# MINLP Model and Solution Strategies for the Long-Term Planning and Development of Shale Gas Supply Chain Networks

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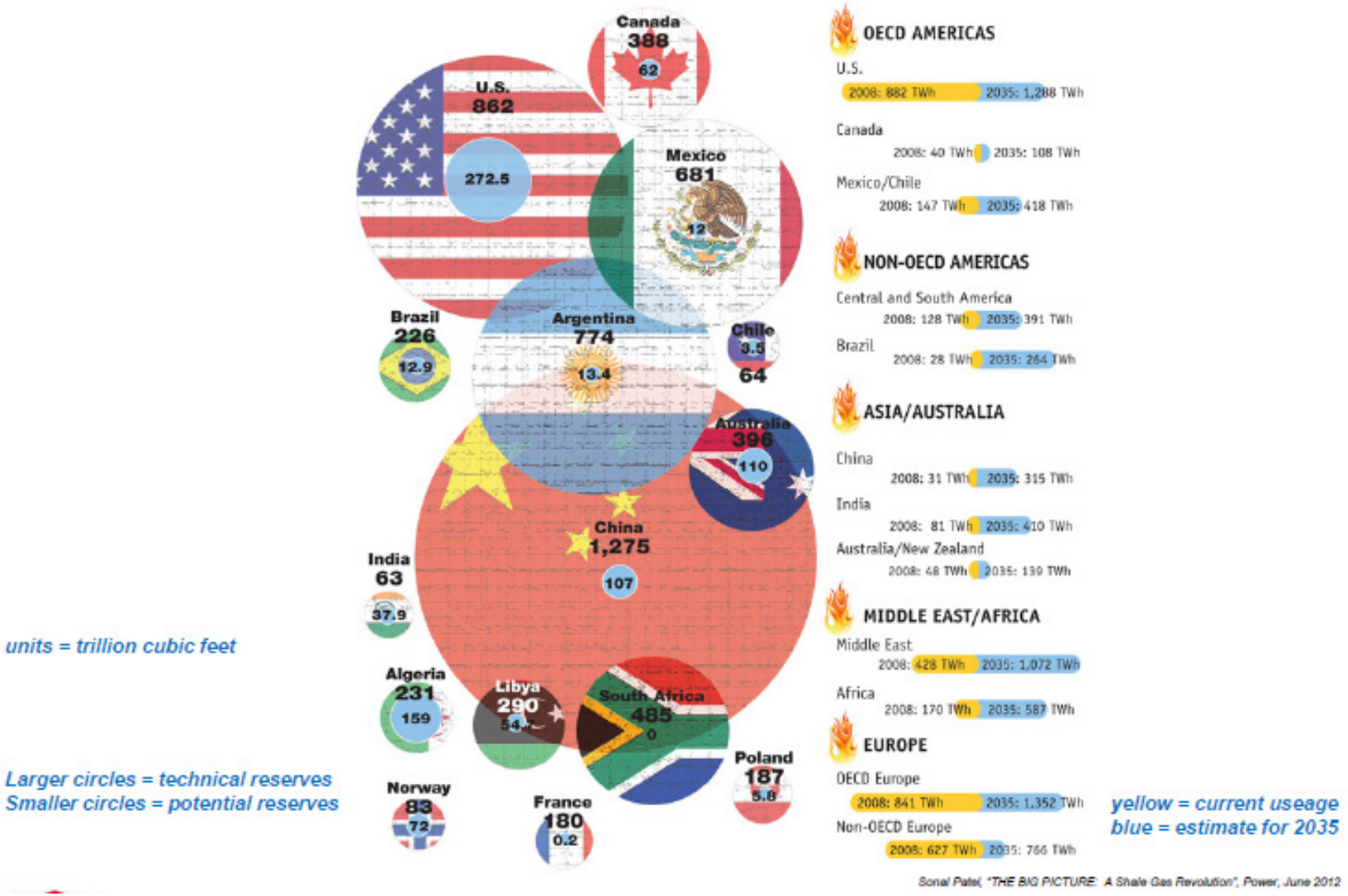
# Motivation: Recent Energy Source

## Gas Reserves in World



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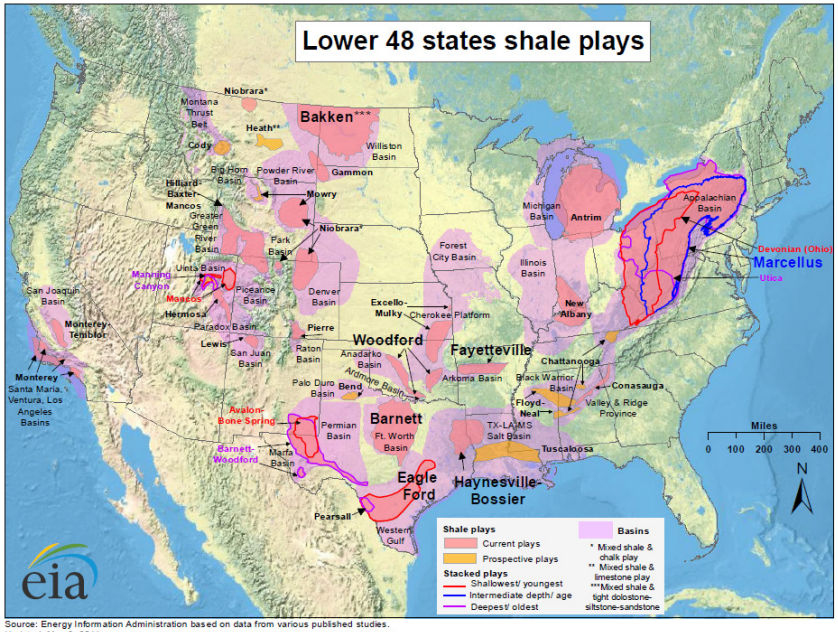
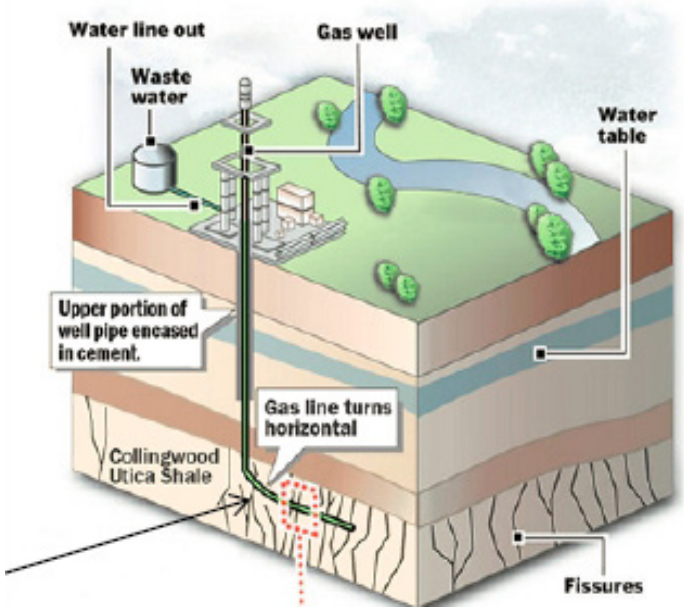
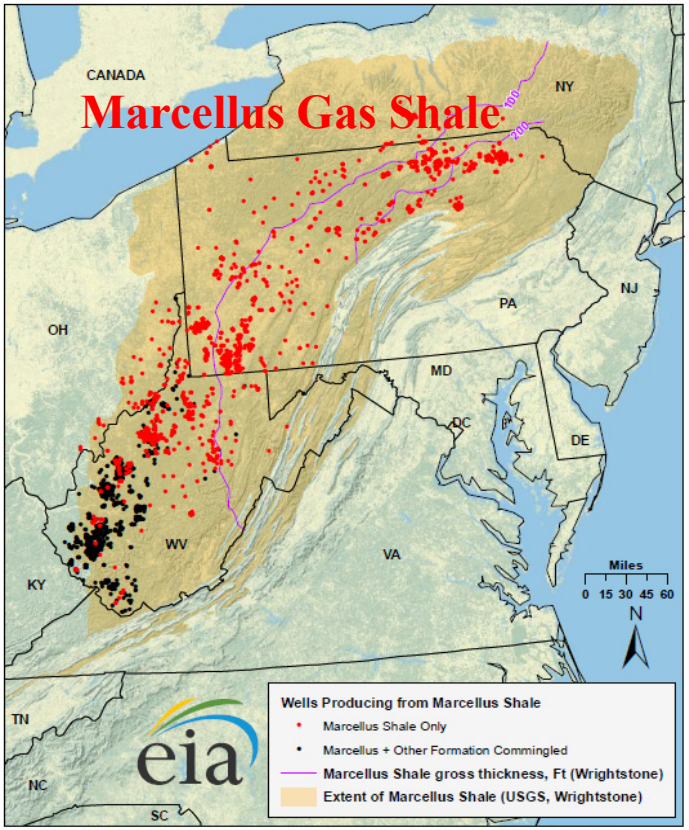
# Shale Gas in US




Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011




Marcellus Shale Gas Play, Appalachian Basin




Source: US Energy Information Administration based on data from WVGES, PA DCNR, OH DGS, NY DEC, VA DMME, USGS, Wrightstone (2009). Only wells completed after 1-1-2003 are shown. Updated June 1, 2011

**Large amount "wet gas"**

**Horizontal drilling**
**Hydraulic fracking**

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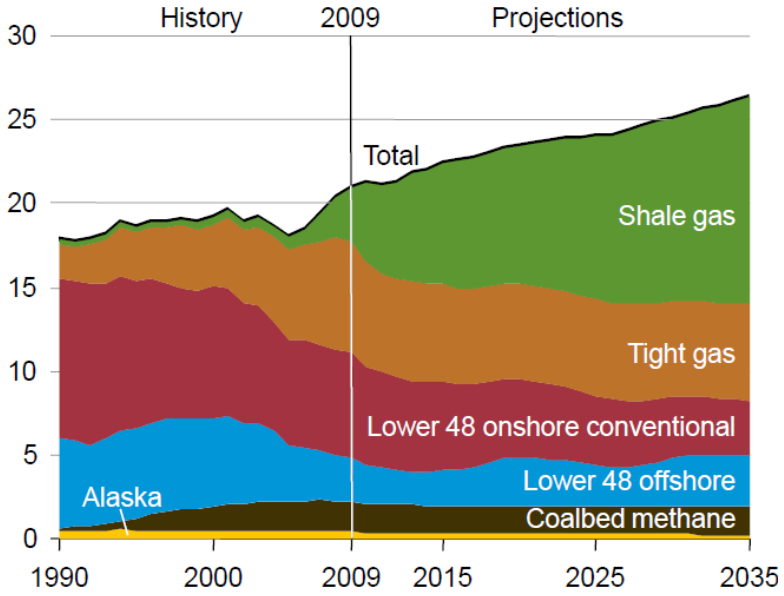
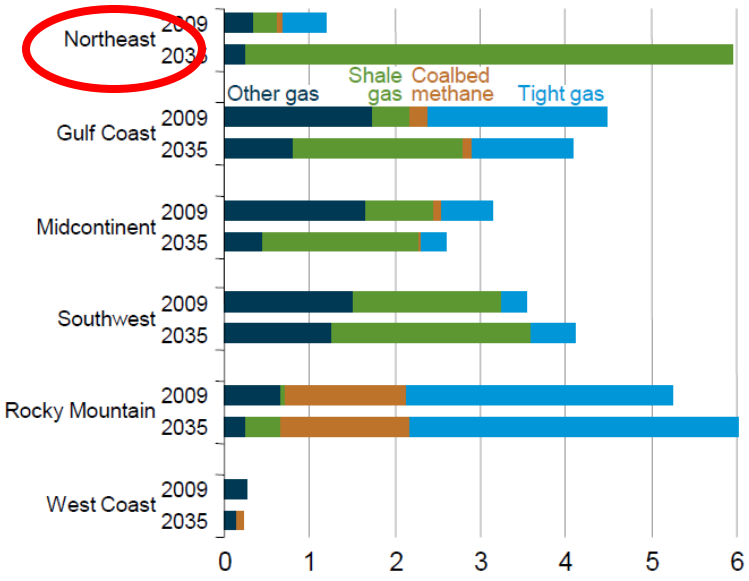
# Growth in Shale Gas




