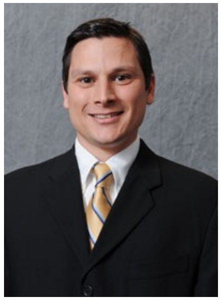
THE VALUE OF STOCHASTIC PROGRAMMING FOR ENERGY SYSTEMS PLANNING

Anderson Rodrigo de Queiroz, Ph.D.

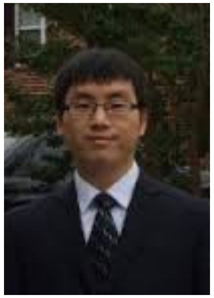
Joseph F. DeCarolis, Ph.D.

Research Team

Res. Prof. A.R. de Queiroz



Prof. Joseph DeCarolis



Binghui Li, Ph.D cand.

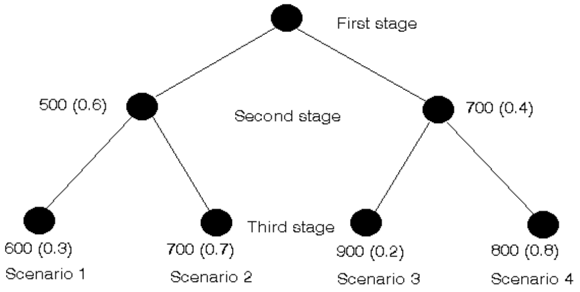
Neha Patankar, Ph.D. student

Hadi Eshraghi, Ph.D. student

Introduction

- **Energy system models** should reflect the reality that planners must **make decisions prior to** the **realization** of future **uncertainties**

- Multi-stage stochastic linear programs (**MSLP**) optimize over future possibilities to yield a **near-term decision strategy**



- We use the expected value of perfect information (**EVPI**) and the value of the stochastic solution (**VSS**) as metrics in long-term capacity expansion of energy systems modeled as **MSLP**

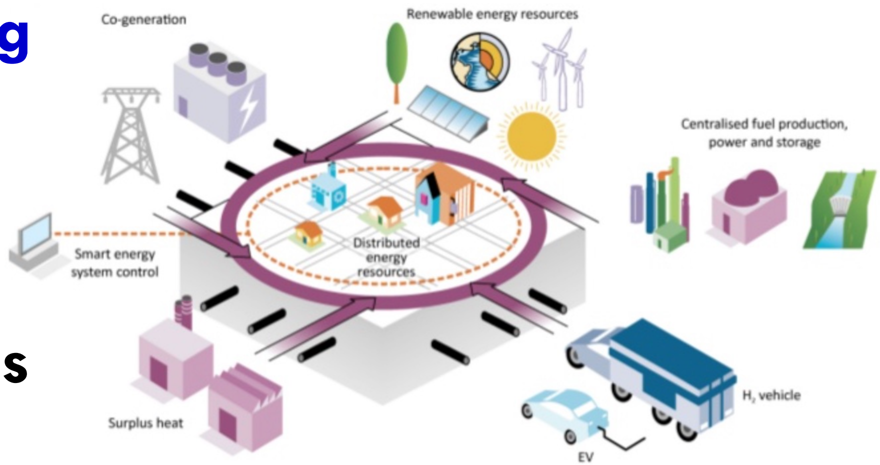
Overview

- Introduction
- Planning Capacity Expansion for Energy Systems
  - Background
  - Modeling and Characteristics
  - Tools for Energy Model Optimization and Assessment (TEMOA)
- Energy Systems Planning Problem as a Stochastic Program (SP)
  - ESPP in a multi-stage stochastic programming scheme
  - Uncertainty representation
  - Metrics to asses the value of SP for ESPPs
- Case Study
- Remarks and Comments

Planning Capacity Expansion for Energy Systems

Background

- The **energy system planning** requires a deep knowledge from the decision maker about **commodities**, **technologies**, **demand**, **costs** and network infrastructure



- **Decisions** in such systems are **driven by** information available at the **present** time as well as **future projections**
- To expand the existent installed supply-demand energy infrastructure, one has to consider the intrinsic characteristics of each subsystem (or sector) represented in the process

Some Literature…

- Expansion planning of electricity power generation (**Massé & Gibrat, 57; Jenkins & Joy, 74; Majumdar & Chattopadhyay, 99; Bistline, 15**), transmission interconnections (**Lee et al., 74; de la Torre et al., 08; Sauma & Oren, 07**) and distribution networks (**Asakura et al., 03; Hemmati et al., 15**)

- **Energy system planning**, however, can be used in a much **broader analysis** including a combination of electricity, vehicle transportation, fuel supply-chains, district heating/coaling and other systems (**Leung & Hsu, 84; Bhatt et al., 10; Chaudry et al., 14; Gironès et al., 15; Gómez et al., 16**)
- The energy system planning problem (**ESPP**) is known for several decades (**Kroneberg, 50**) and one of the first formulations as a linear programming model is presented in (**Massé and Gibrat, 57**)
- Mathematical models have being extensively used to represent such problems (**Jebaraj & Iniyan, 06; Connolly et al., 10**), eg. Markal (**Fishbone & Abilock, 81**)

