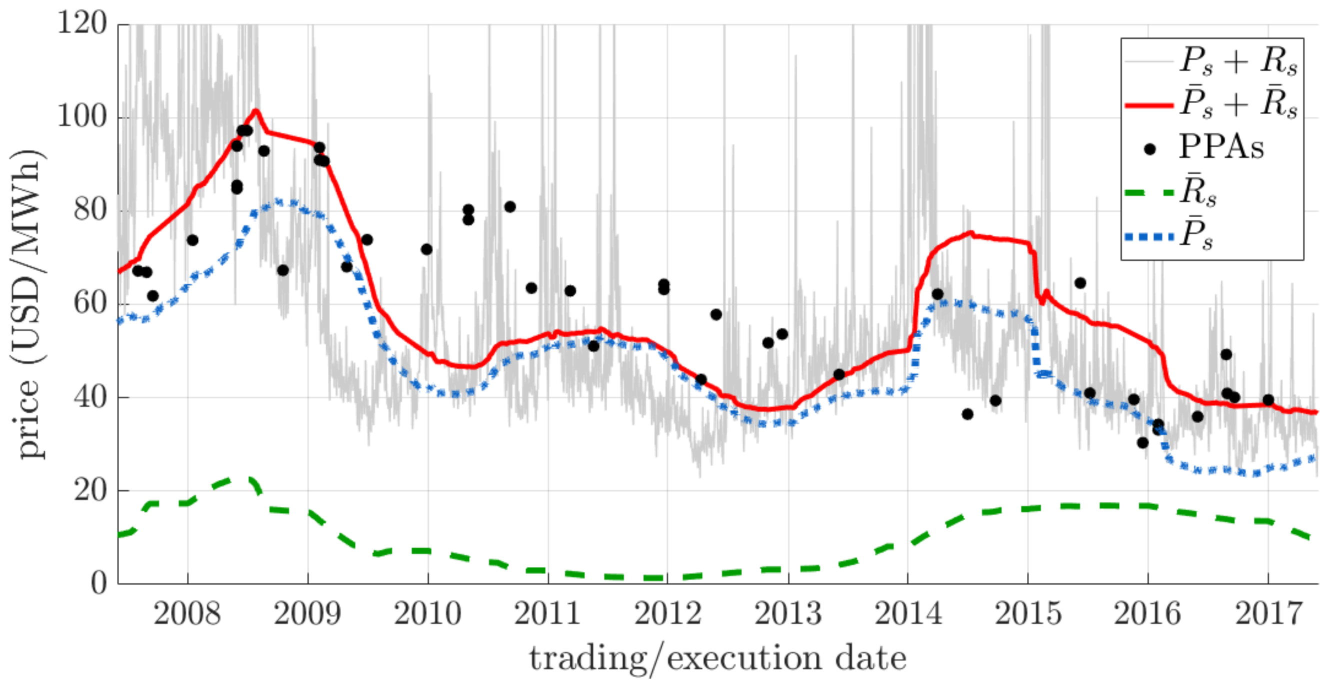
- Electricity prices: mean reverting process with jumps and seasonality (Lucia and Schwartz 2002, Cartea and Figueroa 2005, Weron 2014)
- Renewable energy supply: mean reverting process (Loukatou et al. 2018)
- RECs prices: Jacobi diffusion process (Zeng et al. 2015)
- Contract availability: Bernoulli random variables

Numerical Study

3 PPA strike price

Generator model: calculate NPV and set strike price such that NPV is positive after return on investment (NREL 2017)

Market model: baseline value based on electricity and REC prices, plus a latent variable / stochastic variations



- Baseline: past-year averages
- Stochastic factor: mean-reverting and bounded process (Jacobi)
- Calibrated on electricity price, REC price, and PPA prices (Berkeley Lab 2020)

Summary of methods

Policy	Accounts for the uncertainty	Includes PPAs	Has timing flexibility	Has sourcing flexibility
Short-term policy	NO	NO	NO	NO
FBH_m (single-contract)	NO	YES	NO	NO
FRH_m (single-contract)	NO	YES	YES	NO
FRH (portfolio)	NO	YES	YES	YES
IRH_m (single-contract)	YES	YES	YES	NO
IRH (portfolio)	YES	YES	YES	YES

IRH can be used with:

- Zero penalty vs optimized penalty (local search guided by dual bound estimate)
- Mean vs median decision measure

