A Multi-Stage Optimization Model for Flexibility in Engineering Design

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Engineering System Design

Power generation

25 de Abril bridge

Previous Works

- Flexibility in engineering system design:
  - Flexibility in system design and implications for aerospace systems (Saleh et.al 2003)
  - A flexible and robust approach for preliminary engineering design based on designer's preference (Nahm et.al, 2007)
  - A real options approach to hybrid electric vehicle architecture design for flexibility (Kang et.al 2016)

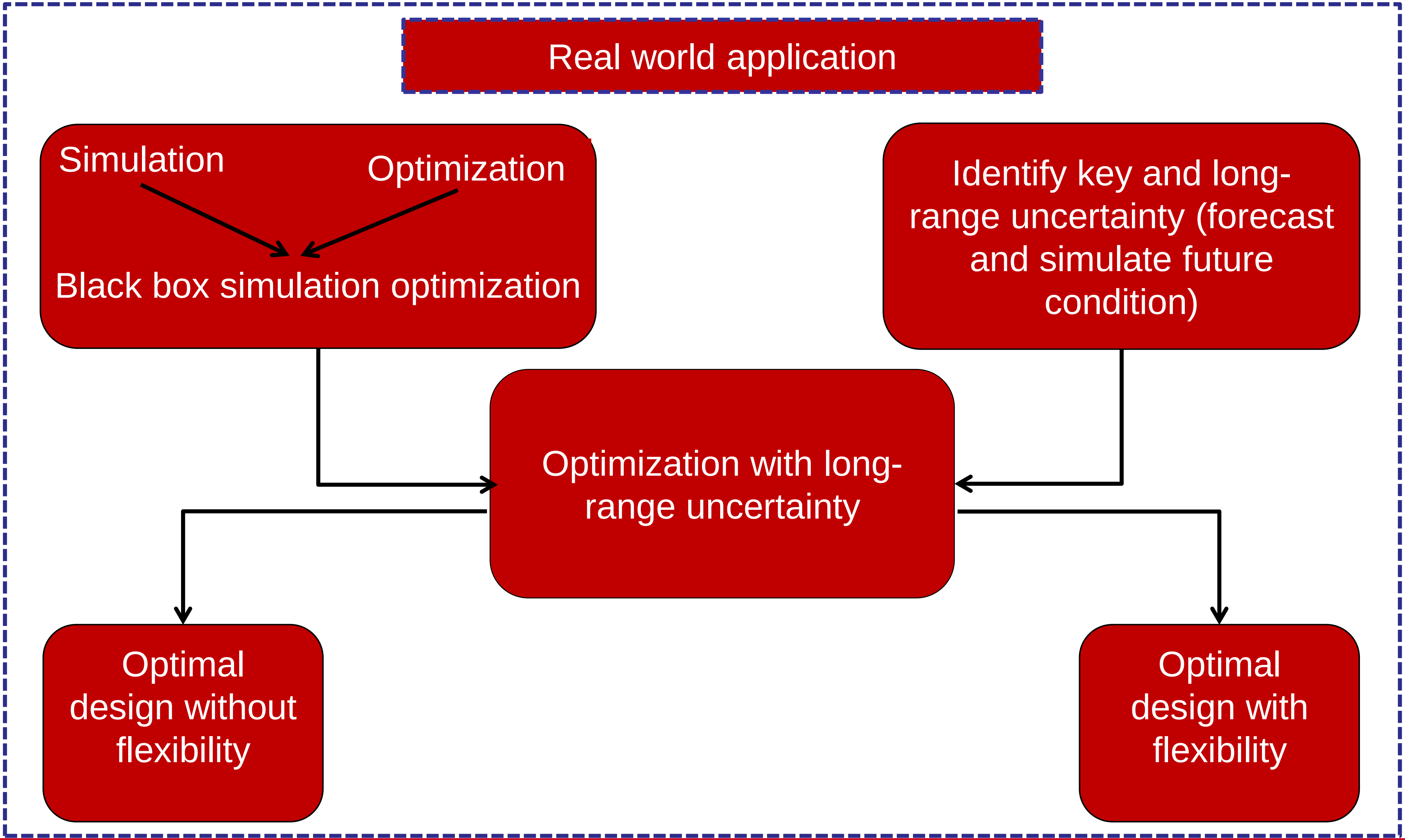
Our Research Contribution To The Engineering Design

- Challenges with flexible design:
  - Operation of engineered systems for long time
  - Evaluation of the objective function with the use of computationally expensive simulation

- Our contribution:

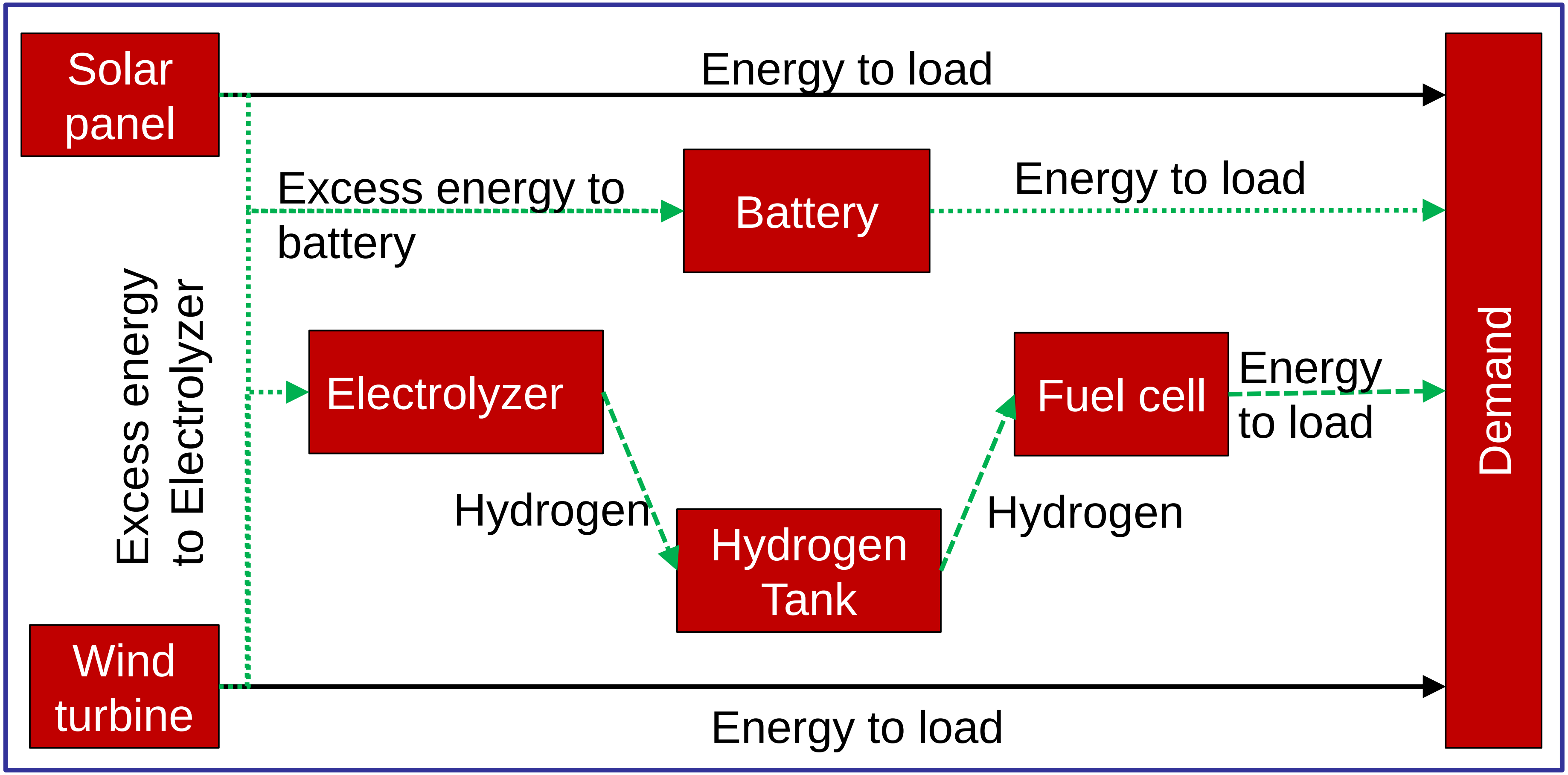
  Optimize the design when the objective function must be evaluated via simulation considering long range uncertainty and flexibility in design

Research Framework



Application: Hybrid Renewable Energy System

Hybrid Renewable Energy Systems

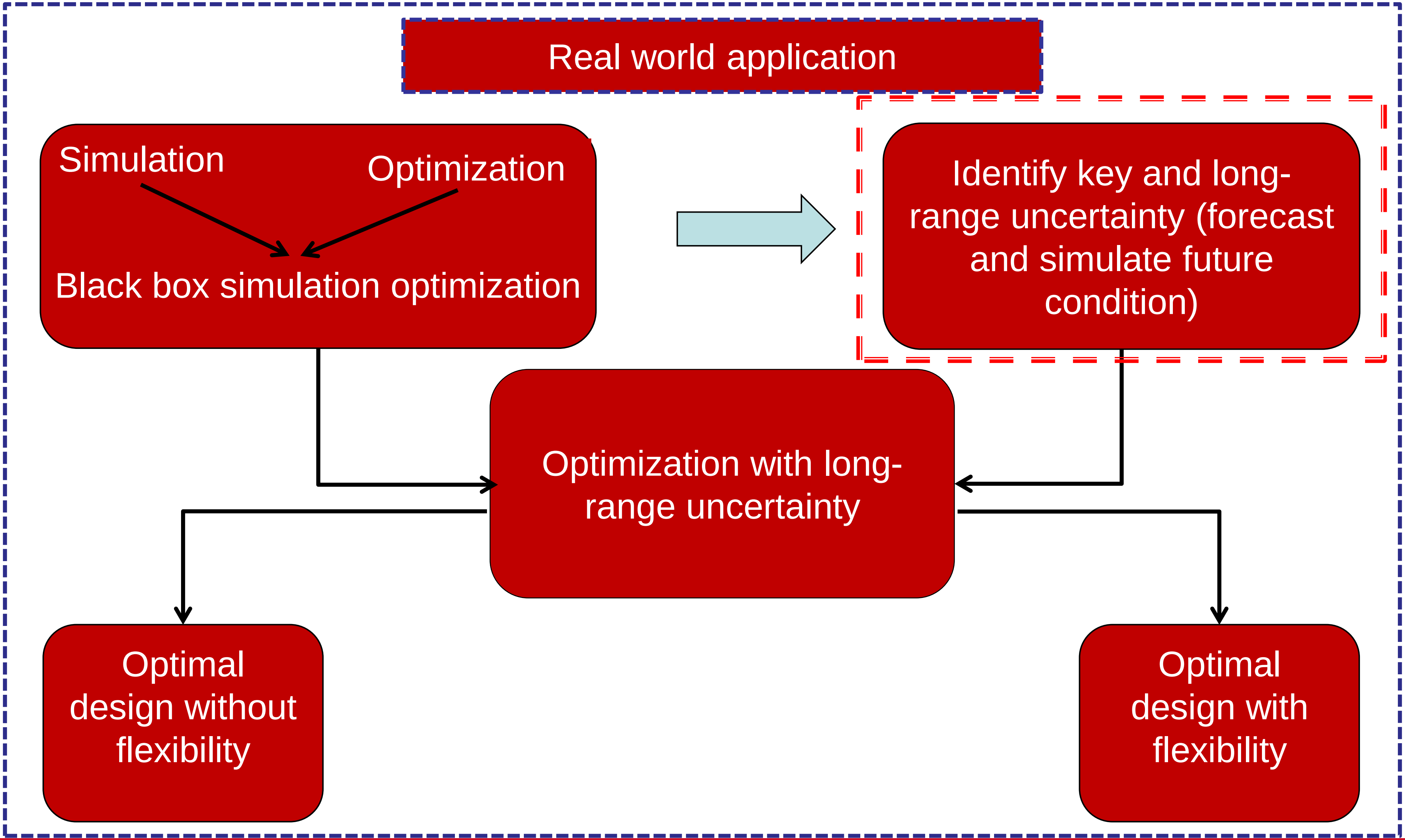


Sharafi, Masoud, and Tarek Y. ELMekkawy. "Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach." *Renewable Energy* 68 (2014): 67-79.