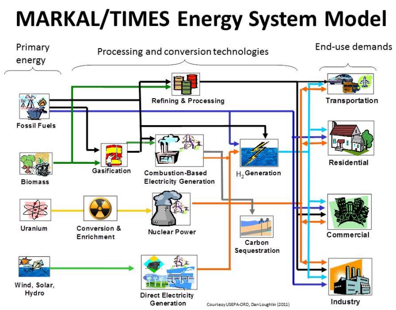
Uncertainty and Metrics in MSLP

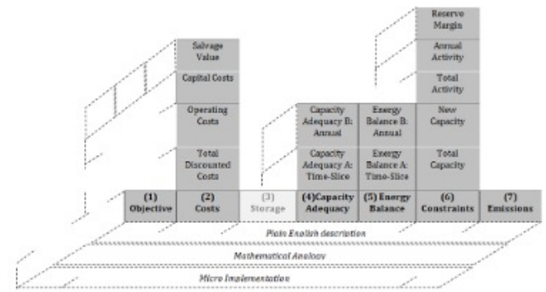
- **Uncertainty plays a fundamental role** in the definition of strong strategies which aim **to minimize the total combined expansion and operational costs** over a particular time horizon using mathematical models
- Understanding uncertainty is also a pre-requisite to correctly use such information in mathematical models **(Kann & Weyant, 00)**
- The representation of each uncertainty type will result in different models and different results and values that can be achieved with such models
- We aim to investigate long-term ESPP under uncertainty and what is the value of a MSLP representation of the problem instead of a deterministic
- Expected cost of perfect information **(EVPI)** **(Raiffa & Schlaifer, 61; Birge & Louveaux, 97)** → **how much to pay to eliminate uncertainty?**
- Value of the stochastic solution **(VSS)** **(Birge, 82)**

How much money the hedging strategy saves relative to the total cost obtained by an optimization model when uncertainty is ignored

Models and Characteristics

- Models for conducting energy system analysis:
  - Markal/Times
  - OSeMOSYS
  - Message





- TEMOA
  - Energy economy optimization model
  - Technology assessment and policy analysis at ≠scales
  - Model is implemented in a general algebraic formulation combined with PYOMO
  - Stochastic Programming capabilities (extensive LP and Progressive Hedging)

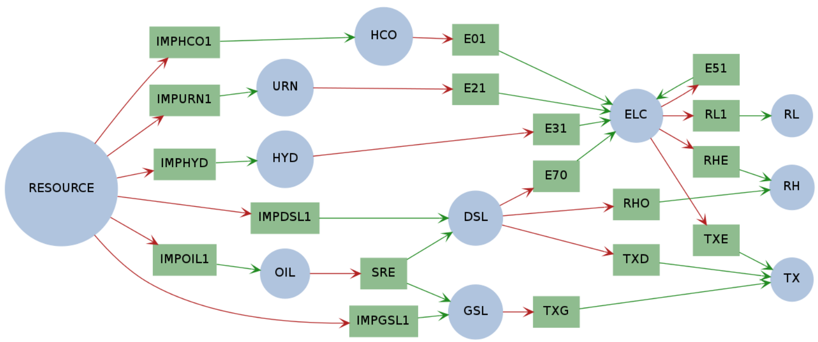
http://www.temoaproject.org

https://github.com/TemoaProject/temoa/

TEMOA – General Purpose

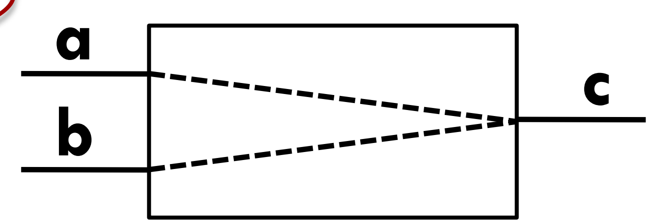
The TEMOA Project

Tools for Energy Model Optimization and Analysis



- TEMOA represents a capacity expansion and operational model for energy systems
- Represents a MSLP in a network with multiple technologies and multi-commodities
- **Model's objective:** minimize cost of energy supply over a defined time horizon (present + expected future cost)
- Processes represented in a macro level

Satisfying



Commodity flow balance

Mathematical Formulation

$$\text{LoanCost} = \sum_{t,v}\left(\left[IC_{t,v} \cdot LA_{t,v} \cdot \sum_{y=0}^{MLL_{t,v}} \frac{1}{(1+GDR)^{y+v-P_0}}\right] \cdot \mathbf{CAP}_{t,v}\right)$$

$$\text{FixedCost} = \sum_{p,t,v}\left(\left[FC_{p,t,v} \cdot \sum_{y=0}^{MTL_{p,t,v}} \frac{1}{(1+GDR)^{y+p-P_0}}\right] \cdot \mathbf{CAP}_{t,v}\right)$$

$$\text{VariableCost} = \sum_{p,s,d,t,v}\left(\left[VC_{p,t,v} \cdot \sum_{y=0}^{LEN_p} \frac{1}{(1+GDR)^{y+p-P_0}}\right] \cdot \mathbf{ACT}_{p,s,d,t,v}\right)$$

$$\min_{\substack{\text{ACT,FI,FO}\\ \text{CAP,CAPVAL}}} \quad \text{Total Cost} = \text{LoanCost} + \text{FixedCost} + \text{VariableCost}$$

s.t.

$$\mathbf{ACT}_{p,s,d,t,v} = \sum_{i,o} \mathbf{FO}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$$

Process activity

$$\left(CF_{s,d,t,v} \cdot C2A_t \cdot SEG_{s,d} \cdot TLF_{p,t,v}\right) \cdot \mathbf{CAP}_{t,v} \geq \mathbf{ACT}_{p,s,d,t,v} \quad \forall\{p,s,d,t,v\} \in \Theta_{\text{activity}}$$