Value of uncertainty and its impact on procurement decisions

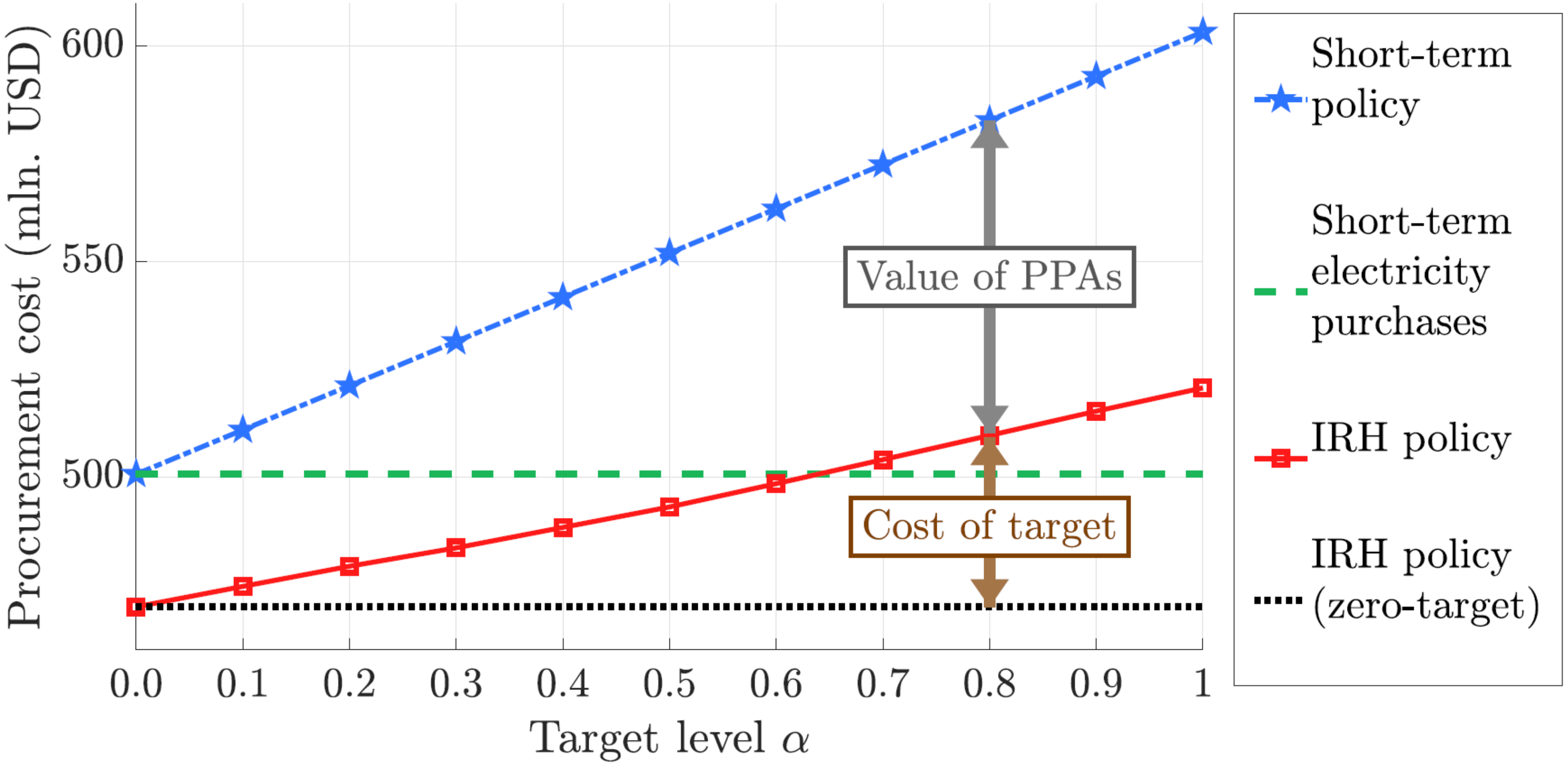
Procurement cost (mln.USD) and optimality gap (%) for reference instance using 90% target, and on average over 11 instances with target varying from 0% to 100%.