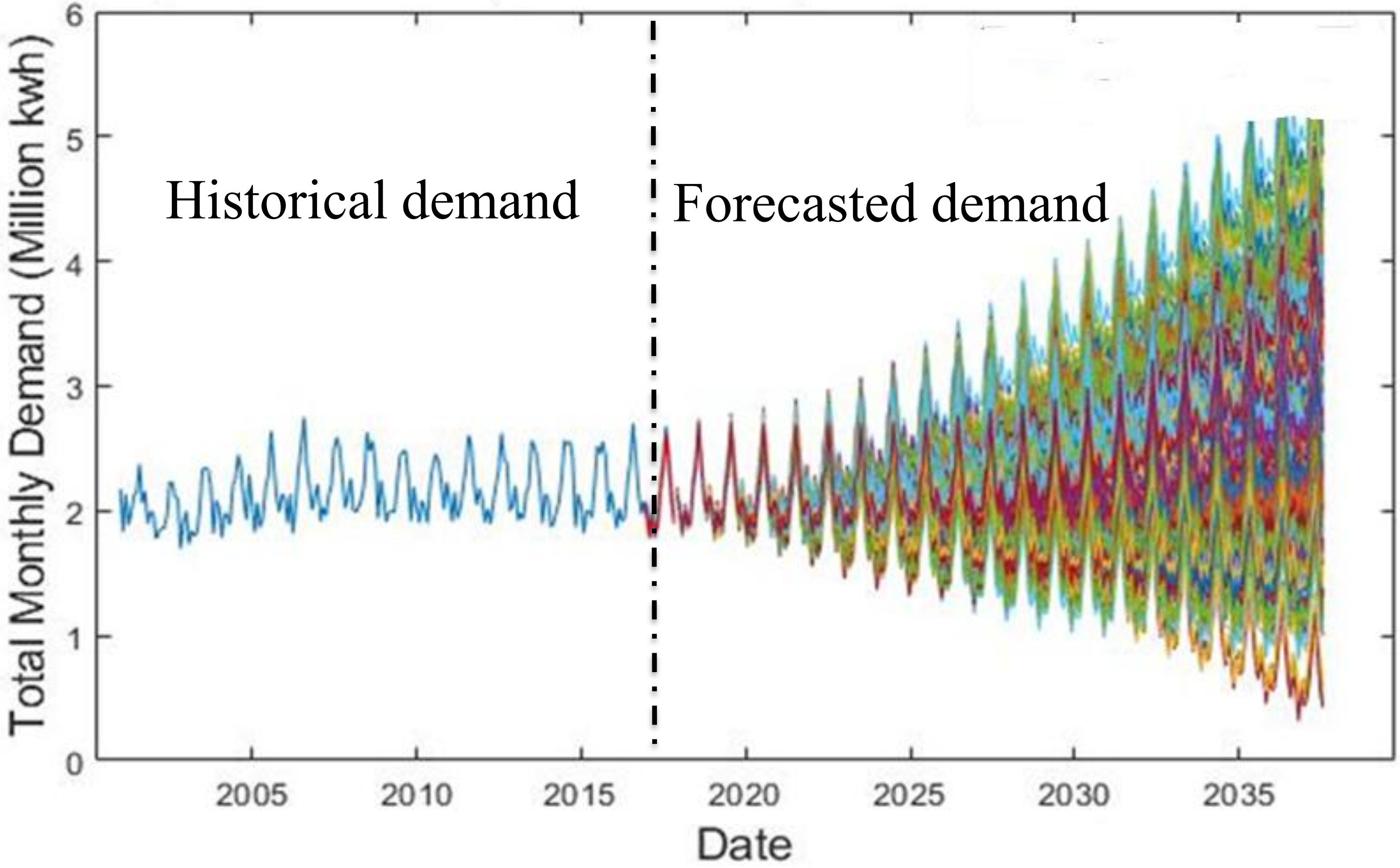
Application: Hybrid Renewable Energy System

- Design of hybrid renewable energy system
- Hybrid renewable system includes: PV panels, wind turbine, battery storage, electrolyzer, and fuel cell
- Design variables: capacity of the components of the system
- Identify the optimal capacity of each component to minimize the expected discounted cost