Technology capacity

$$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,c} \geq DEM_{p,c} \cdot DSD_{s,d,c} \quad \forall\left\{p,s,d,c \in C^d\right\} \in \Theta_{\text{demand}}$$

Supply-demand

$$\mathbf{FO}_{p,s,d,i,t,v,o} \leq EFF_{i,t,v,o} \cdot \mathbf{FI}_{p,s,d,i,t,v,o} \quad \forall\{p,s,d,i,t \in T - T^s, v, o\} \in \Theta_{\text{flow}}$$

Process-level commodity flow

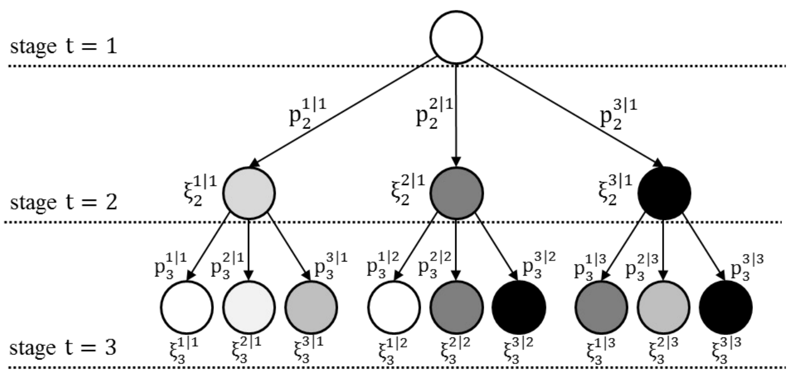
$$\sum_{i,t,v} \mathbf{FO}_{p,s,d,i,t,v,c} \geq \sum_{t,v,o} \mathbf{FI}_{p,s,d,c,t,v,o} \quad \forall\{p,s,d,c\} \in \Theta_{\text{balance}}$$

Global commodity balance

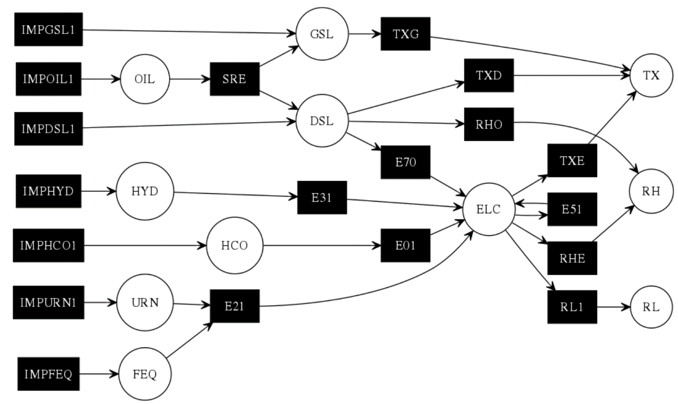
Other constraints and bounds: baseload, emissions, battery storage,…

Energy Systems Planning Problem as a Stochastic Program

ESPP as a MSLP



Ex. of a scenario tree



Ex. of ESSP network topology at a specific stage

$$z_{RP} = \min_{x_1} \; c_1 x_1 + \mathbb{E}_{\xi_2|\xi_1} h_2(x_1, \tilde{\xi}_2)$$

$$\text{s.t.} \quad A_1 x_1 = B_1 x_0 + b_1$$

$$x_1 \geq 0$$

$\tilde{\xi}_t$ denote the random elements from (A_t, B_t, c_t, b_t) for $t = 2, \ldots, T$

where for $t = 2, \ldots, T$ the recourse function $h_t(x_{t-1}, \tilde{\xi}_t)$ can be viewed as:

$$h_t(x_{t-1}, \tilde{\xi}_t) = \min_{x_t} \; \tilde{c}_t x_t + \mathbb{E}_{\tilde{\xi}_{t+1}|\xi_t,\ldots,\xi_1} h_{t+1}(x_t, \tilde{\xi}_{t+1})$$

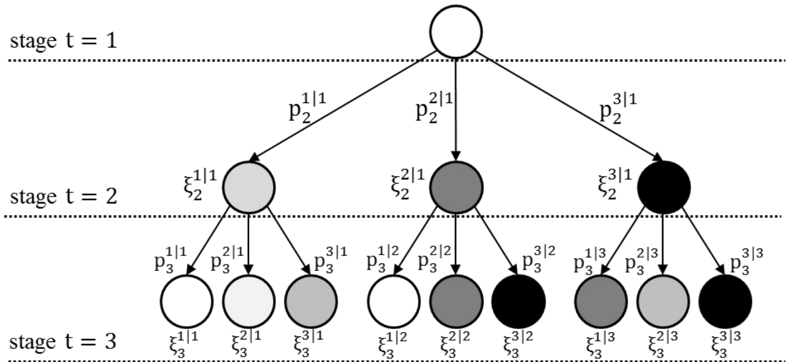
$$\text{s.t.} \quad \tilde{A}_t x_t = \tilde{B}_t x_{t-1} + \tilde{b}_t$$