**In 2035 close to 50% from Shale Gas**

**Northeast: from 0.3 trillion scft 2009 to 5.8 trillion scft 2035**

**Goal: Develop Comprehensive Optimization Model for the Design of Supply Chain for Shale Gas Production**

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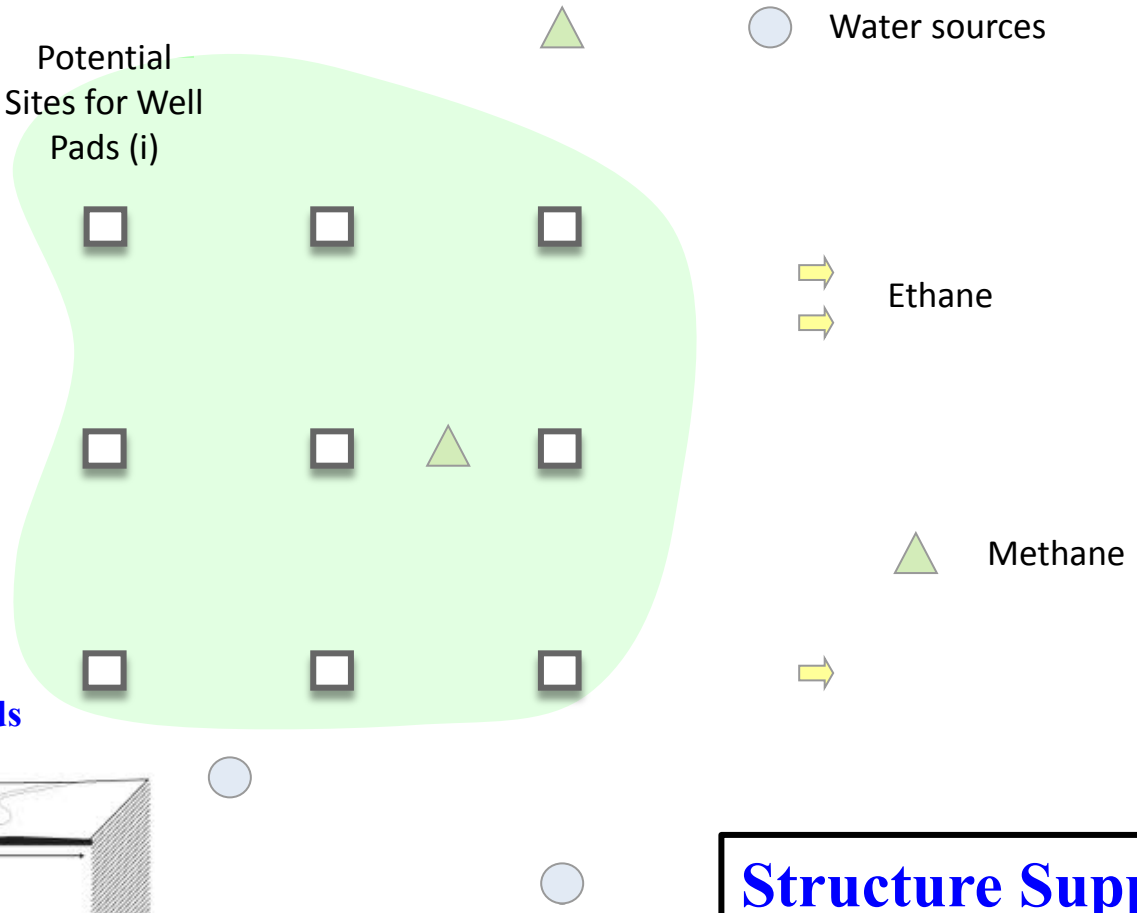
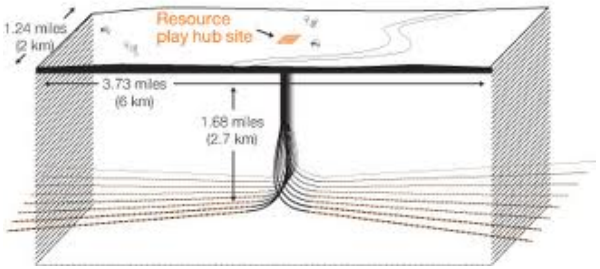
# Strategic Planning of Supply Chain for Shale Gas Production

- Given:




**Multi-well pads**




**Structure Supply chain?**

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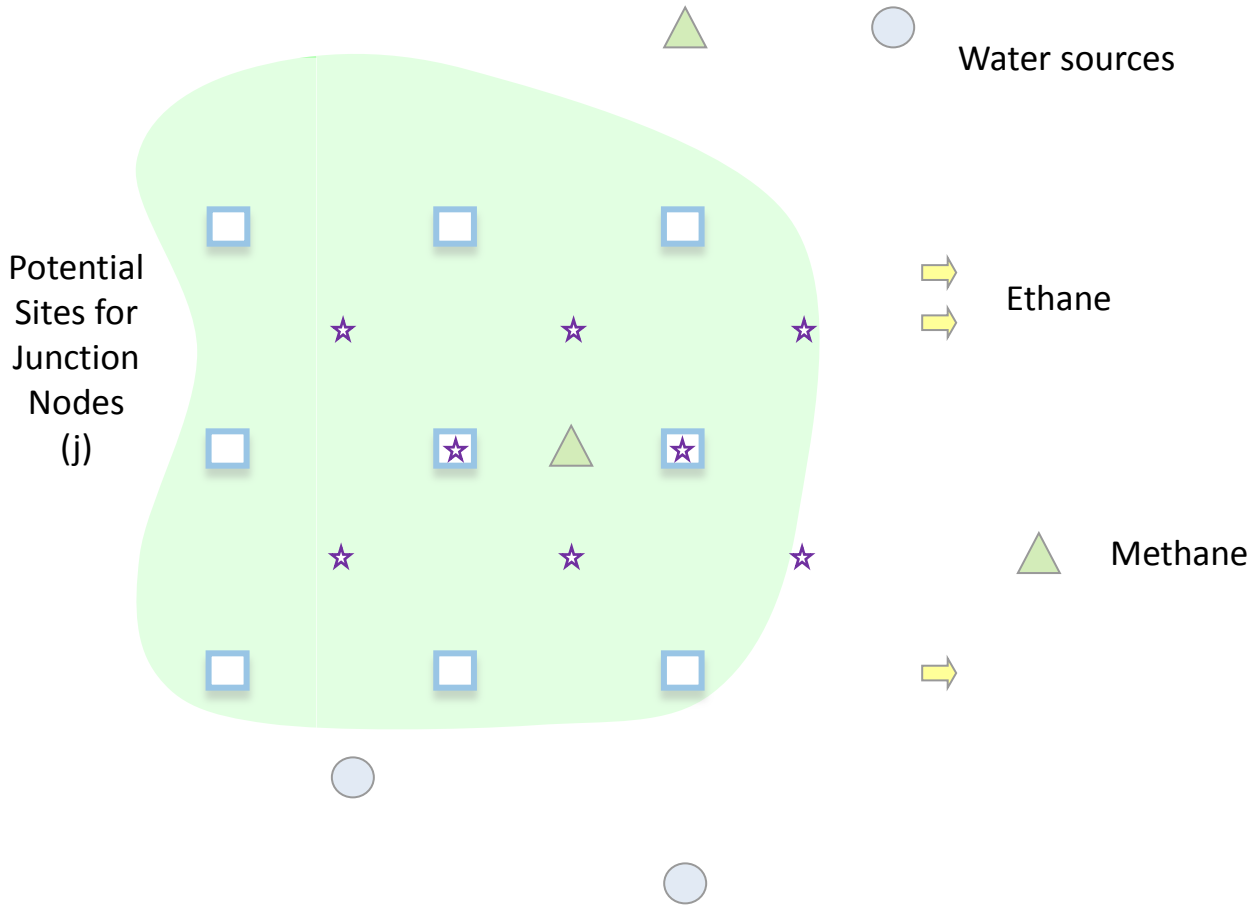
# Water Supply?

