Single Pad Planning under Uncertainty for Shale Gas Development

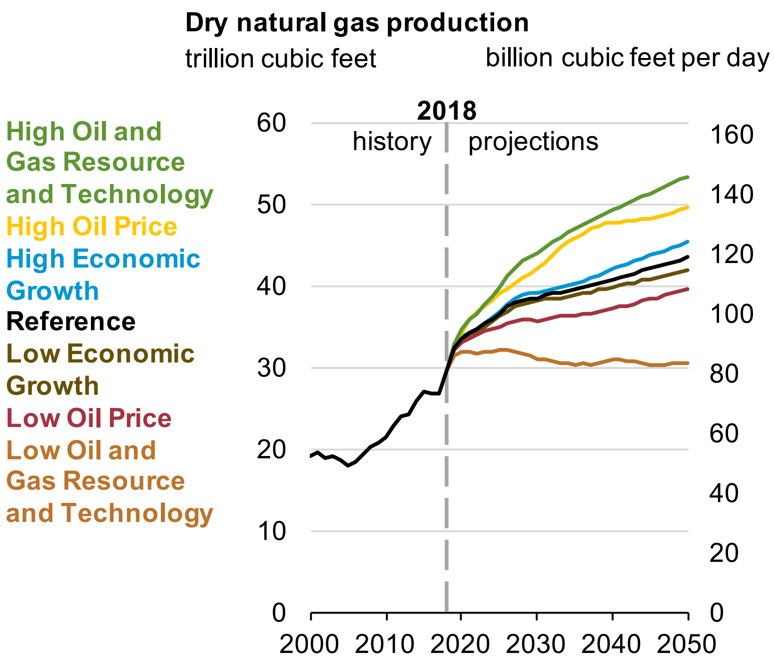
Can Li[1], Ignacio E. Grossmann[1], John P. Eason[2], Markus G. Drouven[2]

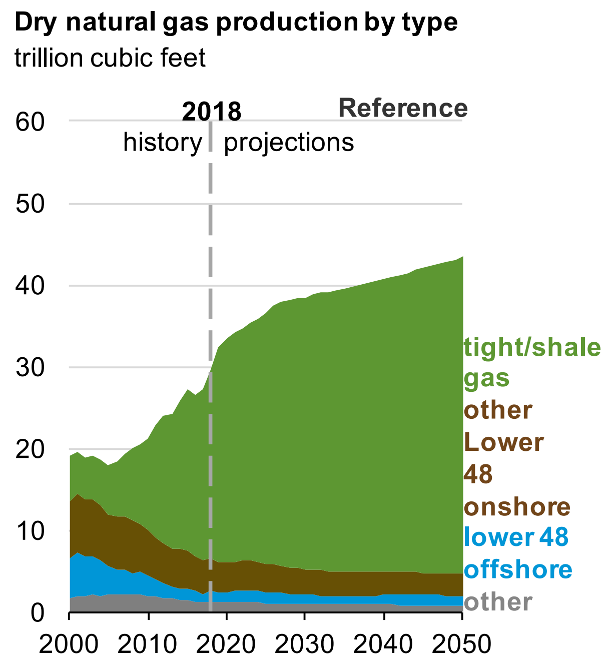
[1]Department of Chemical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

[2]Optimization Engineering
EQT Corporation
Pittsburgh, PA 15222

Motivation

- **Shale gas** production expected to **increase** by almost **50%**
- Shale gas production will satisfy vast **majority** of the expected total natural gas demand going forward
- Determine profitable method of shale gas **development**

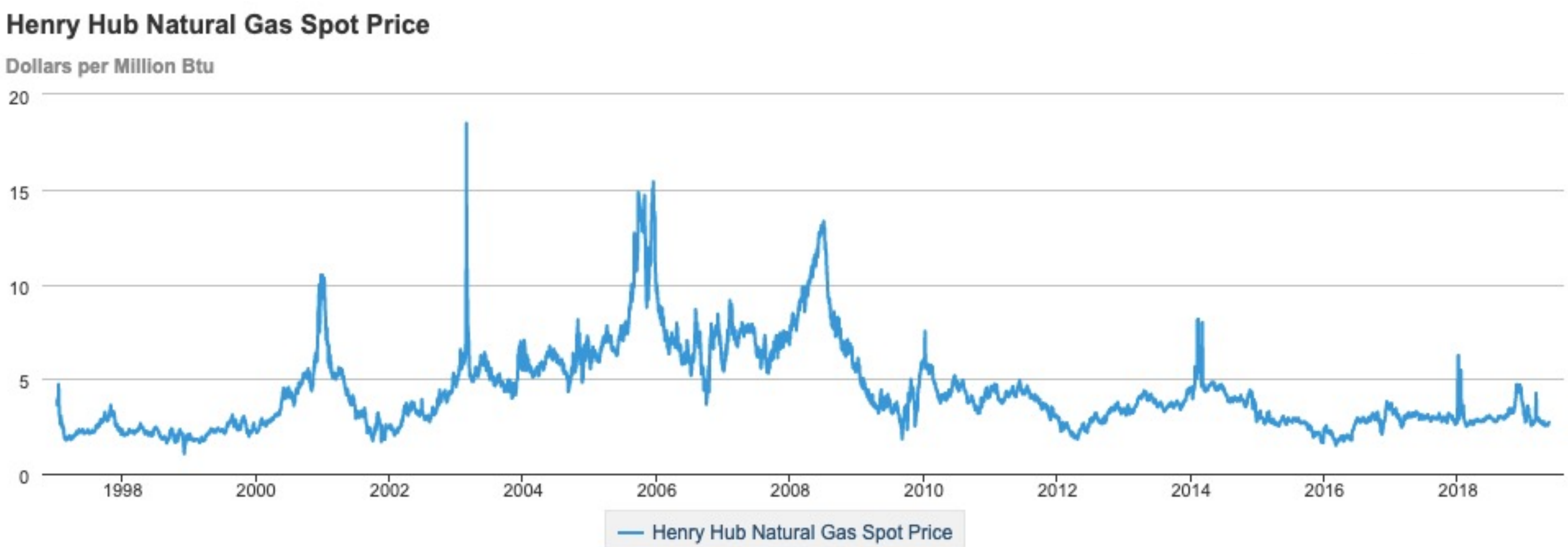




From Annual Energy Outlook 2019
by U.S. Energy Information Administration

Motivation

- Shale gas production expected to increase by almost 50%
- Shale gas production will satisfy vast majority of the expected total dry natural gas demand going forward
- Determine profitable method of shale gas development
- We need to hedge against **uncertainty** in natural gas **price**