$$x_t \geq 0$$

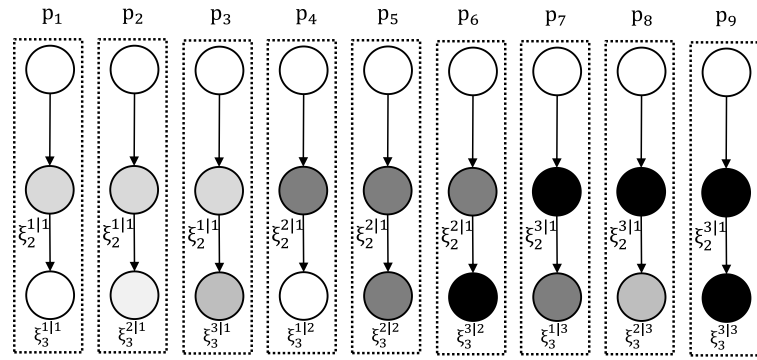
Uncertainty Representation

- Uncertainties may be represented by scenarios of:
  - Economic grow
  - Commodity/technology price trajectories **(Van der Weijde & Hobbs, 12)**
  - Demand realization **(Pineda and Morales, 2016)**
  - Technology reliability **(Hajipour et al., 2015)**
  - Policies related to greenhouse gases emissions **(Bistline & Weyant, 13; Park & Baldick, 15)**
  - Renewable generation penetration **(Munoz et al., 14)**
  - Renewable resources availability **(Gil et al., 15)**
  - Technological, economic, and policy-related **(Bistline, 15)**

EVPI & VSS Computation

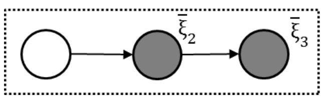


z_{RP}



$$z_{WS} = \mathbb{E}_{\omega}[Z_{DM}^{\omega}]$$

$$\boxed{\mathrm{EVPI} = z_{RP} - z_{WS}}$$



$$z_{EV} = z_{DM}(\bar{\xi})$$

$$z_{EEV_t} = z_{RP}\,(x_\tau = \bar{x}_\tau, \forall \tau = 1, \ldots, t-1)$$

$$\boxed{\mathrm{VSS}_t = z_{EEV_t} - z_{RP}}$$

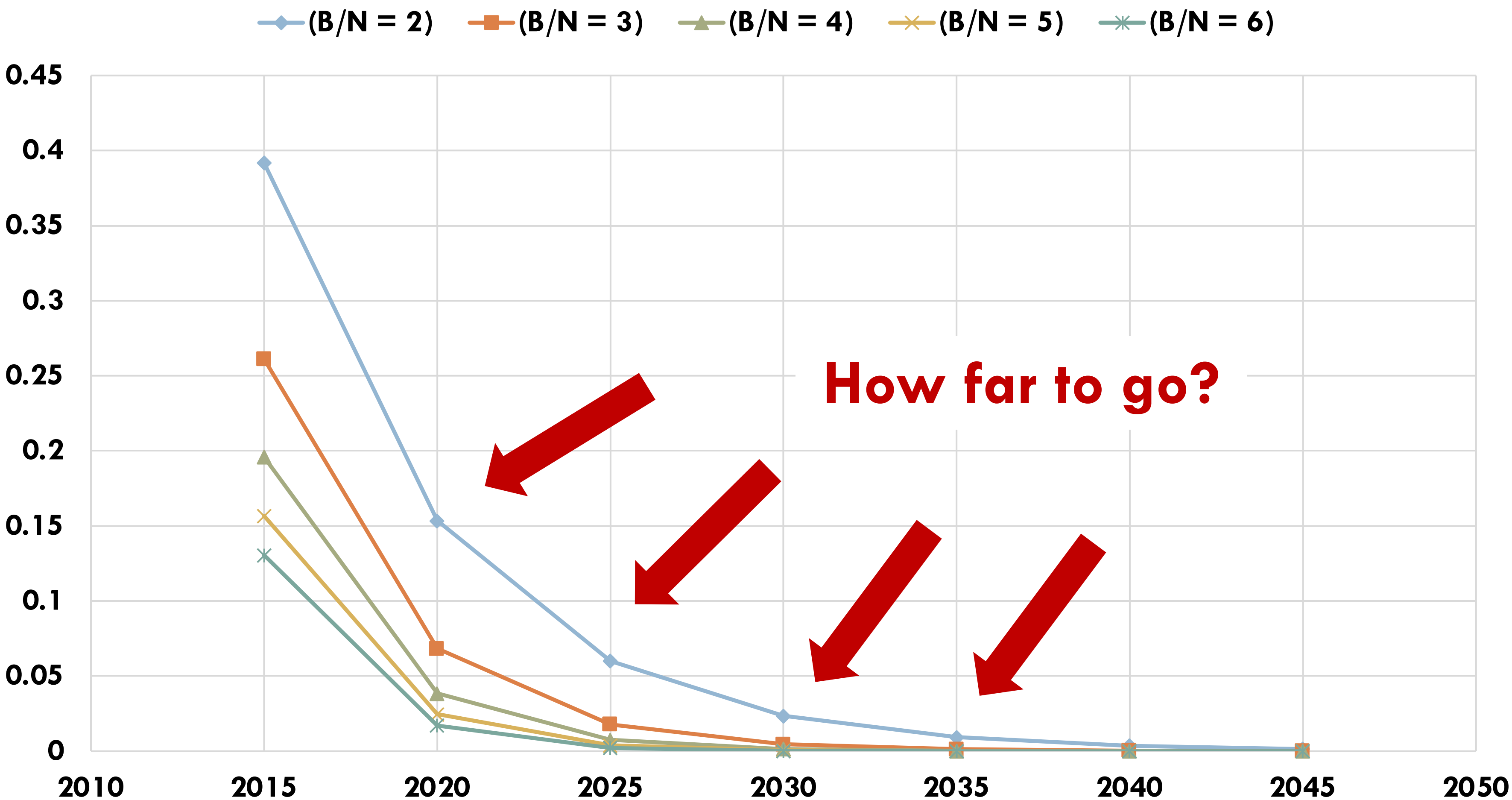
(Escudero et. al., 07) shows that for any MSLP we have $0 \leq \mathrm{VSS}_t \leq \mathrm{VSS}_{t+1}, \forall t = 1, \ldots, T-1$, and for this reason we focus our analysis in VSS_1, i.e., we fix only the decisions $x_1 = \bar{x}_1$

What Influences Decision-making in ESPPs?