	Procurement cost		Optimality gap	
Policy/Bound	Reference	Average	Reference	Average
Short-term	593.1	552.0	23.0	18.0
FRH	537.8	512.8	11.6	9.6
IRH_0(avg)	526.3	502.4	9.2	7.4
IRH_0(med)	522.0	499.5	8.3	6.8
IRH_+(avg)	520.6	499.0	8.0	6.7
IRH_+(med)	515.3	494.2	6.9	5.6
Dual $bound_0$	468.5	457.2	−2.8	−2.2
Dual $bound_+$	482.1	467.5	-	-

- Short-term policy implies very larger costs and gaps
- All IRH variants outperform FRH
- Optimizing the dual penalty is useful
- The median decision measure is slightly better than mean

We focus on the best IRH variant next

Cost of a renewable target and relevance of PPAs



The “cost of the target”

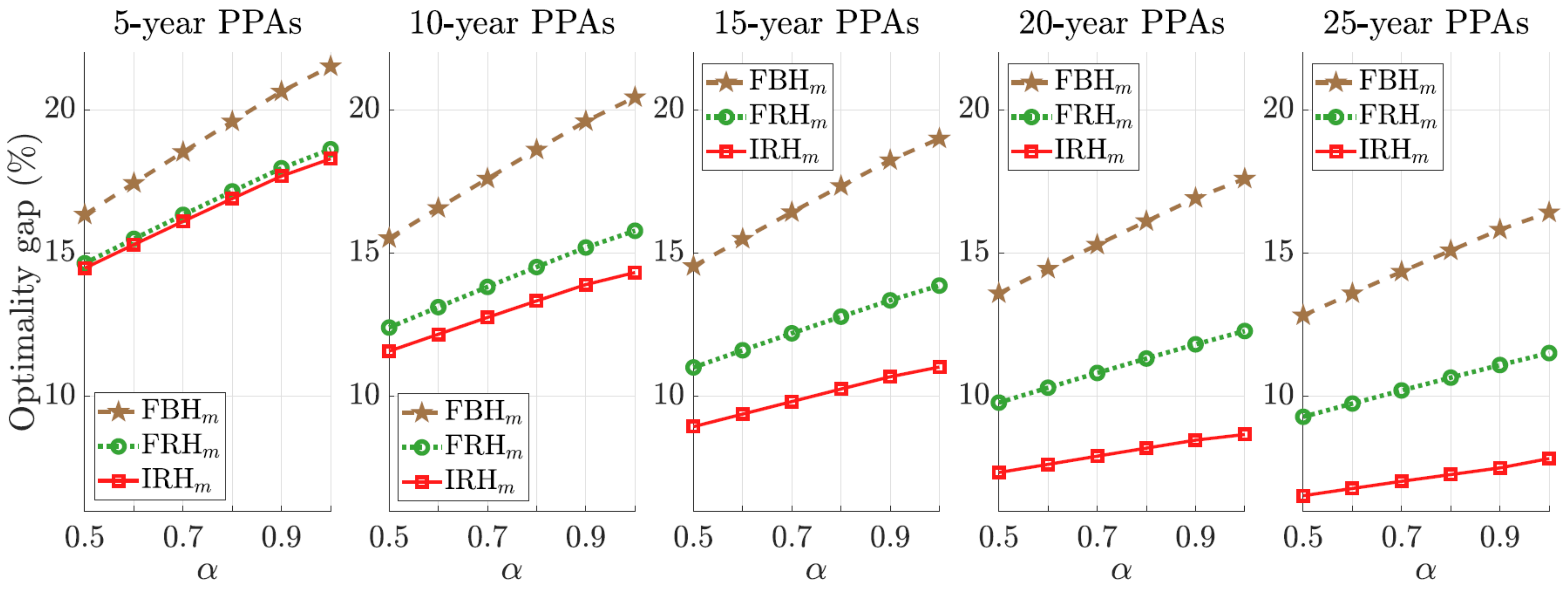
- depends the policy
- increases linearly
- is lower if PPAs are used

PPAs:

- Help decresing the cost of the target
- Are useful even with a zero target

Value of timing flexibility in rolling power purchases

We compare single-contract policies



Value of timing flexibility in rolling power purchases

- Flexible policies FRH_m / IRH_m sign smaller contracts more frequently

	Average frequency (years)					Average contract size (MW)				
$m \in \mathcal{M}$	5	10	15	20	25	5	10	15	20	25
FBH_m	8.6	13.0	17.1	20.7	25.9	186.3	186.5	186.8	187.3	187.5
FRH_m	8.4	11.1	11.9	14.0	15.7	167.5	151.9	139.4	138.4	141.8
IRH_m	8.6	11.2	12.3	13.3	14.5	159.4	146.9	142.2	141.3	148.7