# Junction pipelines and compressors?



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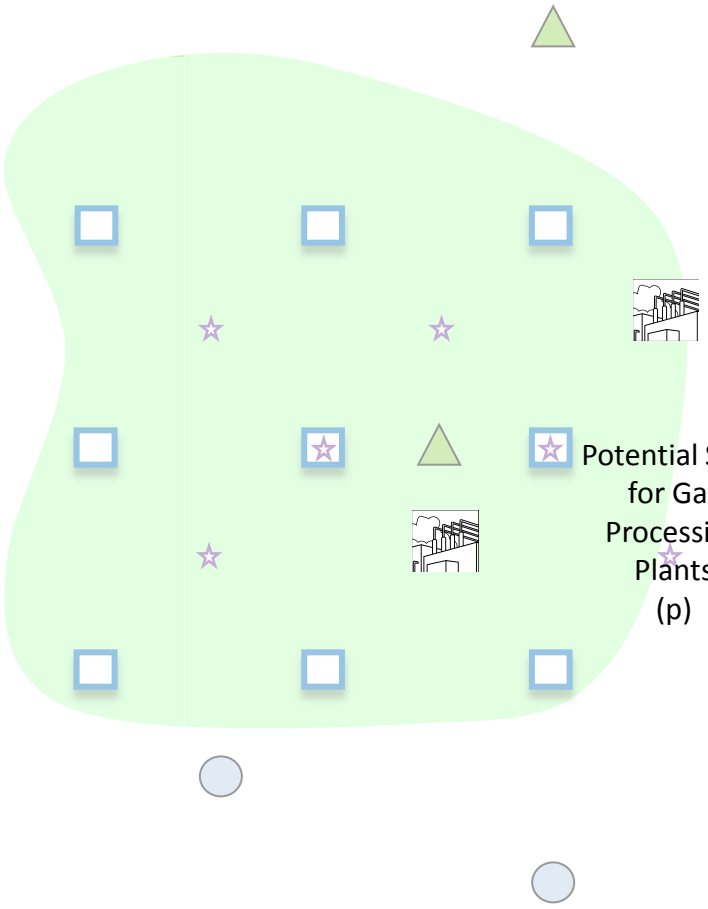
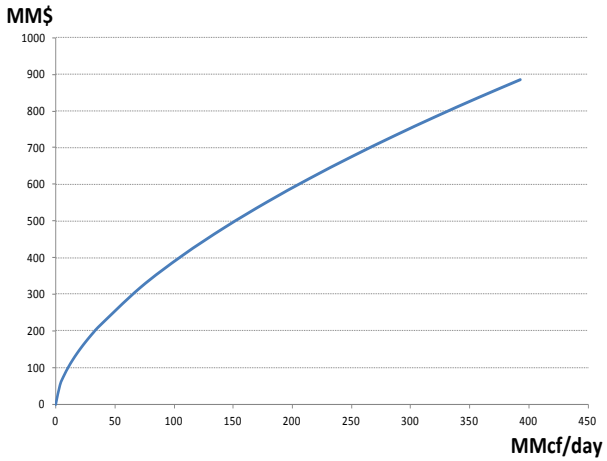
# Where to install gas processing plants?

- Given are:




Cost Correlations

**Economy of Scale Functions**



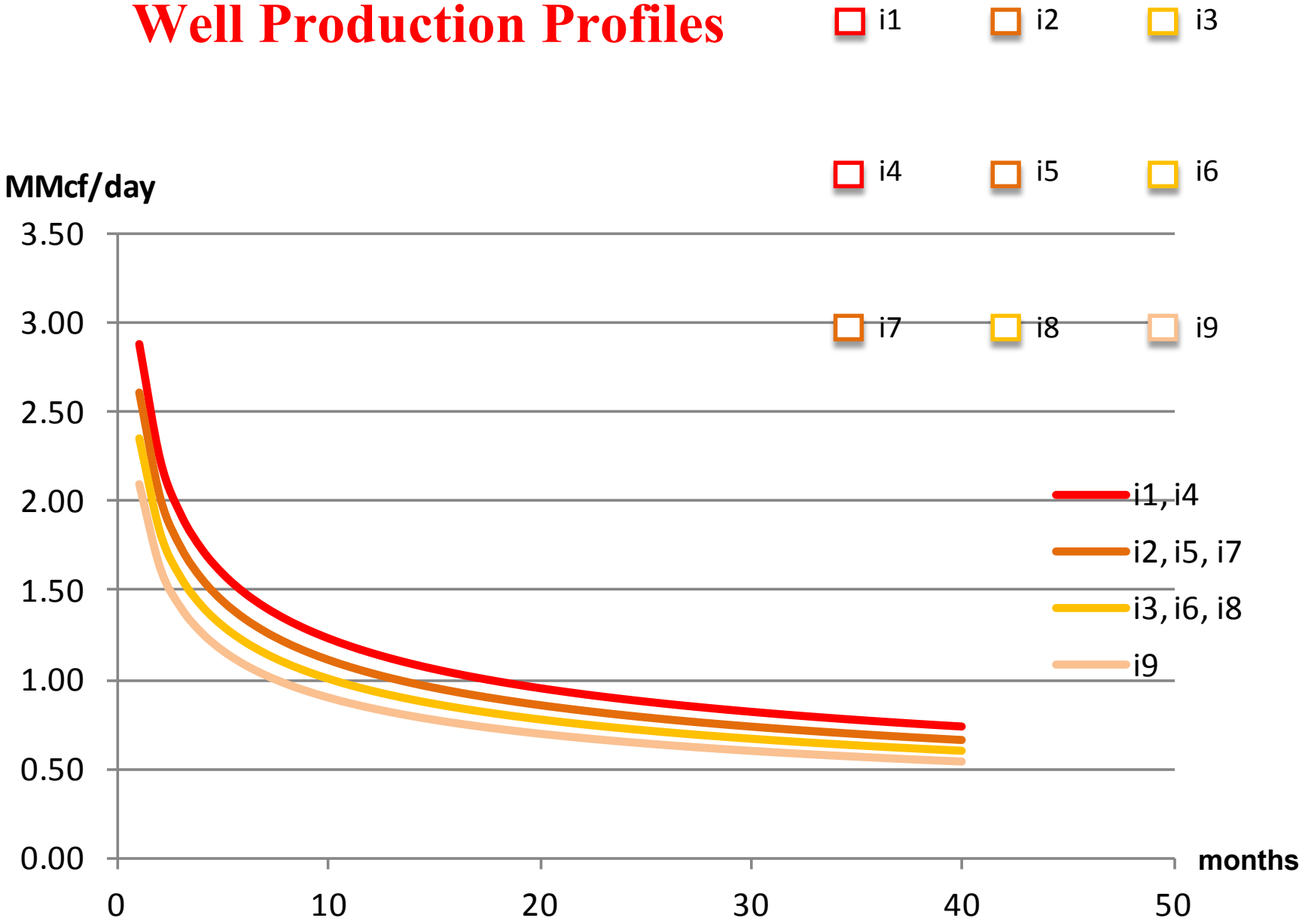
# Optimal Design Supply Chain

- **The Goal is to Determine**:
  - Number of Wells to Drill in Each Pad at Every Quarter
  - Site and Capacity of Gas Processing Plants Installed (or Expanded) at Every Period
  - Diameter and Length of Pipelines Joining:
    - Well Pads and Junction Nodes (Flow Pipelines)
    - Junction Nodes and Processing Plants (Gathering Pipelines)
    - Processing Plants and Gas Demand Nodes (Transmission Pipelines)
    - Processing Plants and Ethane Demand Nodes (Liquid Pipelines)
  - Power of Compressors Installed at Every Period in:
    - Junction Nodes
    - Processing Plants
  - Fresh Water Transportation from Reservoirs to Well-Pads at Every Period