- **Cost vectors**
- Existent capacity
- **Commodities demand**
- Bottlenecks in the network
- Efficiency of processes
- **Reliability**
- Availability of resources
- Time-delay between decisions and physical use
- **Linking decisions and constraints**
- Bounds that will limit investments
- **Discount rate**

Value of Money & Time

- Branch weighting (discount rate of 5% per 5 years)



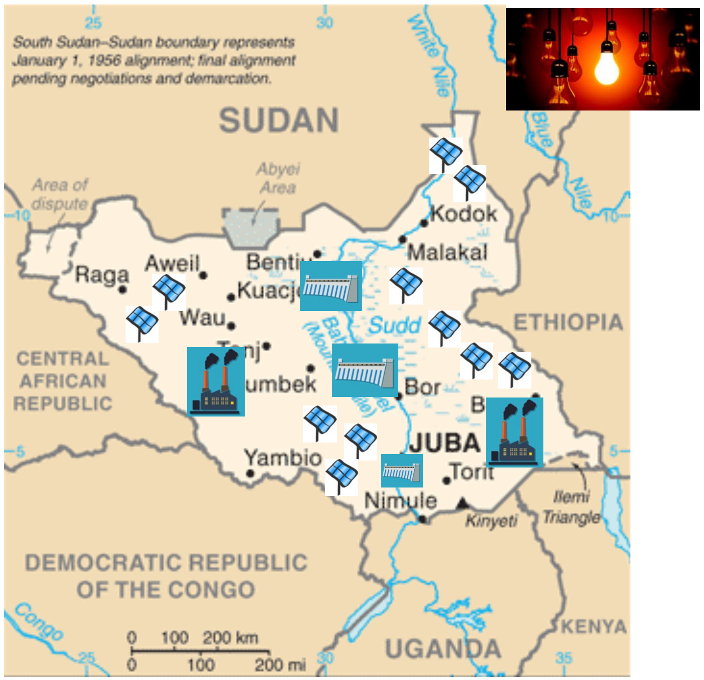
Case Study

System Description

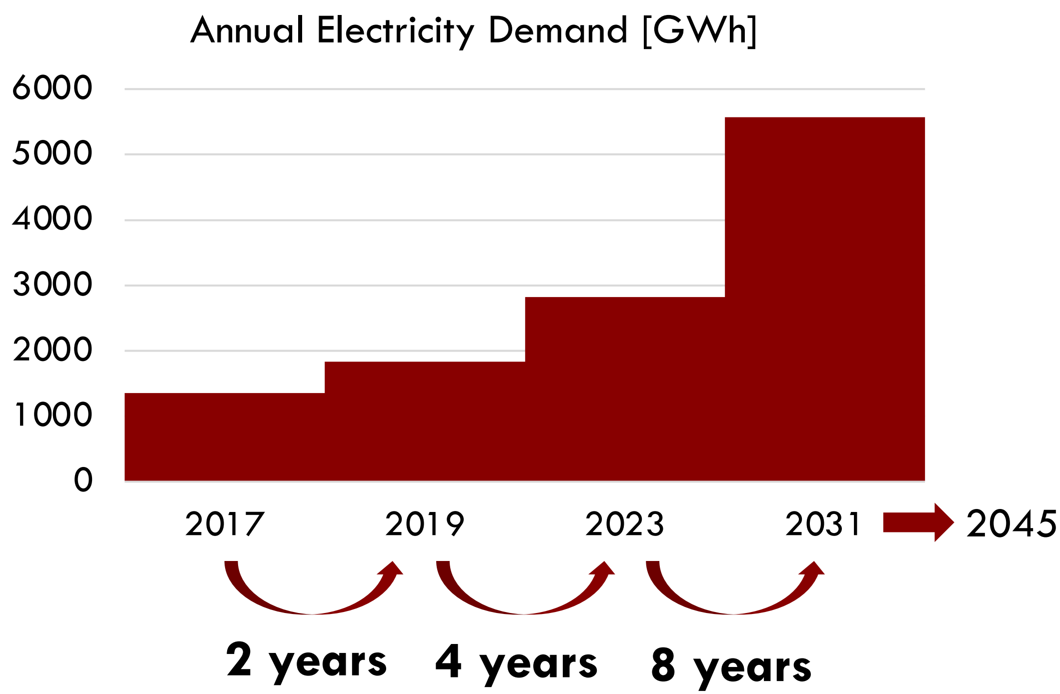
- How to design a power generation expansion plan for South Sudan?
- Significant size and abundant natural resources
- The country has ~ 30 [MW] of existent capacity

- Existent studies for hydropower investments
- However, is it the best option?