- Timing flexibility translates to the optionality of reserving some renewable power capacity to future better deals, that occur in the future with a certain probability

- Thus, FRH_m / IRH_m sign cheaper deals on average

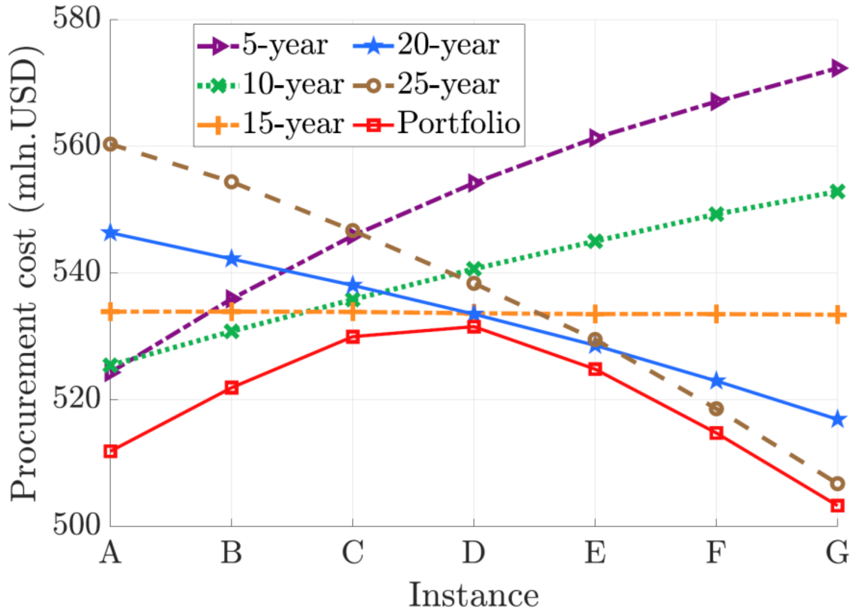
$m \in \mathcal{M}$	5	10	15	20	25
FBH_m	43.7	43.5	43.2	41.9	41.7
FRH_m	38.2	38.5	38.5	38.2	37.6
IRH_m	36.6	35.9	35.5	34.7	34.1

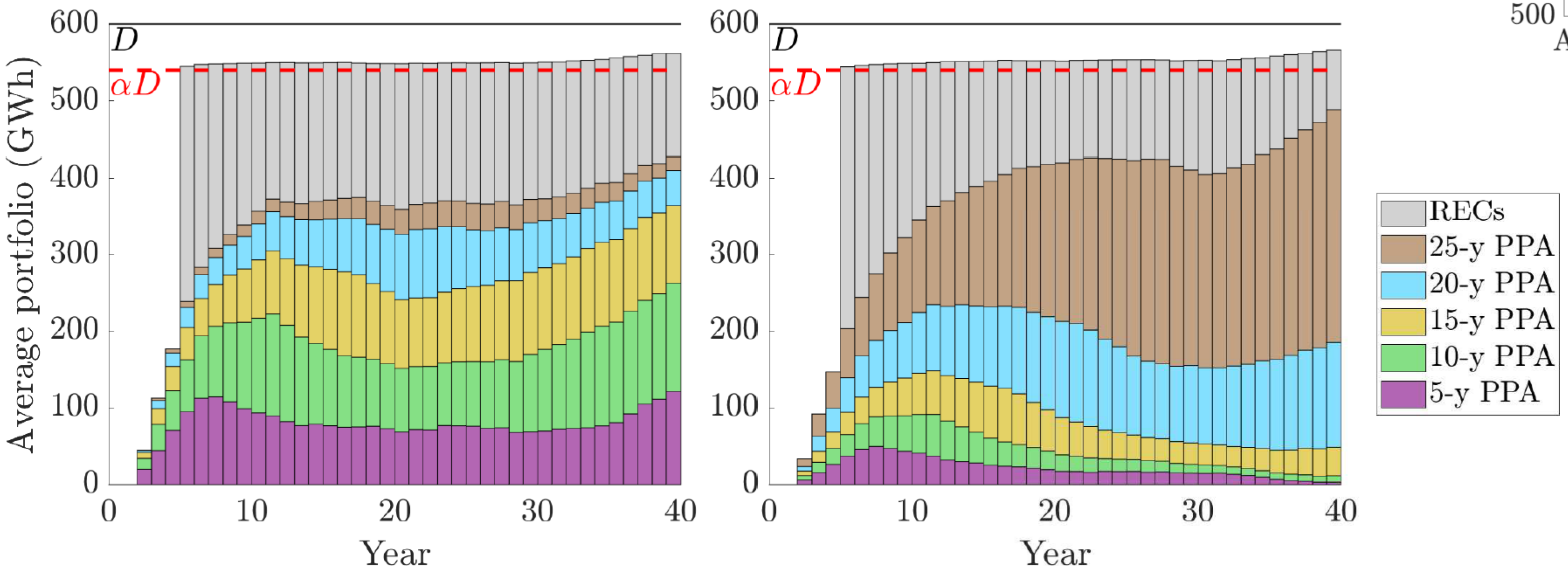
Average weighted strike price in USD/MWh of the contracts signed