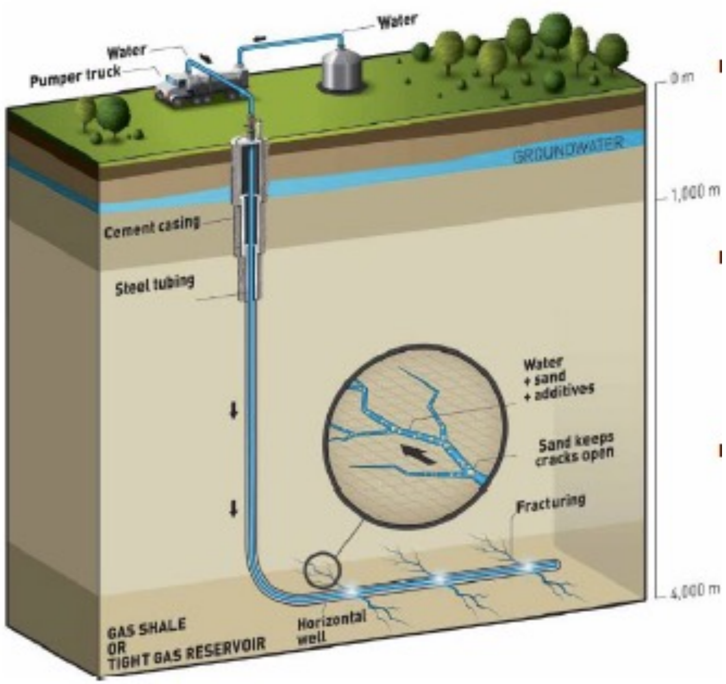


Literature

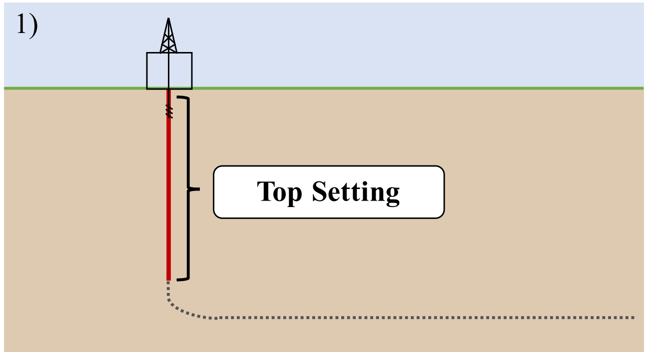
- Deterministic shale gas models
  - **Ondeck et al. (2019),** Cafaro and Grossmann (2014), Drouven and Grossmann (2016), Guerra et al. (2016), Gao and You (2015), Arredondo-Ramírez et al.(2016), Yang et al. (2014), Forouzanfar and Reynolds (2014) …

- Stochastic shale gas models
  - Gao and You (2015), Guerra et al. (2019), Zeng and Cremaschi (2017) …

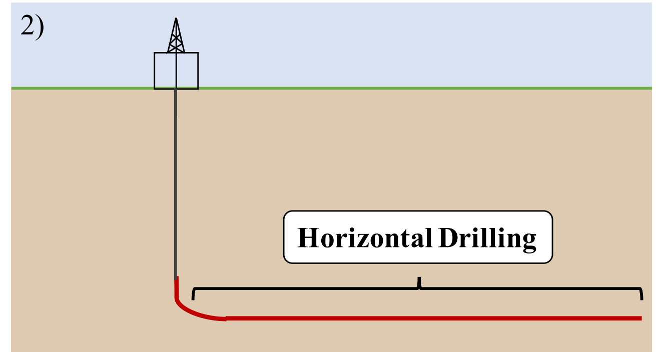
Fixed Sequence of Well Operations



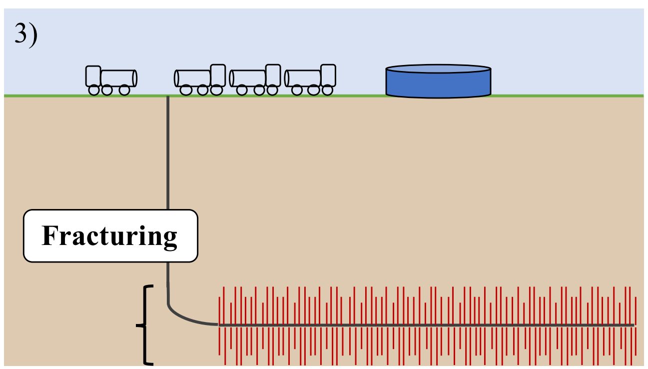
Fixed Sequence of Well Operations



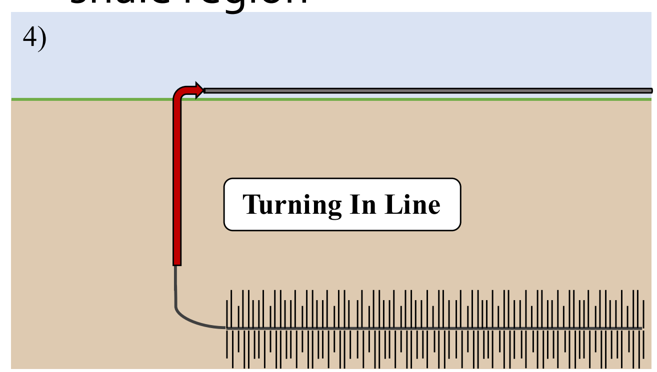
- Drill and encase a well down to the targeted shale region



- Continue drilling the well horizontally in the targeted shale region



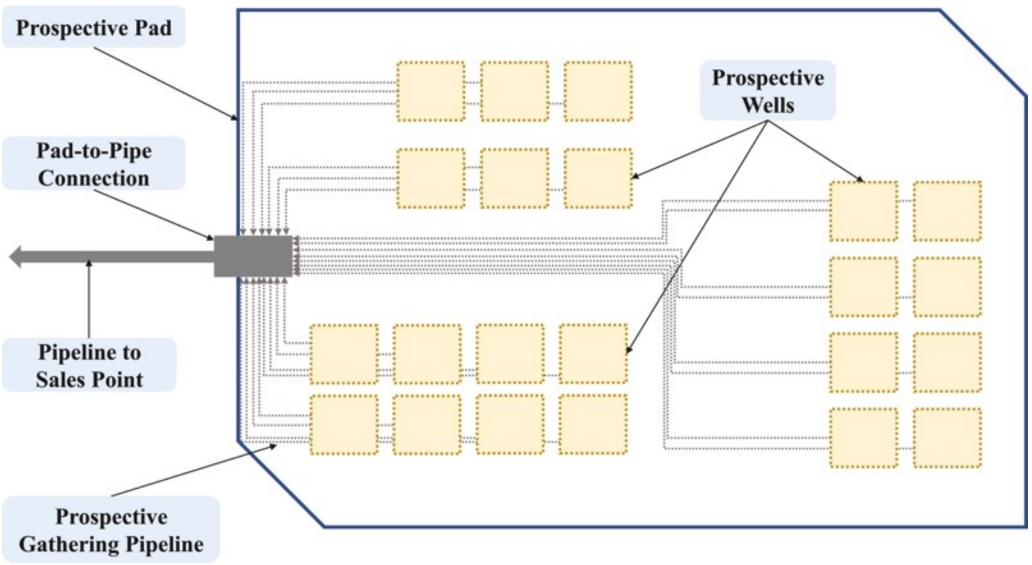
- In stages, apply pressure using a water-based solution to create fissures in the shale



- Open up the well to produce gas

Problem Statement & Assumptions

- Given a **single** shale gas well pad with given **prospective wells**
- Fixed planning horizon (**discrete** time representation)
- At most **one operation** can be done at given time
- **Mobilization** costs and **operational** costs are considered
- Gas **curtailment/storage** is allowed