Problem Characteristics



Curtailment



Solar investment cost: 3.35 $/kW

Hydro: 2.5 – 13.2 $/kW, **Thermal**: 1.5$/kW

Thermal variable cost: 40 – 46 $/MWh

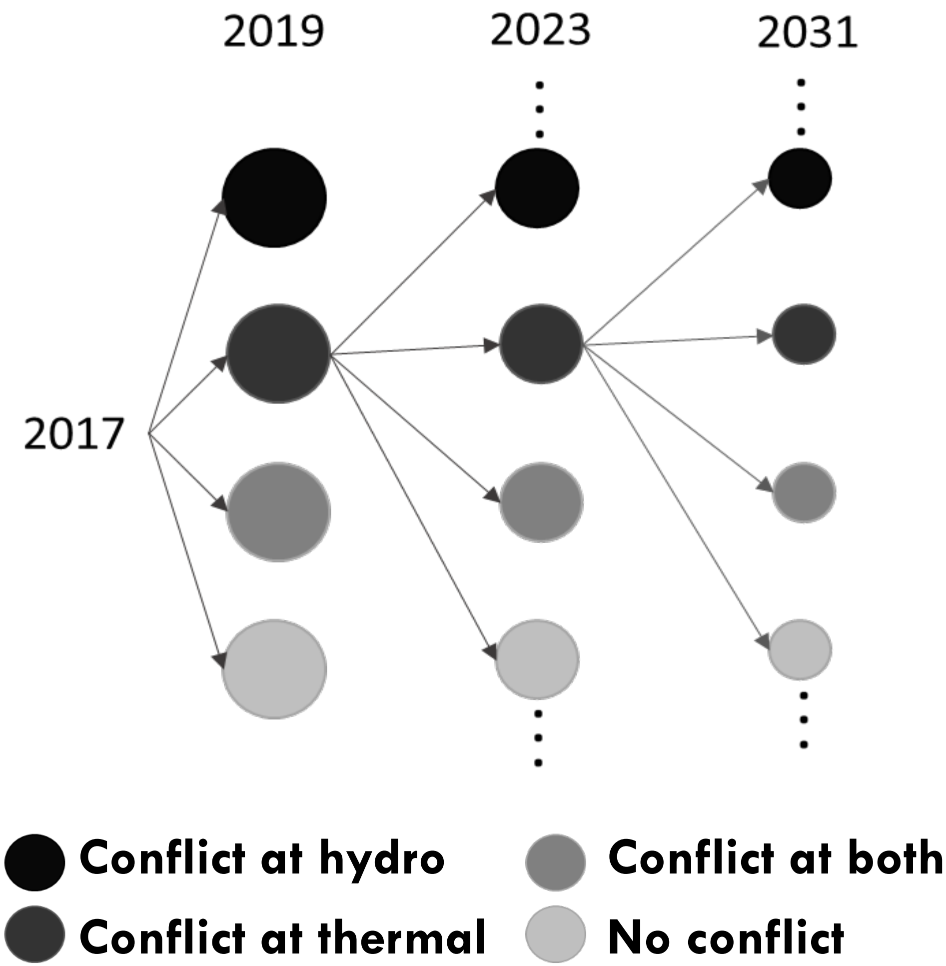
Curtailment cost: 300, 600 and 5000 $/MWh

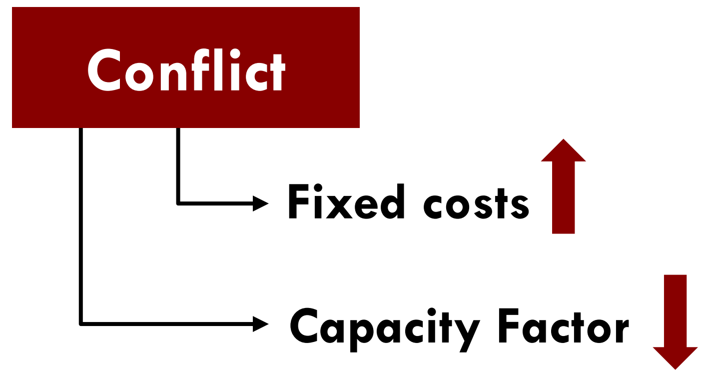
Transmission lines investment cost, fixed costs, capacity factors, efficiency, etc

Minimize total cost

Most information extracted from: (Hatch Report, 2014)