Value of sourcing flexibility and optimized PPA portfolios

- Portfolios including multiple contracts with different duration are more robust when market parameters vary

- E.g., portfolios allows for better adapting to the relative attractiveness of different PPA types





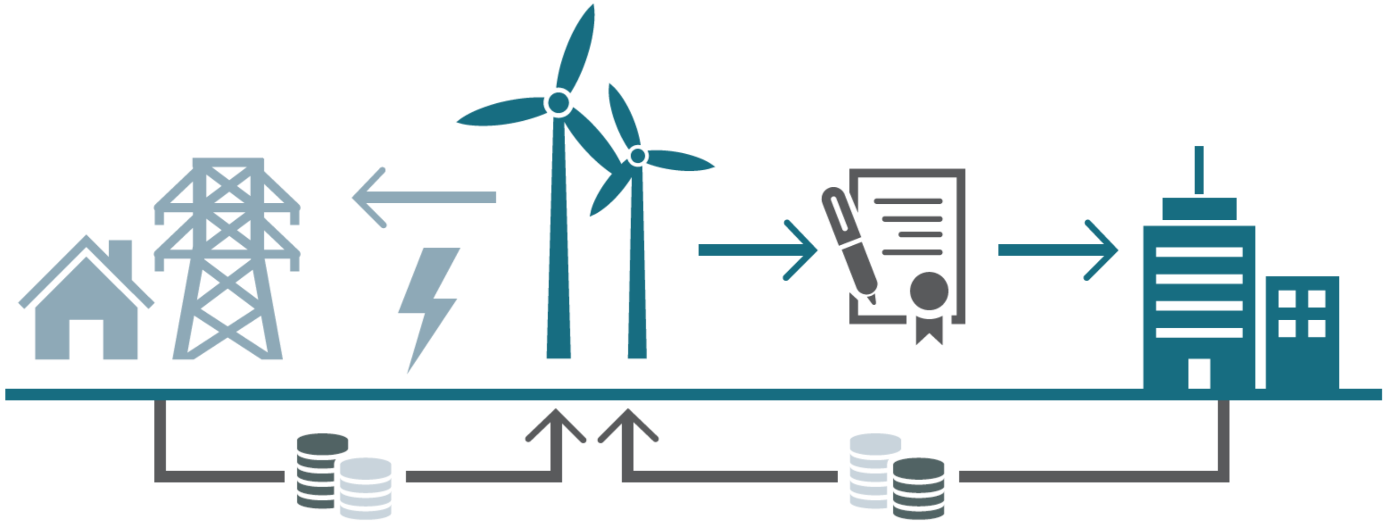
Other results

We also performed other experiments that largely support the previous findings:

- Sensitivity of portfolios to changes to contract availabilities
- Sensitivity of procurement policies to strike price changes (volatility, mean)
- Variations of the strike price model (e.g., number of months defining the baseline)
- Possibility of selling back extra RECs at a secondary market

Conclusion

- Corporate renewable power purchases can significantly help with the renewable energy transformation to meet global climate goals
- We study the use of **PPAs** to meet a renewable power purchase target while managing costs, which is a **contemporary** and **challenging** OM problem
- We consider simple benchmarks and forecast-based reoptimization heuristics consistent with practice, and develop a novel information relaxation-based reoptimization heuristic
- Sourcing and timing flexibilities significantly decrease procurement costs, and our information-relaxation policy is near-optimal and outperforms other policies
- The managerial insights we uncovered can help companies balancing **climate goals** (i.e., meeting the renewable target) and **financial performance** (i.e., energy costs)



Thank you

Current version of the paper (being revised in MS) available at: https://ssrn.com/abstract=3294724

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