# Economic Objective

- **Maximize NPV**:
  - + Gas Sales Income
  - + Ethane Sales Income
  - + LPG Sales Income
    - - Shale Gas Production Cost
    - - Processing Plants Construction/Expansion Cost
    - - Pipeline Construction Cost
    - - Well Drilling and Hydraulic Fracturing Cost
    - - Compressor Installation Cost
    - - Fresh Water Acquisition and Transportation Cost

# Well Production Profiles



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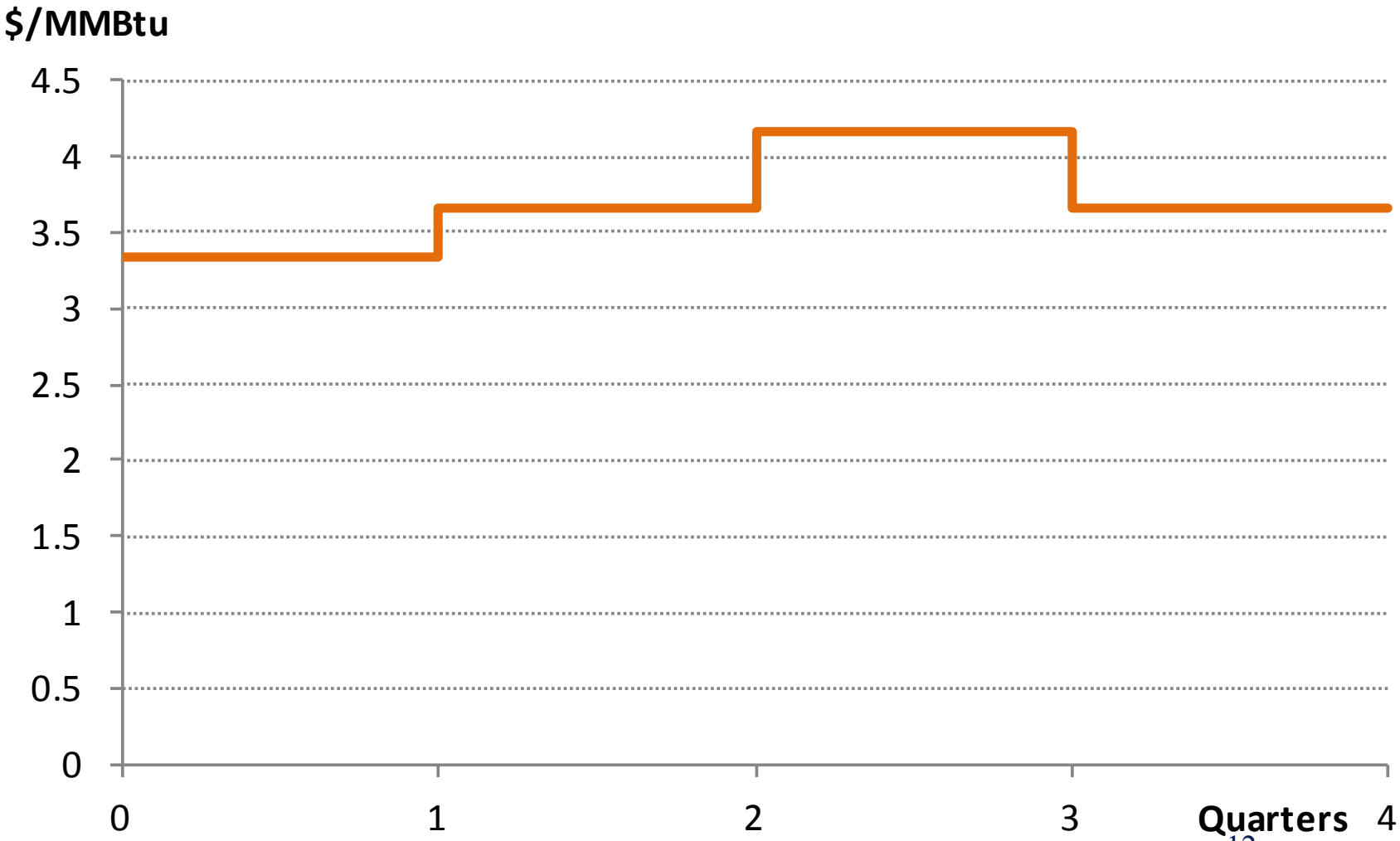
# Natural Gas Price (Seasonal)



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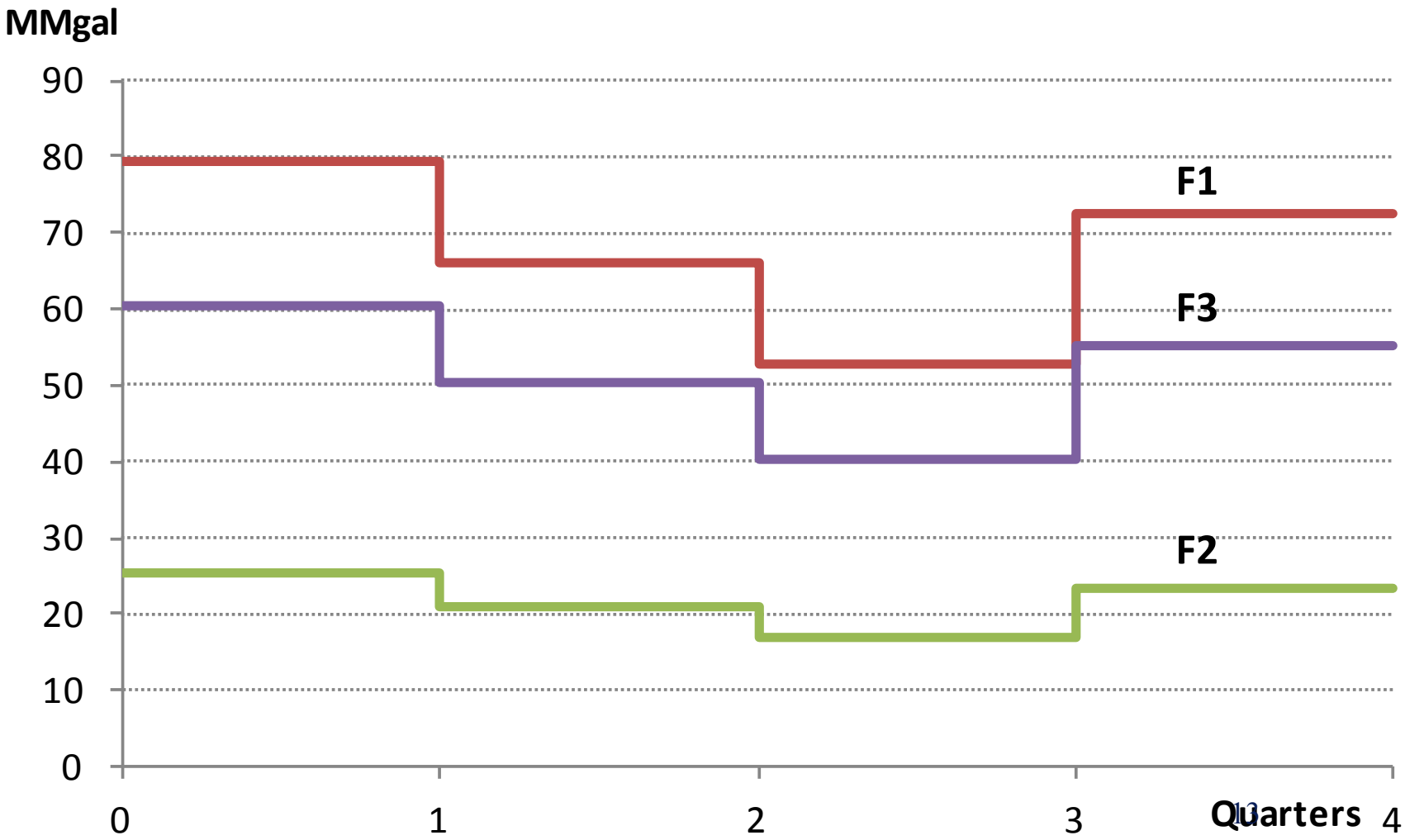
# Water Availability (Seasonal)