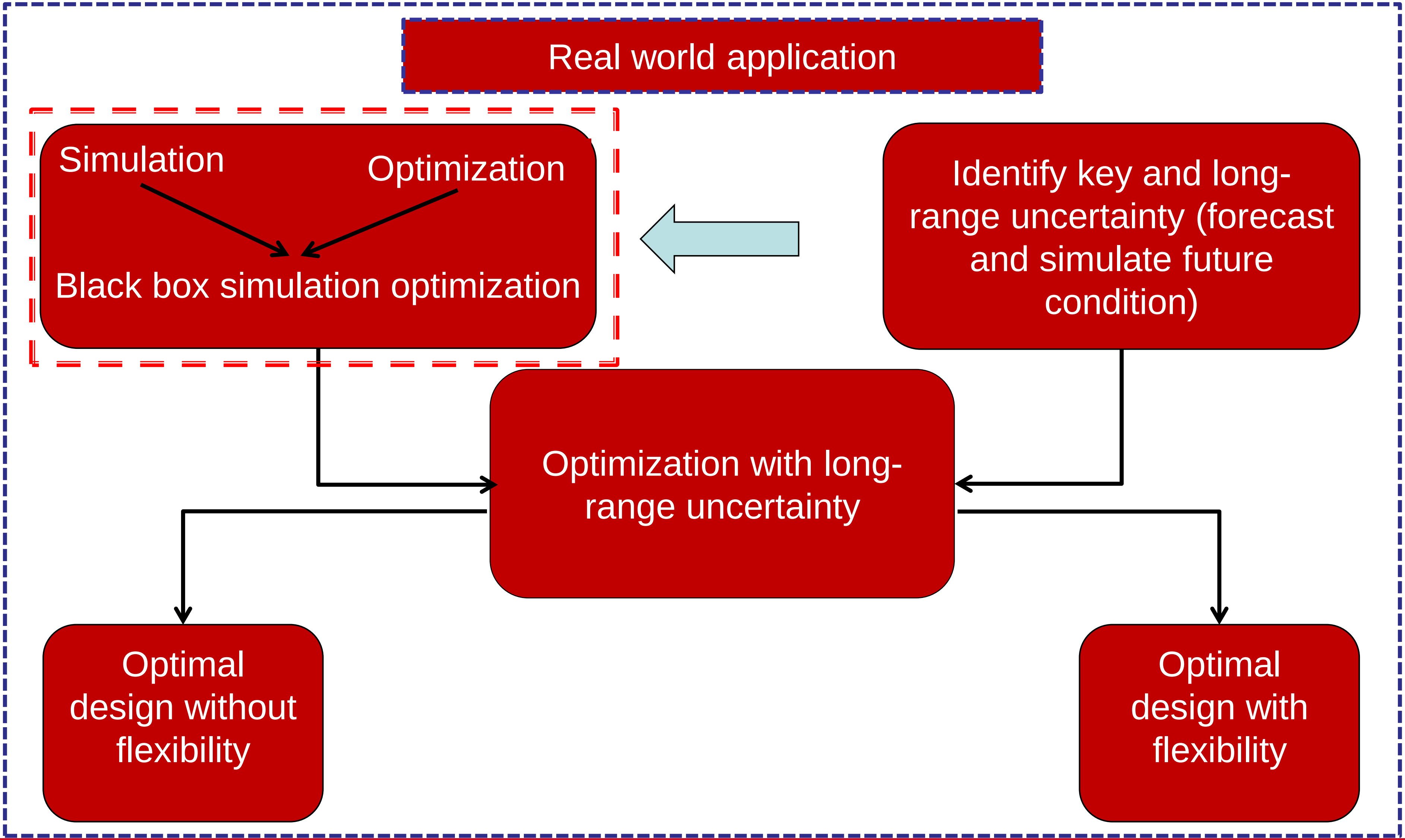
Research Framework



Simulation of Energy Demand for California, 2017-2036



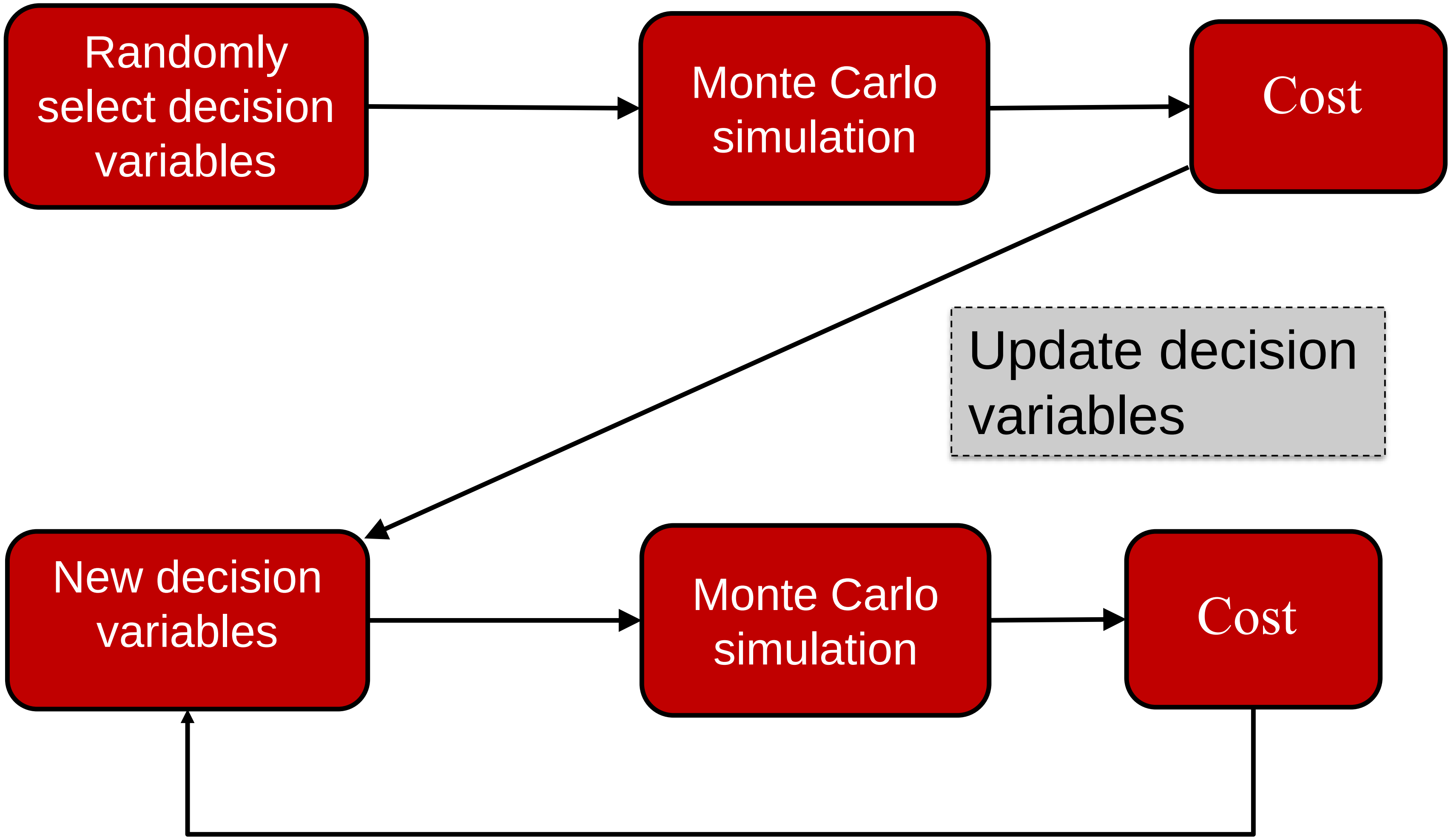
Research Framework



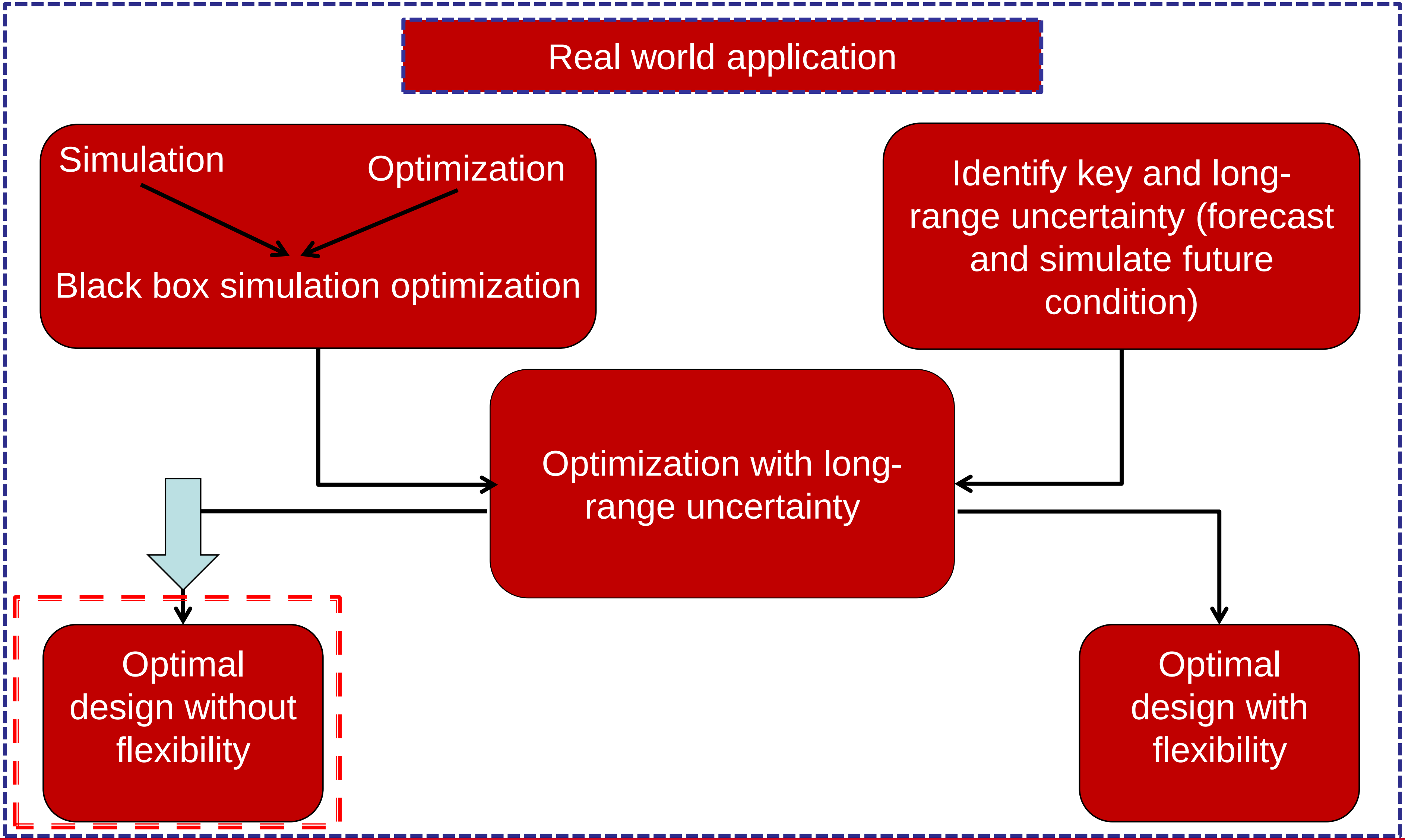
Mathematical Model

- Goal: Find the optimal design of hybrid renewable energy system
- Minimize expected discounted costs
  - Investment
  - Replacement
  - Maintenance
- Decision variables: Capacity of solar, wind, battery, fuel cells, electrolyzer, and hydrogen tank