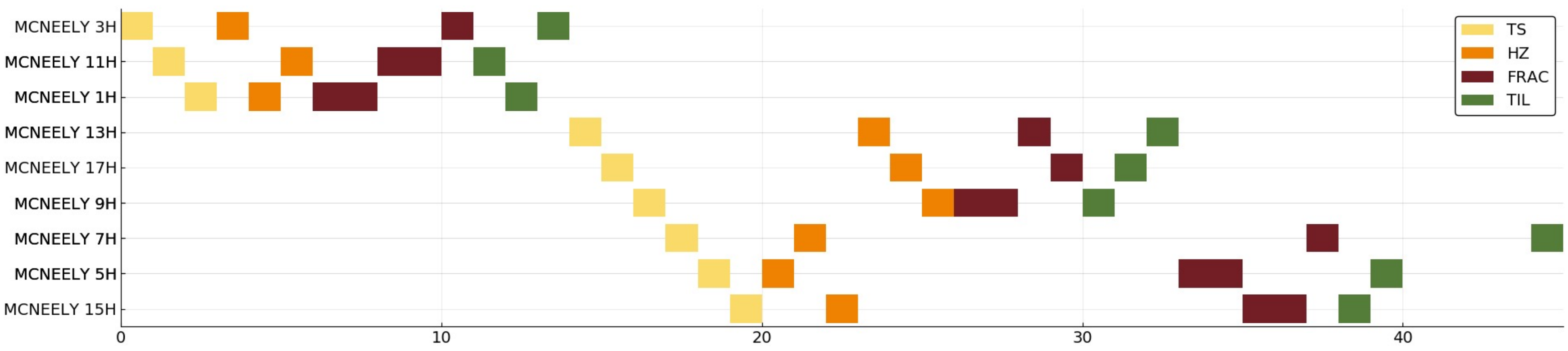
Ondeck et al. (2019)

Output from the Optimization Model

- Given a single shale gas well pad with given prospective wells
- Fixed planning horizon (discrete time representation)
- At most one operation can be done at given time
- Mobilization costs and operational costs are considered
- Gas curtailment/storage is allowed

- **Schedule** of operations on the single pad generated with MILP model

Wells **Operations**



Deterministic MILP Model

Sequence of operations.

Mobilization costs

Production

Operating costs

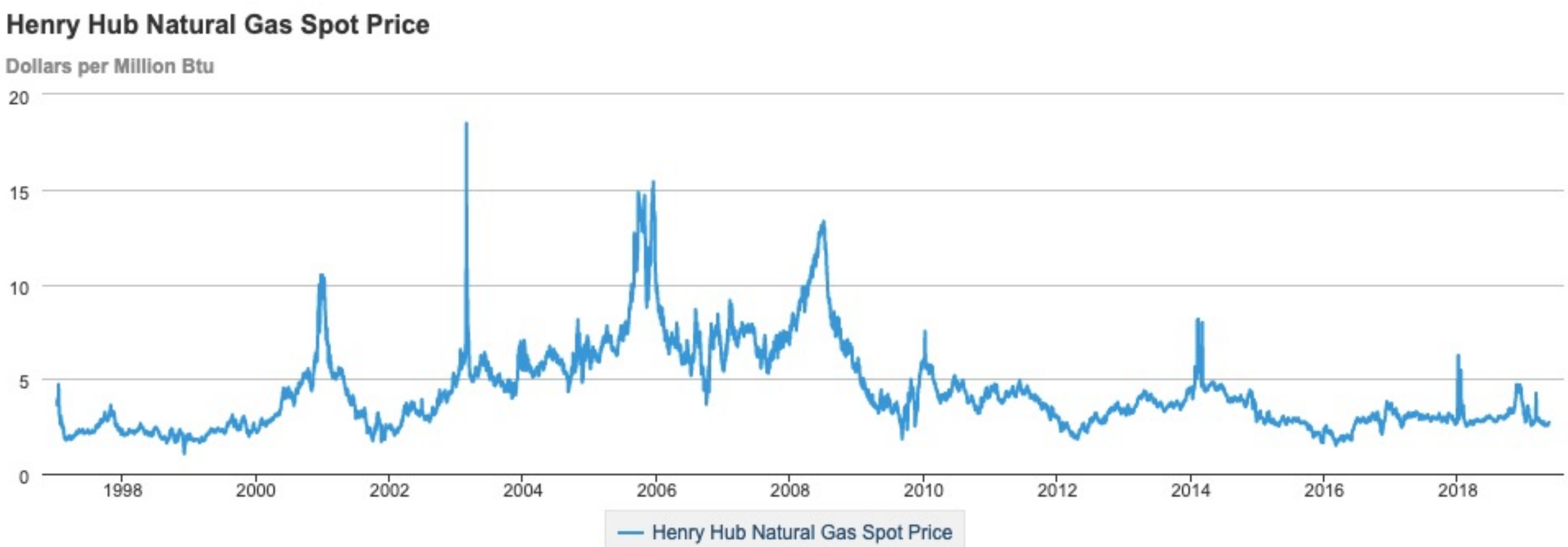
Storage constraints

Revenues

Objective: Maximize NPV

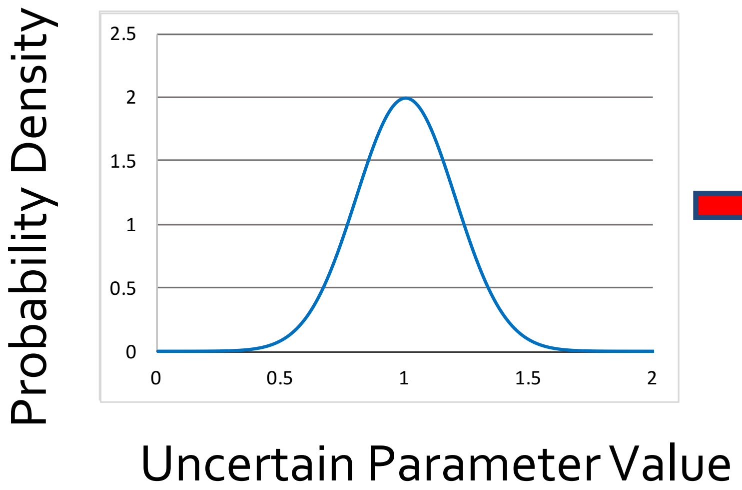
Hedge Against Uncertainty

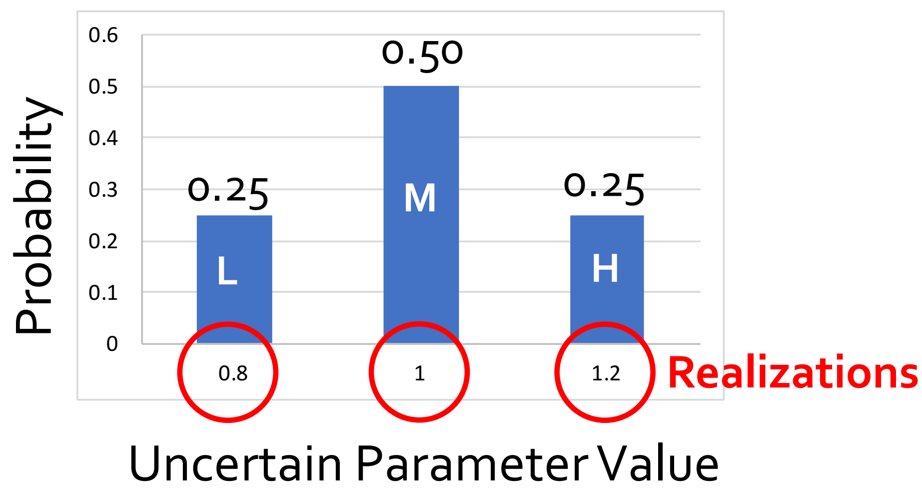
- We need to hedge against **uncertainty** in natural gas **price**