# MINLP Optimization Model

- **MINLP Model comprising:**
  - **Discrete Variables:**

    **number of wells to drill**
  - **Continuous Variables:**

    **plants, pipelines, and compressor sizes, flows, etc.**
  - **Linear Constraints:**

    **shale gas production, flow balances, etc.**
  - **Nonlinear Objective Function**

    **economies of scale**

**Remark:** **Nonconvex MINLP**

# MINLP Model

## Main Model Variables

$N_{i,t}$ number of wells drilled in pad $i$ during period $t$

$S_{p,t}$ plant capacity installed at site $p$ in period $t$

$D_{i,j,t}$ diameter of pipeline installed between nodes $i$ and $j$ in period $t$

$W_{j,t}$ compressing power installed at site $j$ in period $t$

$GF_{i,j,t}$ shale gas flow in pipeline $i$-$j$ during period $t$

$GF_{j,p,t}$ shale gas flow in pipeline $j$-$p$ during period $t$

$GF_{p,k,t}$ methane flow in pipeline $p$-$k$ during period $t$

$LF_{p,l,t}$ ethane flow in pipeline $p$-$l$ during period $t$

# MINLP Model

## Model Constraints

1. The shale gas production at site *i* is determined by the total number of wells drilled, and its age

$$\sum_{\tau=1}^{t-1} N_{i,\tau}\ pw_{i,t-\tau} = SP_{i,t} = \sum_{j \in J} GF_{i,j,t} \qquad \forall i \in I, t > 1$$

2. Flow balances at junction nodes

$$\sum_{i \in I} GF_{i,j,t} = \sum_{p \in P} GF_{j,p,t} \qquad \forall j \in J, t > 1$$

3. Flow balances at plants

$$\sum_{j \in J} GF^{G}{}_{j,p,t} = \sum_{k \in K} GF_{p,k,t} \qquad \sum_{j \in J} GF^{E}{}_{j,p,t} = \sum_{l \in L} LF_{p,l,t} \qquad \forall p \in P, t > 1$$

Methane Ethane

# MINLP Model

## Model Constraints

4. Plants, Pipelines and Compressors Sizing

$$SepCap_{p,t} = SepCap_{p,t-1} + S_{p,t-\tau s} \qquad \forall p \in P, t > 1$$

5. Maximum Capacity Constraint

$$\sum_{j \in J} GF_{j,p,t} \le SepCap_{p,t} \qquad \forall p \in P, t > 1$$

6. Water Supplies

$$N_{i,t}\ wr_i = \sum_{f \in F} WS_{f,i,t} \qquad \forall i \in I, t \in T$$

Demand Fulfillment per Pad

$$\sum_{i \in I} WS_{f,i,t} \le fwa_{f,t} \qquad \forall f \in F, t \in T$$

Availability

# MINLP Model

## Objective Function

$$\textbf{Max}\ NPV = \sum_{t\in T}(1+dr/4)^{-t}\Big[\underbrace{\sum_{p\in P}\sum_{k\in K} gasp_{k,t}\ nd_t\ GF_{p,k,t} + \sum_{p\in P}\sum_{l\in L} ethp_{l,t}\ nd_t\ LF_{p,l,t} + \sum_{p\in P} lpgp_t\ nd_t\ NF_{p,t}}_{\text{Sales Income}}$$

**Shale Gas Cost**
$$-\sum_{i\in I}\sum_{j\in J} shgc_{i,t}\ nd_t\ GF_{i,j,t}$$

**Gas Plant Cost**
$$-\sum_{p\in P} ks\ S_{p,t}^{SepExp}$$

**Drilling/Fracking Cost**
$$-\sum_{i\in I}\sum_{n=1}^{\overline{n}_i} kd\ n^{WellExp}\ y_{i,n,t}$$

**Pipeline Cost**
$$-\sum_{i\in I}\sum_{j\in J} kp\ l_{i,j}\ D_{i,j,t}^{GasPipeExp} - \sum_{j\in J}\sum_{p\in P} kp\ l_{j,p}\ D_{j,p,t}^{GasPipeExp}$$

$$-\sum_{p\in P}\sum_{k\in K} kp\ l_{p,k}\ D_{p,k,t}^{GasPipeExp} - \sum_{p\in P}\sum_{l\in L} kp\ l_{p,l}\ D_{p,l,t}^{LiqPipeExp}$$

**Compressor Cost**
$$-\sum_{j\in J} kc\ W_{j,t}^{CompExp} - \sum_{p\in P} kc\ W_{p,t}^{CompExp}$$

**Water Cost**
$$-\sum_{f\in F}\sum_{i\in I}\left(fix_f + var_f\ l_{f,i}\right)WS_{f,i,t}\Big]$$

**Concave Cost**

# Branch-Refine-Optimize (BRO) Algorithm *(You& Grossmann, 2010)*

***Master Problem: Find a Network***

1. Solve an MILP approximation of the MINLP using convex envelopes of non-linear (concave) cost functions: **Global Upper Bound**