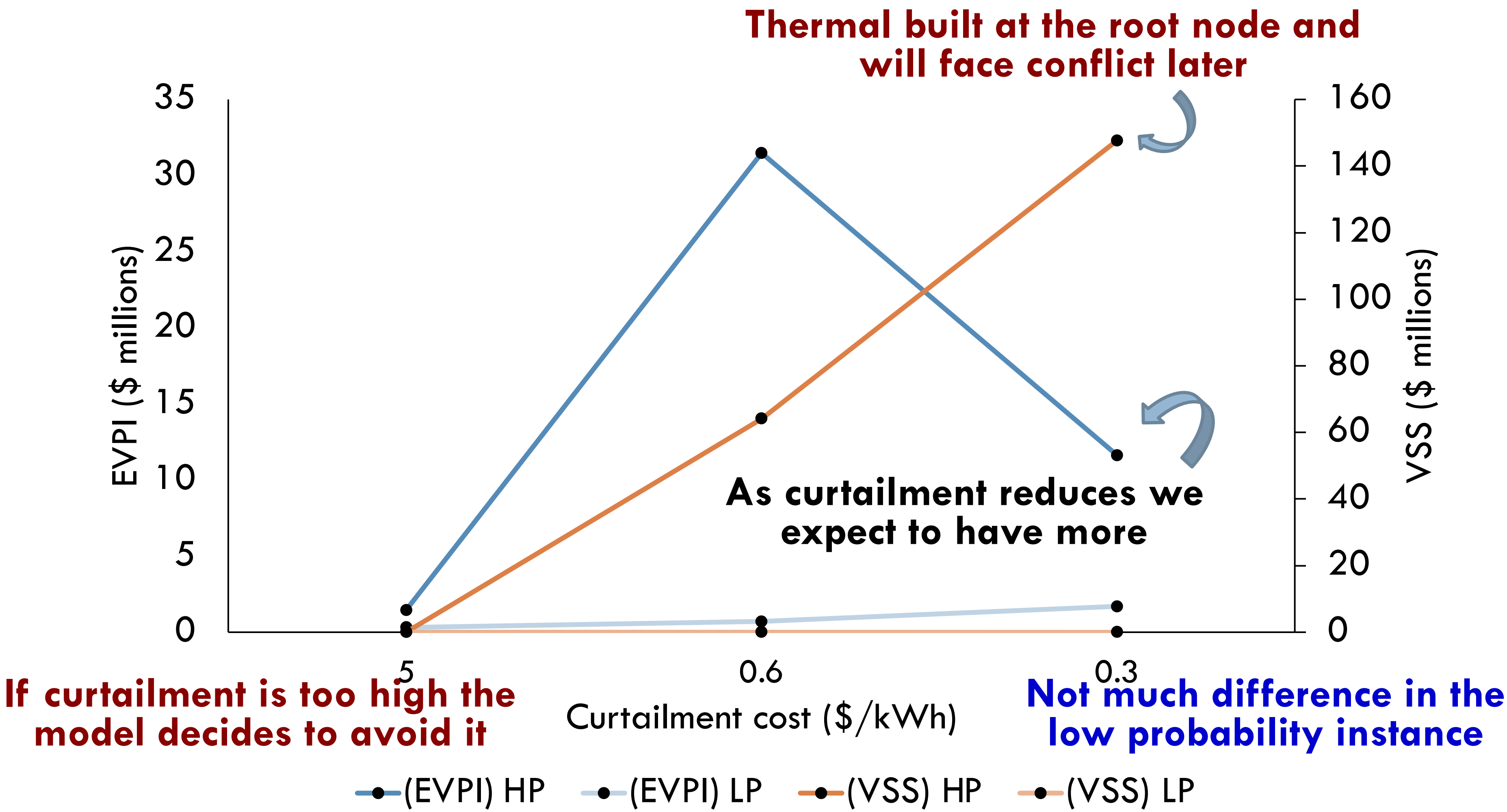
Problem Structure and Uncertainty





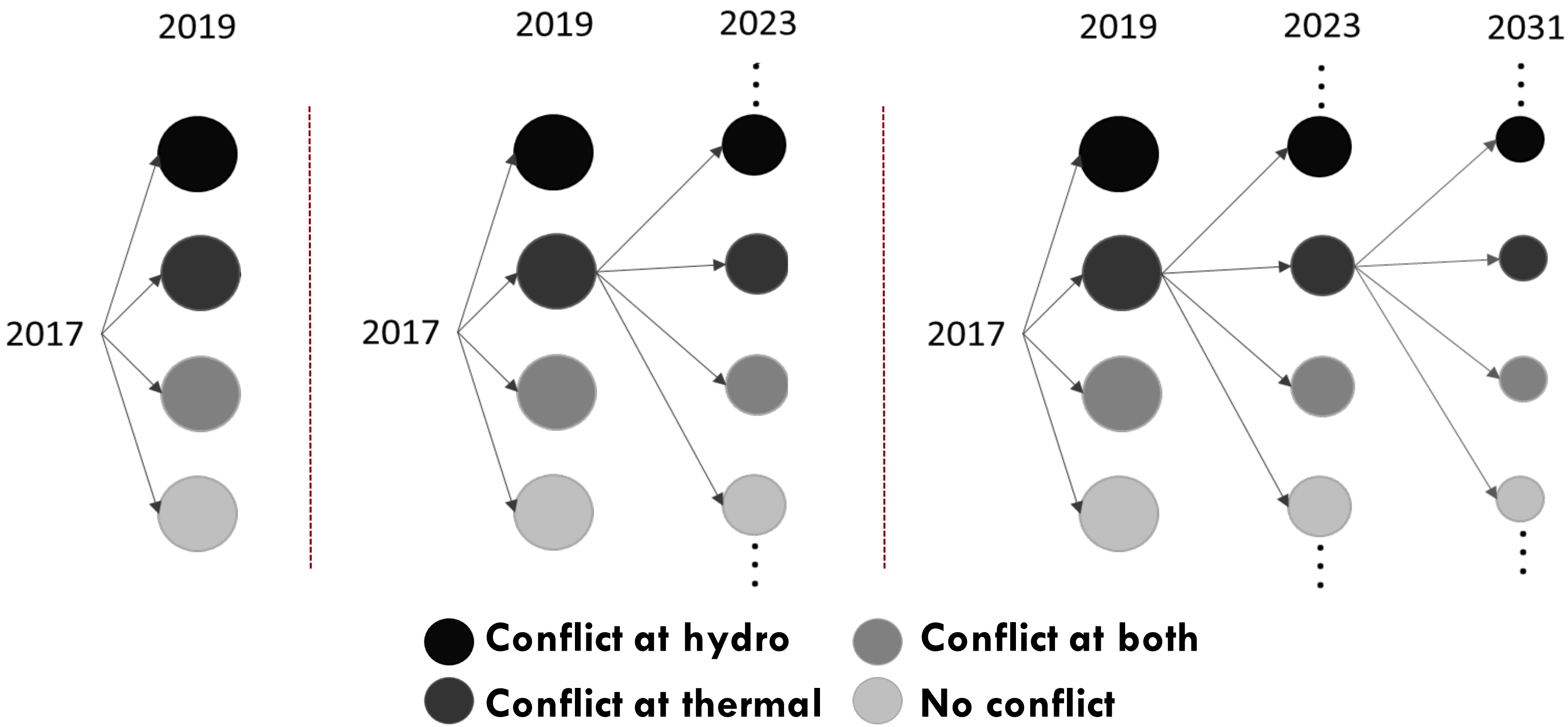
Conflict at	Conflict Scenario Probabilities	
	High	Low
Hydro	0.45	0.05
Thermal	0.25	0.05
Both	0.25	0.05
No conflict	0.05	0.85