Stochastic Programming

- **Stochastic programming** is a framework
  for modeling optimization problems that involve uncertainty
- Uncertainty can be characterized by **probability distributions** known *a priori*
  - Continuous distributions → Discrete distributions



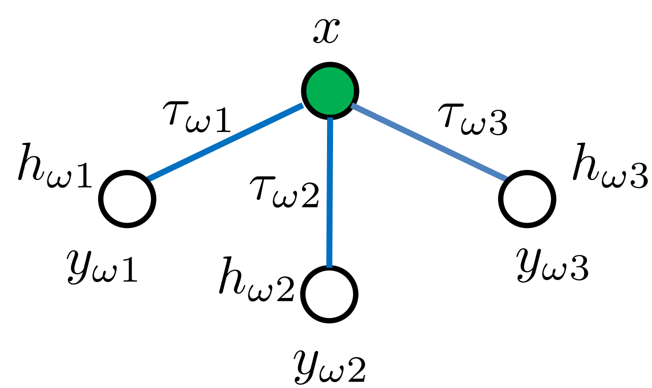


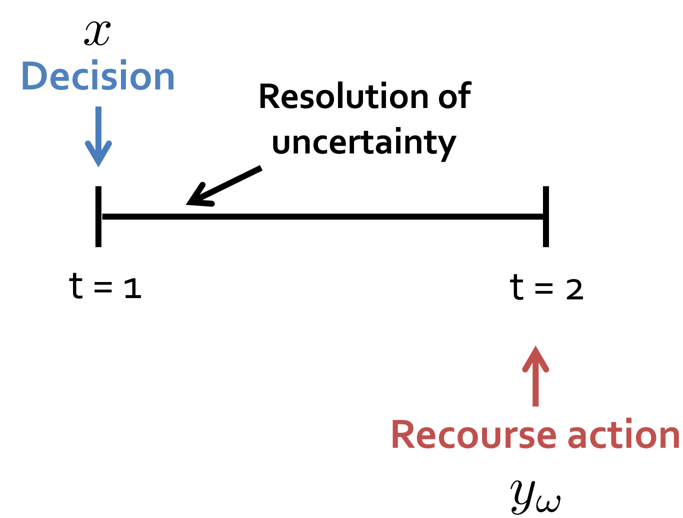
- Each realization of uncertainty parameters is called **a scenario**
- Optimize the **expected value** of the objective over **all possible scenarios**

Two Stage Stochastic Programming

- First stage decisions: **Here and now**
- Second stage decisions: **Wait and see, Recourse decisions**

$$
\begin{aligned}
\min \quad & c^T x + \sum_{\omega \in \Omega} \tau_\omega d_\omega^T y_\omega \\
s.t. \quad & Ax \leq b \\
& W_\omega y_\omega \leq h_\omega - T_\omega x \qquad \forall \omega \in \Omega \\
& x \in \{x = (x1, x2) : x_1 \in \{0,1\}^n, x_2 \geq 0\} \\
& y_\omega \in \{y : y \geq 0\}
\end{aligned}
$$



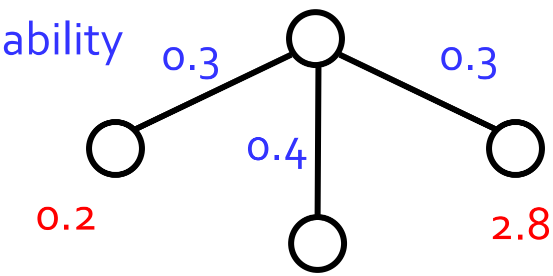


Deterministic Equivalent

Two Stage with Price Uncertainty

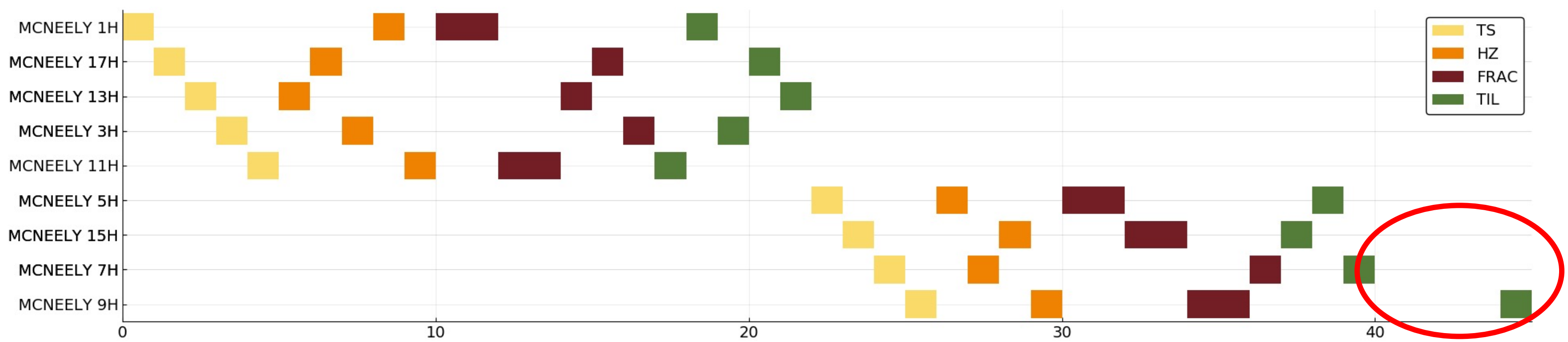
- Input data: Single well pad, 9 wells
  - All the wells are permitted at time 0
- **Stage one**: week 1-week 20
- **Stage two**: week 21-week 45
- Price remains **constant** outside the planning horizon