Simulation Optimization



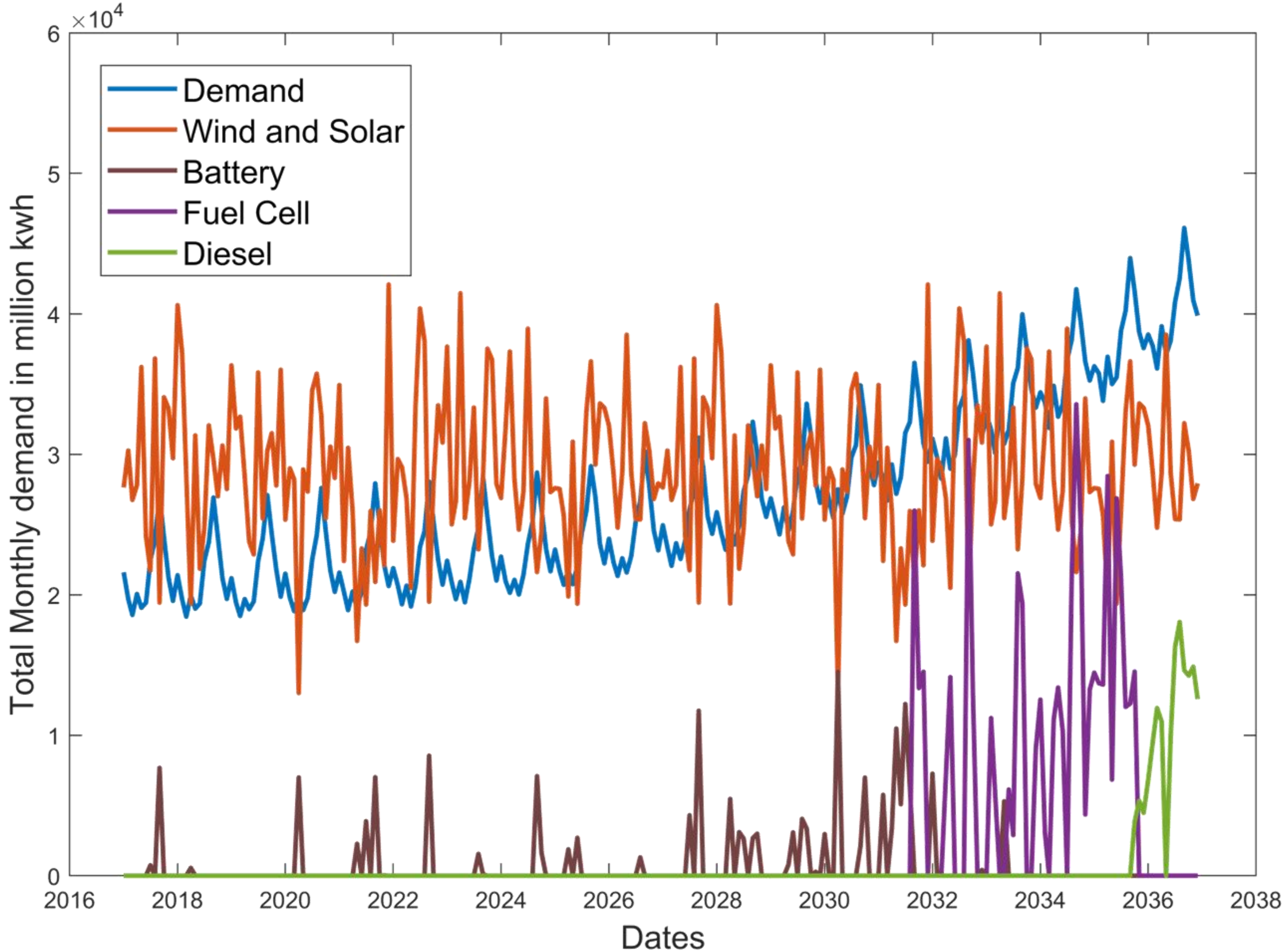
Research Framework



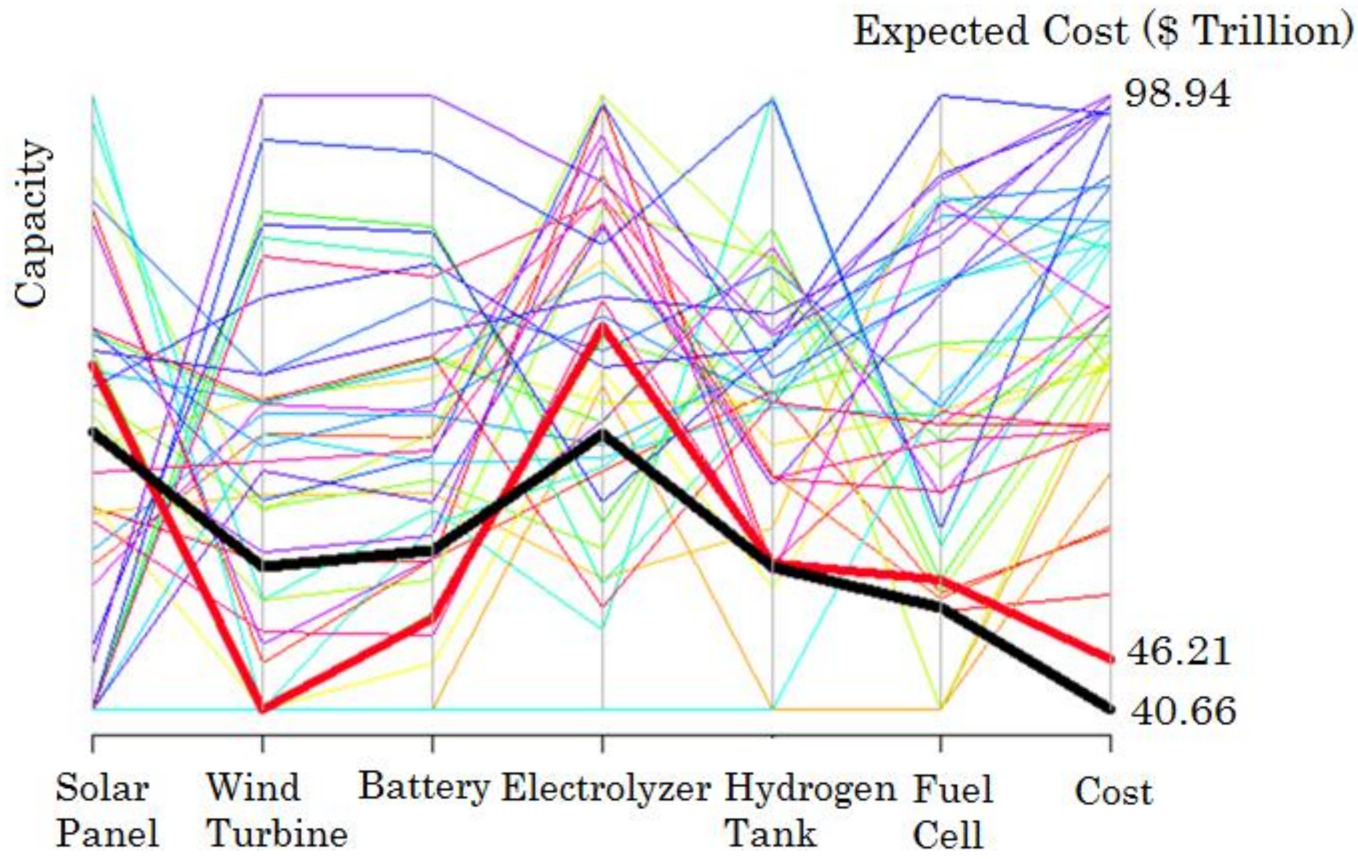
Optimal Solution

Components	Capacity (Giga Watt)	Percentage (%)
Solar panel	392	78
Wind turbine	146	
Battery	89	17
Electrolyzer	104	-
Hydrogen tank	322	-
Fuel cell	138	4
Diesel	-	1
Expected cost	$ 40.66 trillion	-