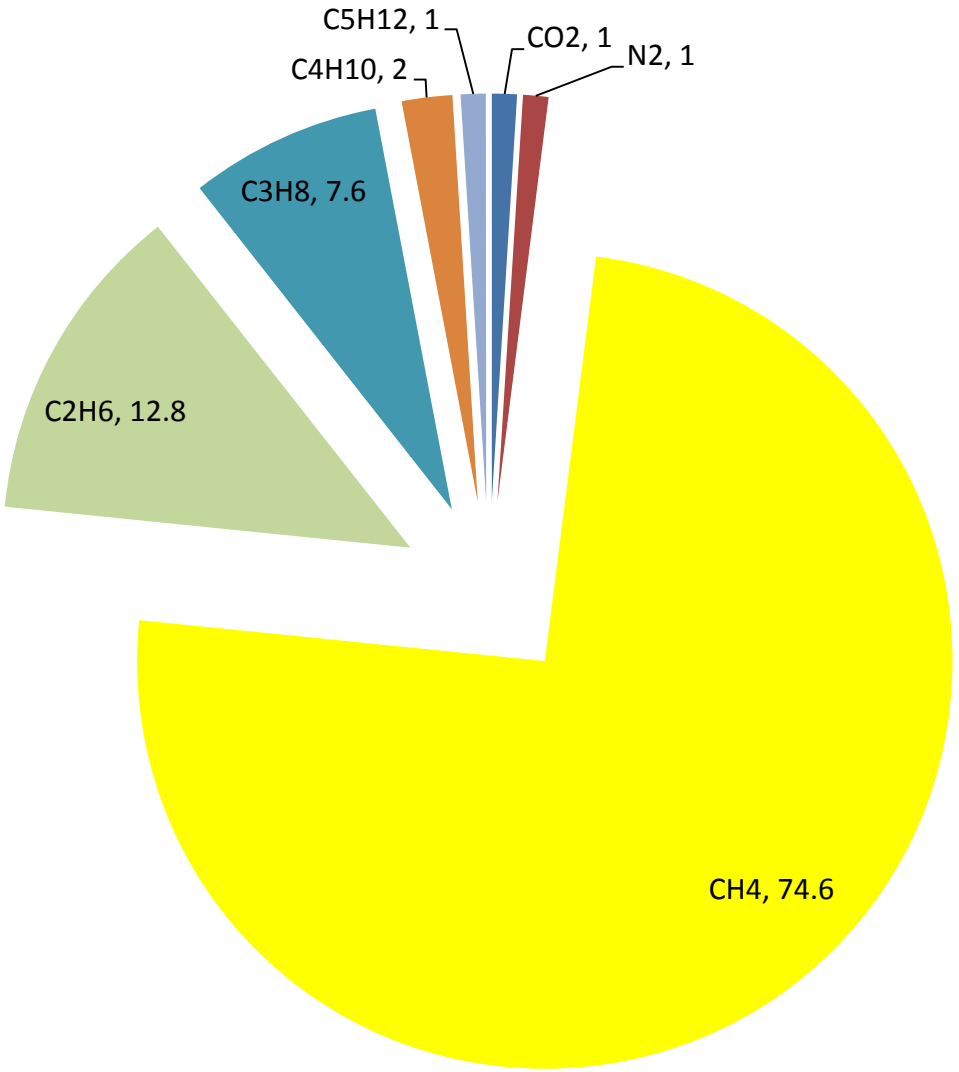
***Reduced Problem: Fix the Network and Refine the Drilling Plan***

4. Remove not used pipelines, plants and compressors.
5. Solve the reduced MINLP problem: **Lower Bound**
6. Refine piecewise linear approximations **Bisectioning** Intervals Containing Values of the MINLP solution.
7. Solve an MILP approximation of MINLP using convex envelopes of non-linear (concave) functions – **Reduced Problem Upper Bound**
8. Repeat Steps 4 to 7 until the reduced problem optimality tolerance is satisfied

9. Refine the first-step piecewise linear approximation
10. Repeat Steps 1 to 9 until the global optimality tolerance is satisfied.

# Example: Uniform Shale Gas Wetness
# Shale Gas Composition

**9** well-pads
*20 wells per pad*
**8** potential junctions
**3** potential sites plants
**10** years *(40 periods)*



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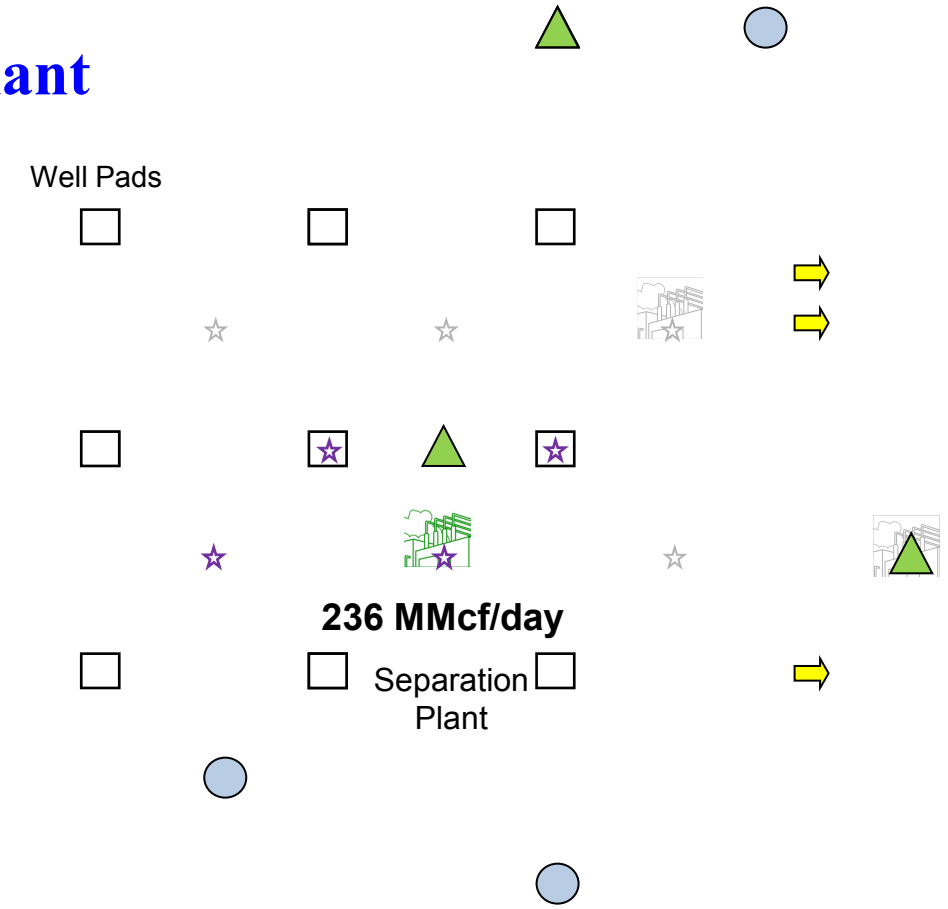
# Optimal Supply Chain Structure