Probability



Price: dollars per million Btu

Solve the expected value problem, i.e., fix the price at 1.5

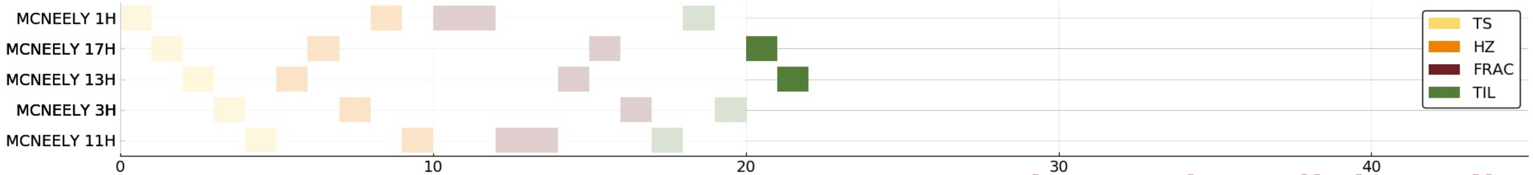


Fix the first stage decisions and see how it performs in different scenarios

due to production/storage capacity constraints

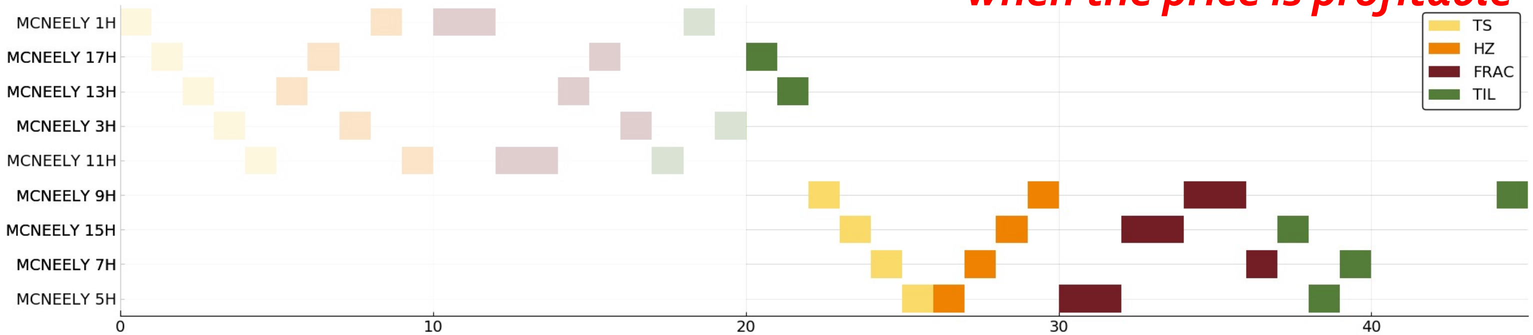
Expected Value Solution

Expected value solution when price = 0.2

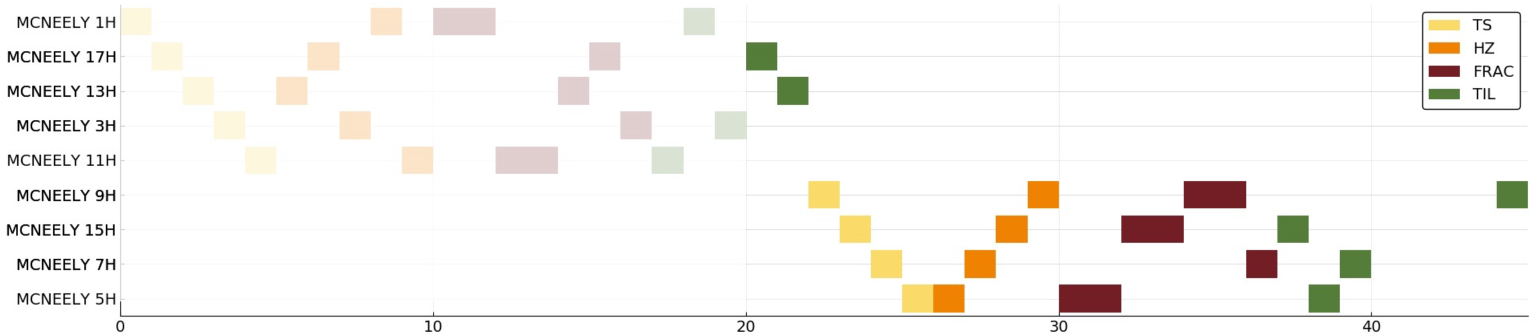


Expected value solution when price = 1.5

Only complete all the wells when the price is profitable



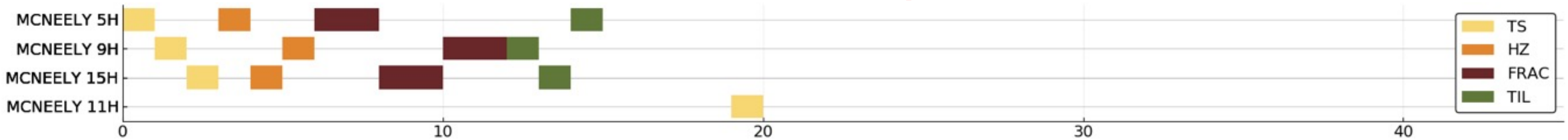
Expected value solution when price = 2.8



Two Stage Stochastic Solution

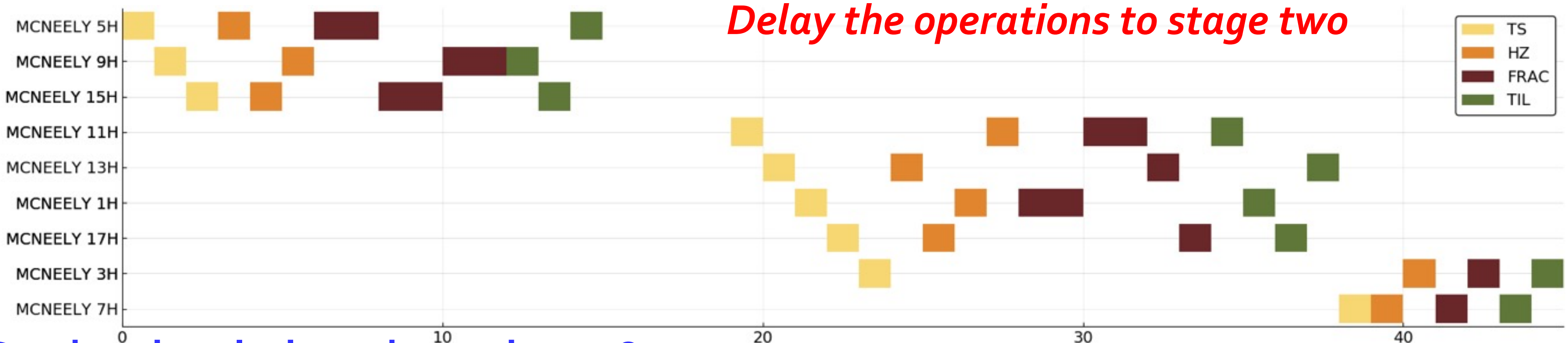
Stochastic solution when price=0.2

In stage 1, frac 2 wells less than expected value solution

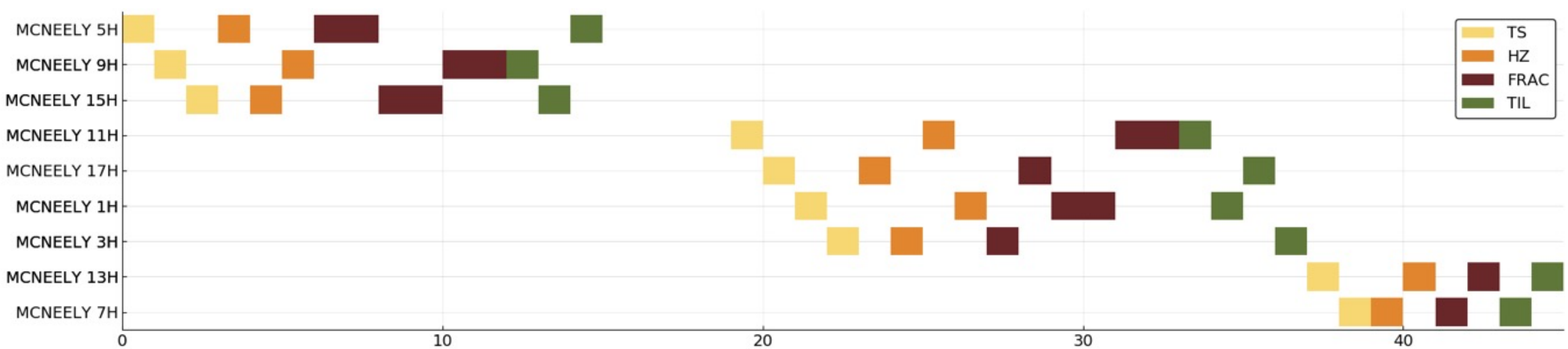


Stochastic solution when price=1.5

Delay the operations to stage two



Stochastic solution when price=2.8



Comparison of Stochastic & Expected Value Problem

	Binary var	Total Var	Constraints	Walltime	gap
Deterministic	3,655	4,522	4,524	19 min	0.01%
Stochastic	9,963	11,822	12,828	12 hrs	2.41%