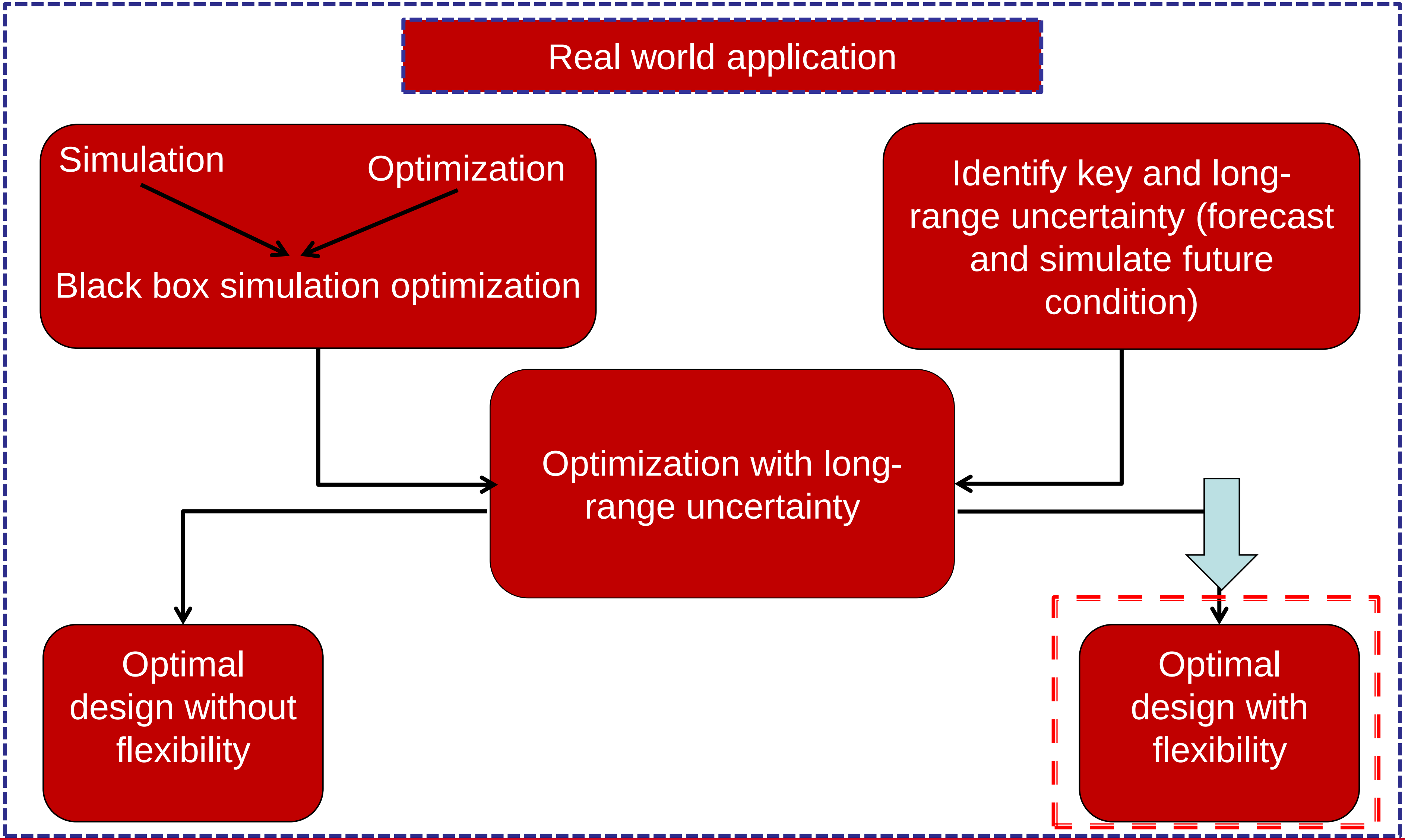
Demand Fulfillment Analysis: 1 Scenario



Parallel Coordinate Plot for Hybrid Renewable Design



Research Framework

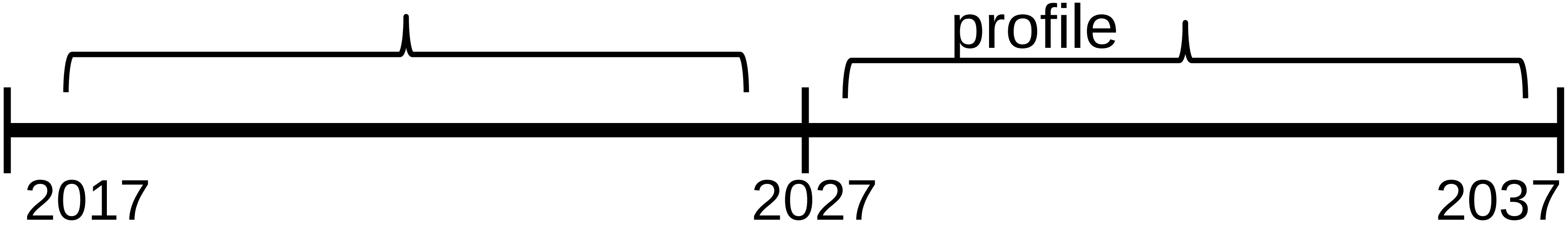


Design Optimization with Flexibility

Case 1: One time design modification at 2027

Optimize design over 2017-2027

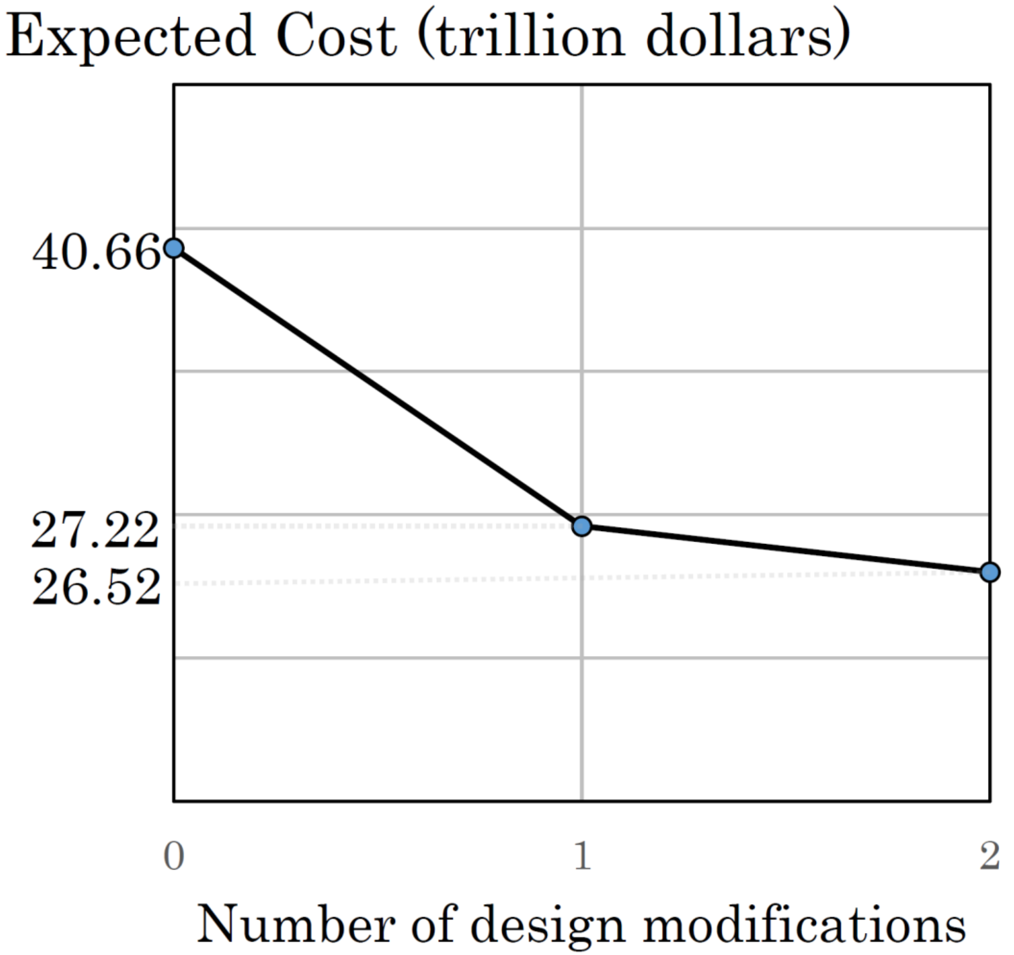
High demand	Optimize additional capacity for high demand profile
Medium demand	Optimize additional capacity for medium demand profile
Low demand	Optimize additional capacity for low demand profile



Design Optimization with Flexibility

- **Case 2:** Two times design modifications at 2027 and 2032
  - **Stage 1:** Optimize design for 2017-2027
  - **Stage 2:** Optimize additional capacity for 2027-2032, given the optimal initial design
  - **Stage 3:** Optimize additional capacity for 2032-2037, given the optimal initial design and each optimal expansion amounts of stage 2
  - Find the expected cost of design (initial design cost + average expansion cost at stage 2 + average expansion cost at stage 3)

Expected Cost of Design with and without Flexibility



Conclusions

- Design under long-range uncertainty
  - Hybrid renewable energy system
  - Monte Carlo simulation of uncertainties (e.g., demand)
  - Optimize design with and without flexibility
  - Compare the design without flexibility with design with flexibility
- Funding through the NSF-funded Center for e-design

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Reference

- Saleh, Joseph H., Daniel E. Hastings, and Dava J. Newman. "Flexibility in system design and implications for aerospace systems." *Acta astronautica* 53.12 (2003): 927-944.
- Nahm, Yoon-Eui, Haruo Ishikawa, and Young-Soon Yang. "A flexible and robust approach for preliminary engineering design based on designer's preference." *Concurrent Engineering* 15.1 (2007): 53-62.
- Kang, Namwoo, Alparslan Emrah Bayrak, and Panos Y. Papalambros. "A Real Options Approach to Hybrid Electric Vehicle Architecture Design for Flexibility." ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, 2016.
- Sharafi, Masoud, and Tarek Y. ELMekkawy. "Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach." *Renewable Energy* 68 (2014): 67-79.