EVPI & VSS for Different Curtailment Costs

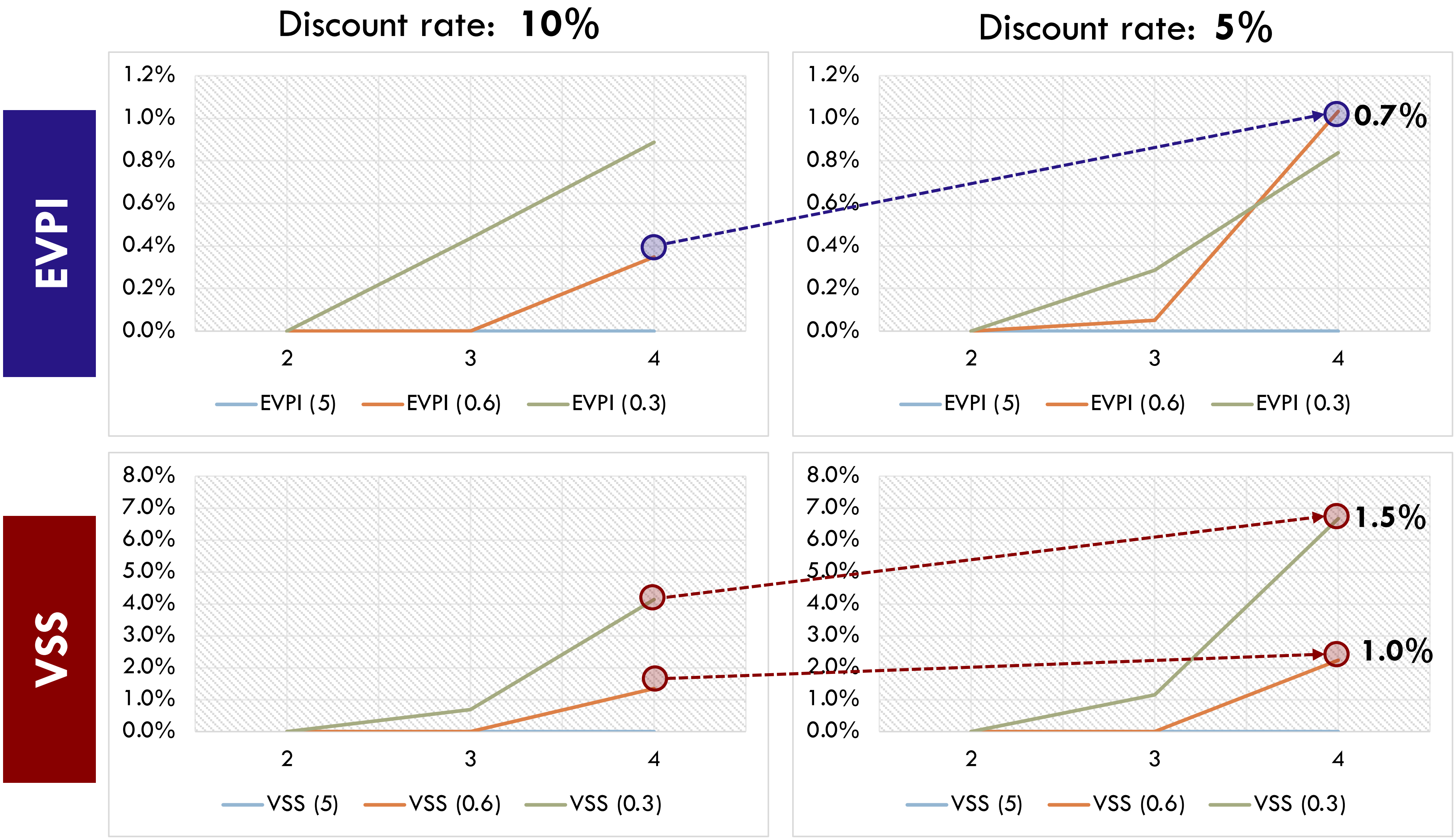


Other Problem Instances

- We keep the instance with high probability of conflict
- Consider two annual discount rates (10% and 5%)
- Analyze problem with different number of stages



EVPI & VSS (Curtailment, # of Stages and Discount Rate)



Remarks & Comments

Remarks & Comments

- We presented an **overview** about the **ESPP and TEMOA**
- We used **EVPI** and **VSS** as metrics to assess the value of representing this problem as a **MSLP**
- Problem's characteristics determines the **optimization design** (What to consider as uncertainty? How many time stages? Discount rate? Relationships with decisions from previous stages, etc)
- We briefly talked about a case study for South Sudan (explained in detail at the poster Section today at 12:30 PM by **Neha Patankar**)
- Future work will analyze EVPI and VSS considering other variations in model formulation as well as uncertainties

Thank You !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