Scenario	Price	NPV(Expected value)	NPV(Stochastic Solution)
1	0.2	-24.28	-7.74
2	1.5	71.45	70.86
3	2.8	182.58	178.48

(million dollars)

Expected value solution performs poorly when price is too low

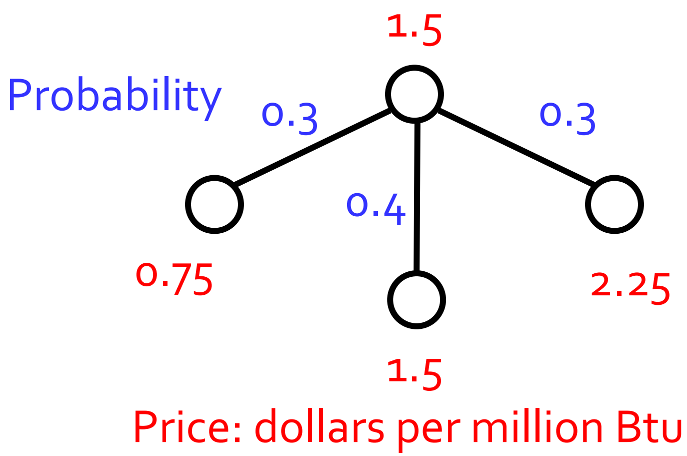
Expected results of using the expected value solution **EEV = 76.07**

Recourse problem **RP = 79.61**

Value of stochastic solution **VSS = 3.54**

Two Stage with Price Uncertainty

- Input data: McNeely. 9 wells
  - All the wells can start at the beginning
- **Stage one:** week 1-week 20
- **Stage two:** week 21-week 45
- Price remains constant outside the planning horizon

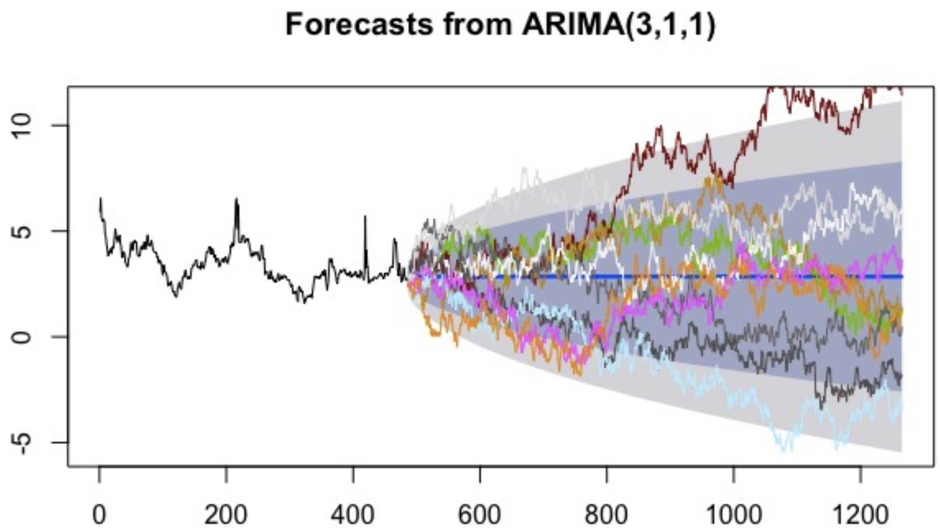


No value in using stochastic programming

Two Stage with Forecast Prices

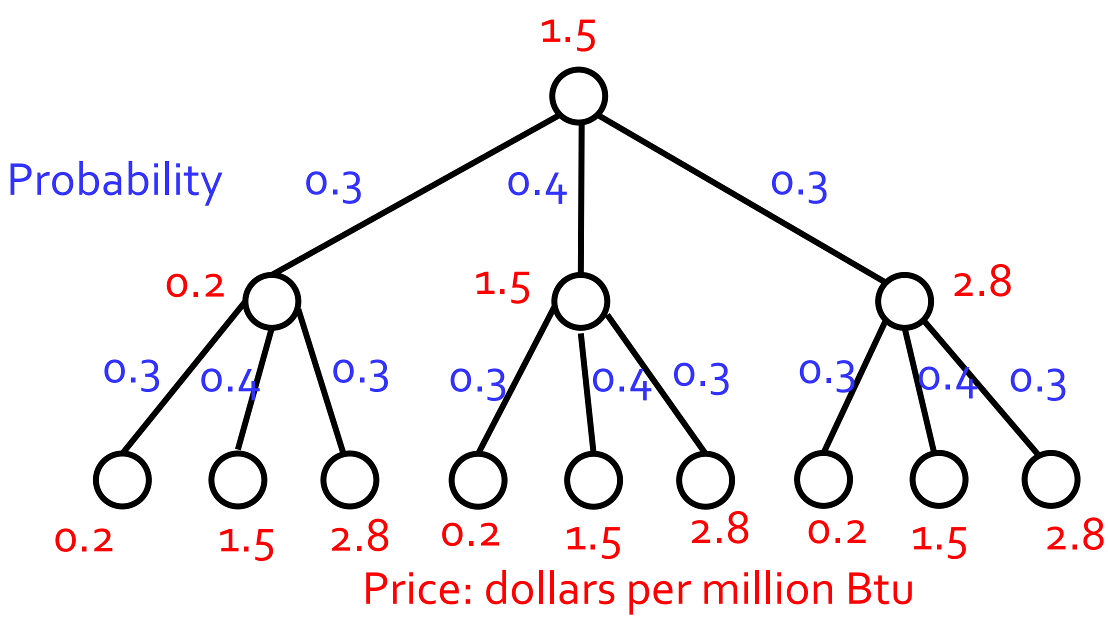
- Input data: McNeely. 9 wells
  - All the wells can start at the beginning
- **Price** comes from **forecast** using **ARIMA** (autoregressive integrated moving average) model
- **Stage one:** week 1-week 20
- **Stage two:** week 21-week 45

No value in using stochastic programming



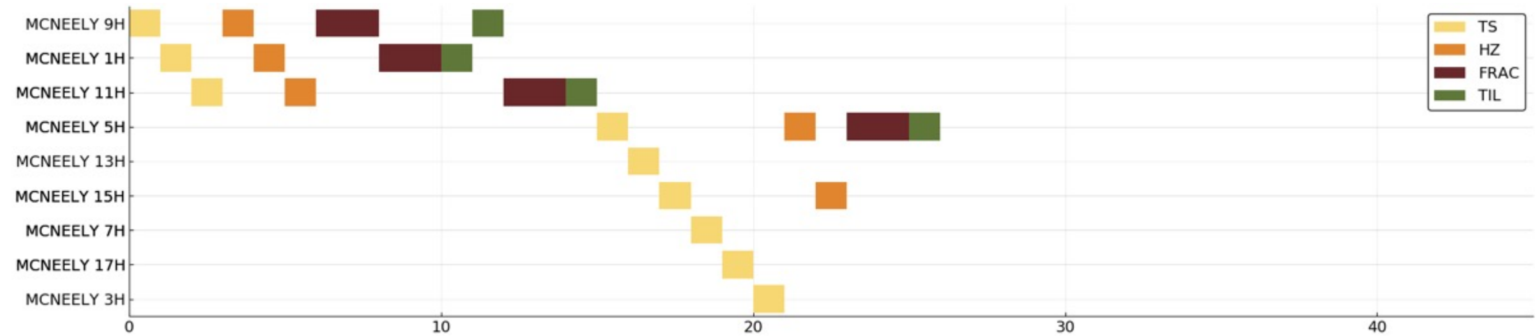
Three Stage with Price Uncertainty

- **Stage one:** week 1-week 16
- **Stage two:** week 17-week 32
- **Stage three:** week 33-week 48
- Price remains **constant** outside the planning horizon
- 31,213 binary variables, 4,153 continuous variables, 49,801 constraints
- 12 hours, gap=3.76%



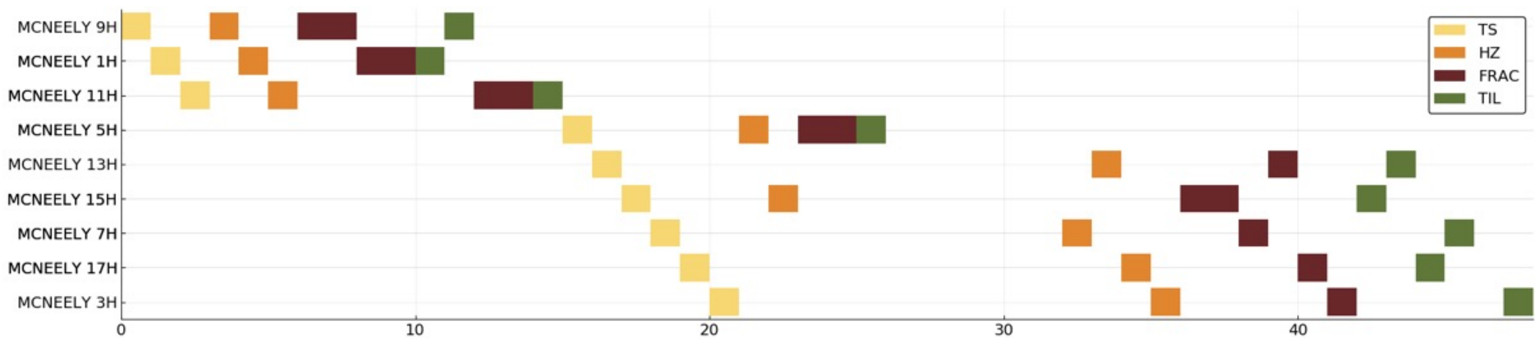
Three Stage Stochastic Solution

Stochastic solution when price=0.2, 0.2

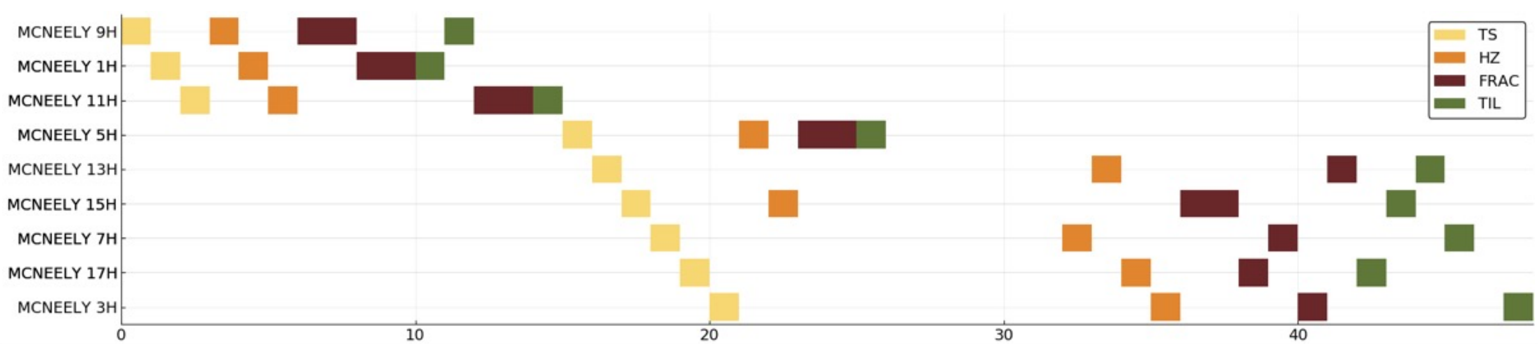


Stochastic solution when price=0.2, 1.5

Delay the operations to stage three



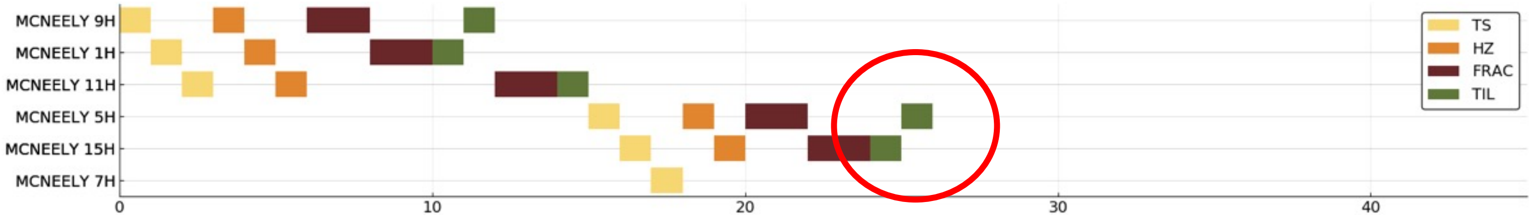
Stochastic solution when price=0.2, 2.8



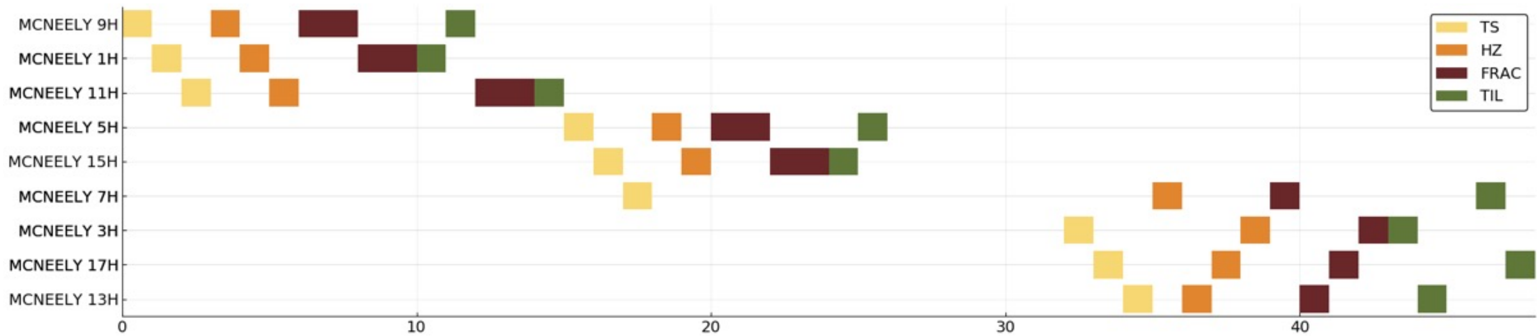
Three Stage Stochastic Solution

Stochastic solution when price=1.5, 0.2

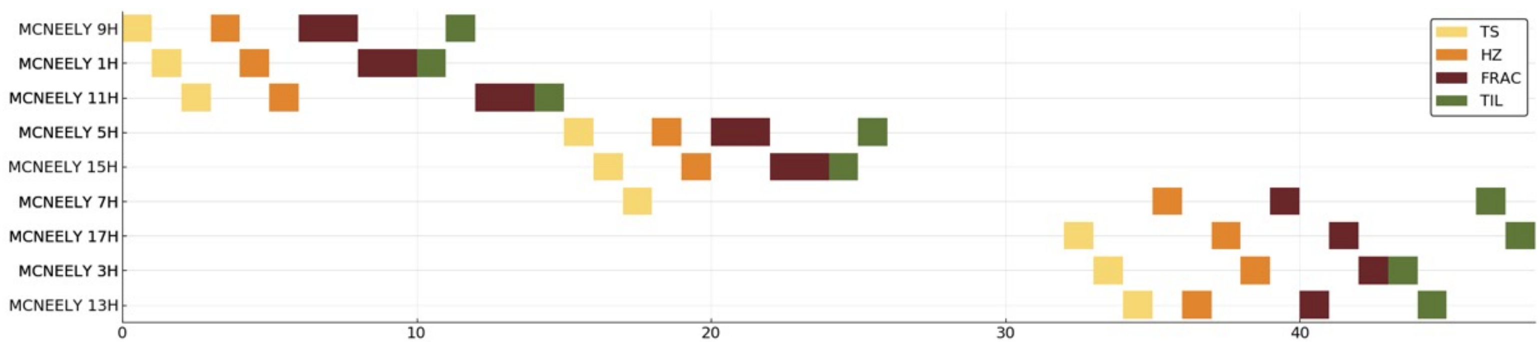
One more well is TIL in stage 2



Stochastic solution when price=1.5, 1.5

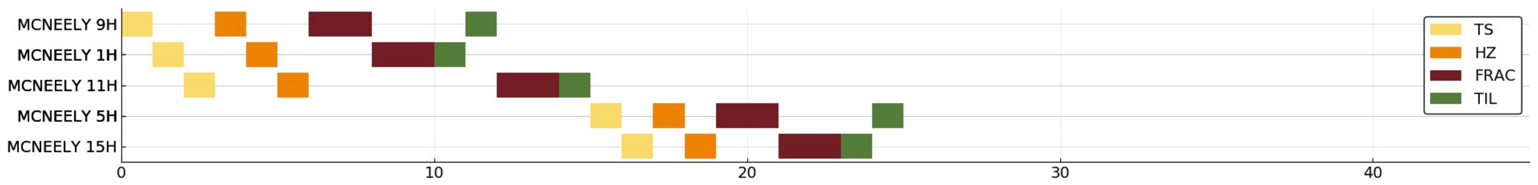


Stochastic solution when price=1.5, 2.8

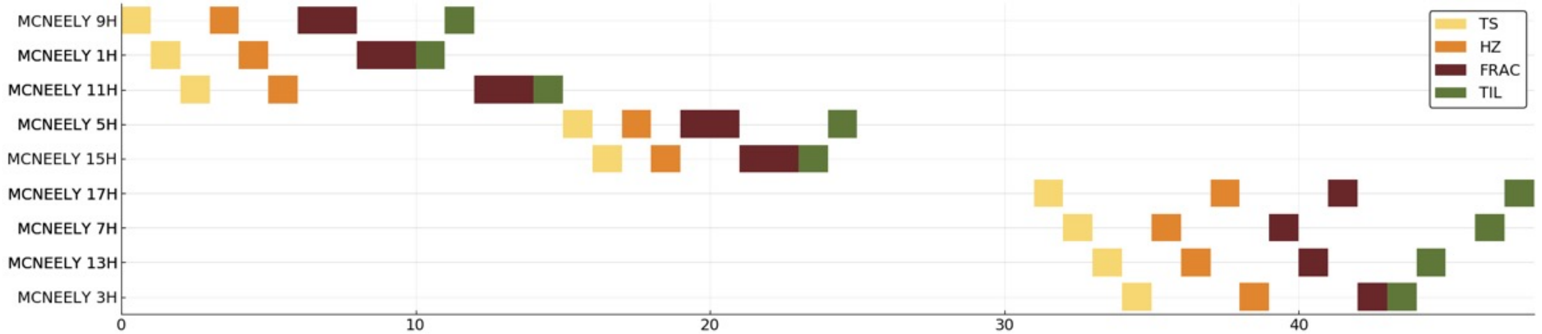


Three Stage Stochastic Solution

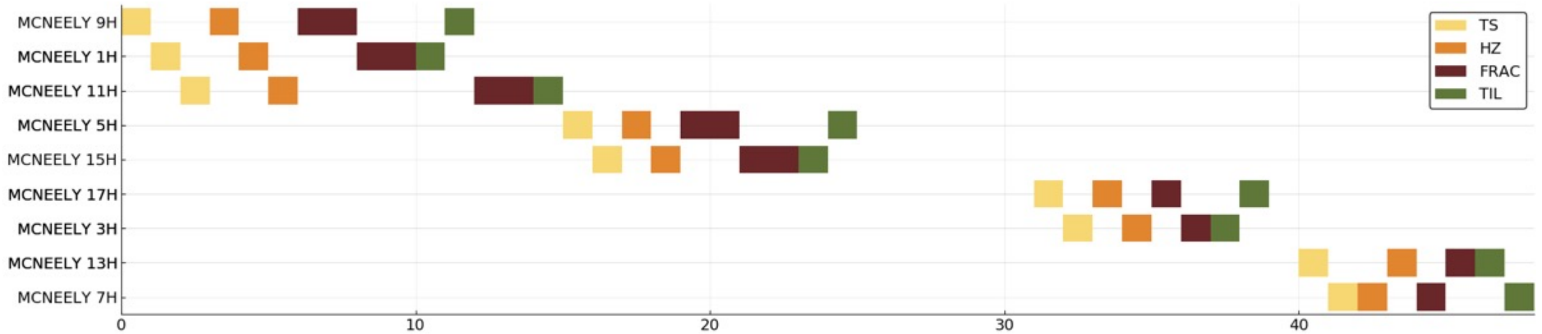
Stochastic solution when price=2.8, 0.2



Stochastic solution when price=2.8, 1.5



Stochastic solution when price=2.8, 2.8



Conclusion & Future Work

- The proposed **stochastic programming** model can help upstream operators to hedge against **price** uncertainty when the **variance** of price is **large**
- There is not always a **value** of using **stochastic programming** under price uncertainty
- Pattern in results: seek **flexibility** as to whether to develop a well
- Need better **algorithm** to solve **multi-stage** stochastic programs of this type faster