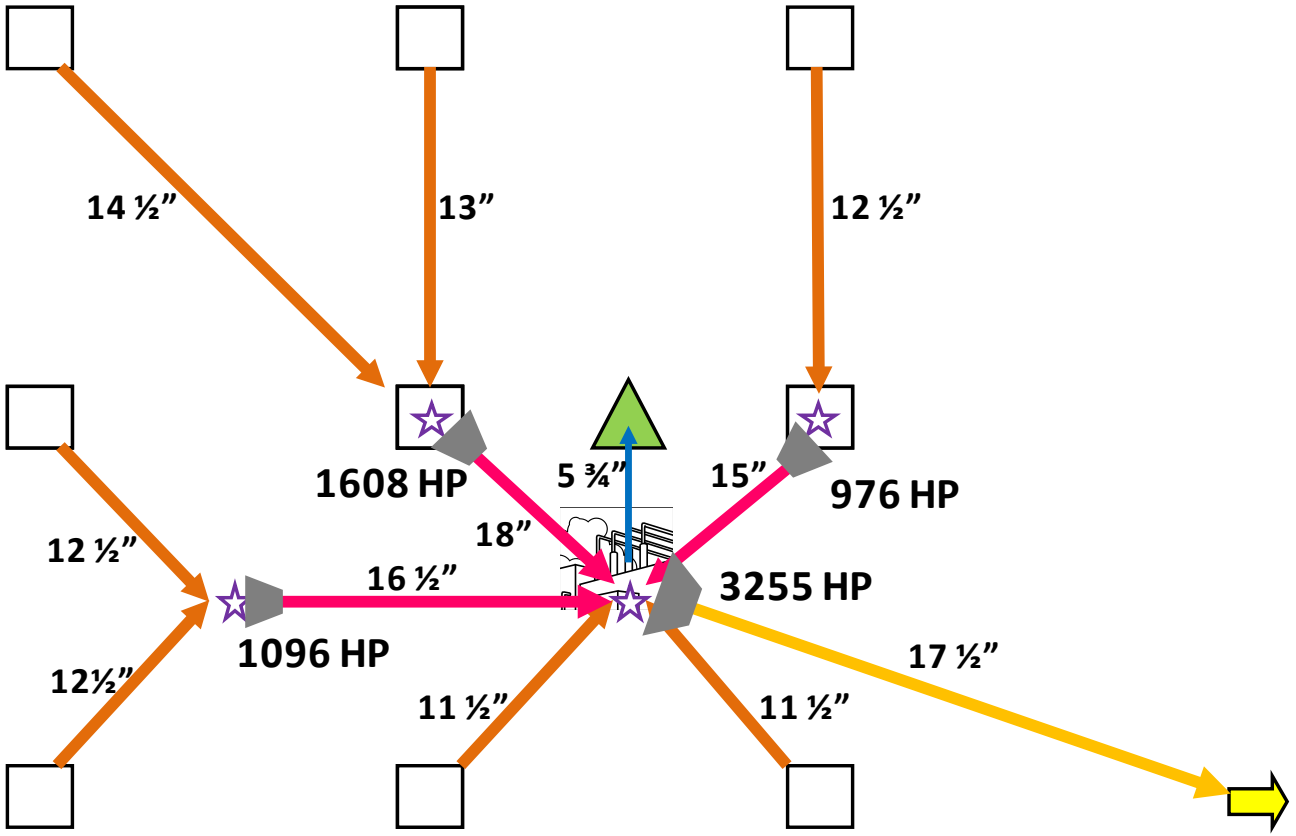
**MINLP: 2,343 binary variables, 14,252 constraints, 16,912 continuous variables**
**Total CPU time= 8.5 hours (<3% optimality gap)**

- **Processing Plant**



# Optimal Supply Chain Structure

- **Pipeline Network and Compressors**



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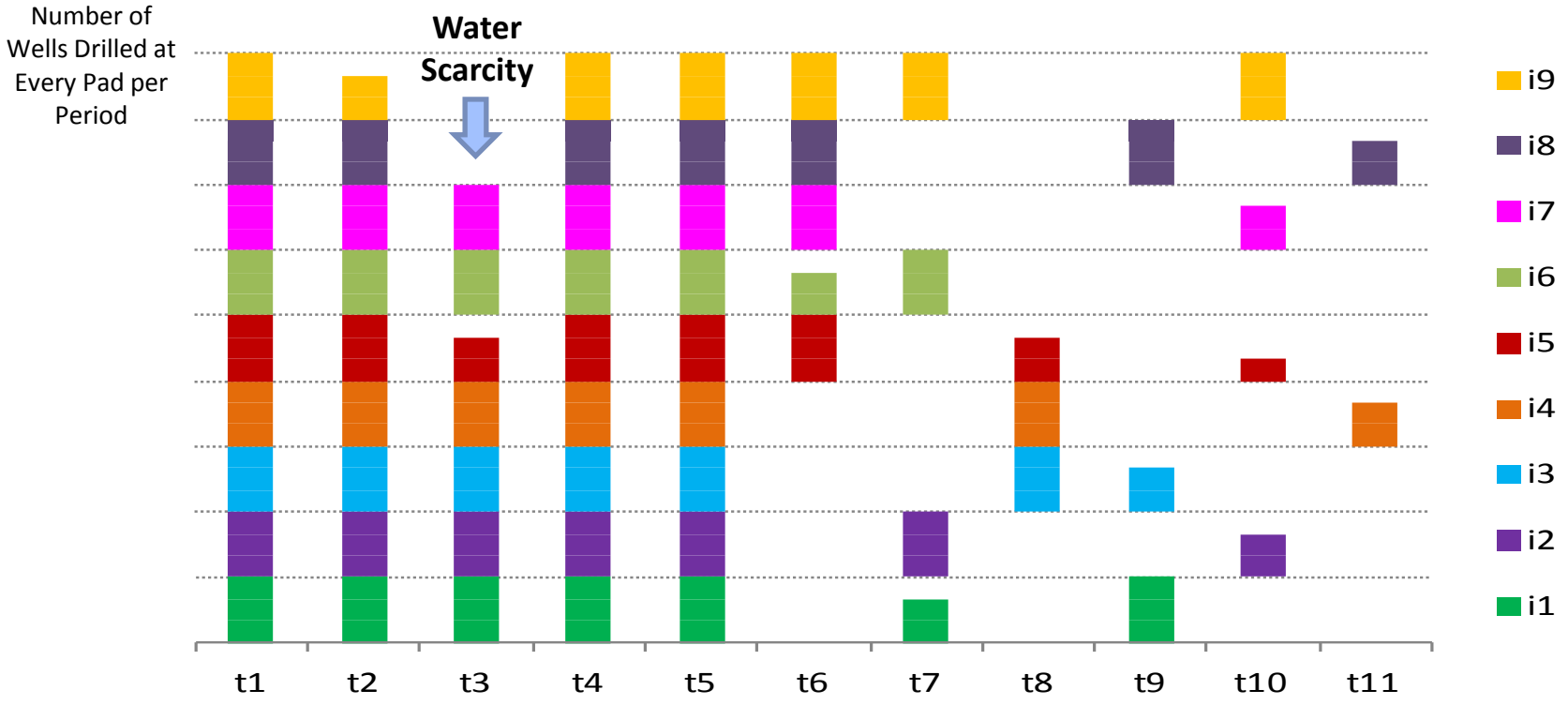
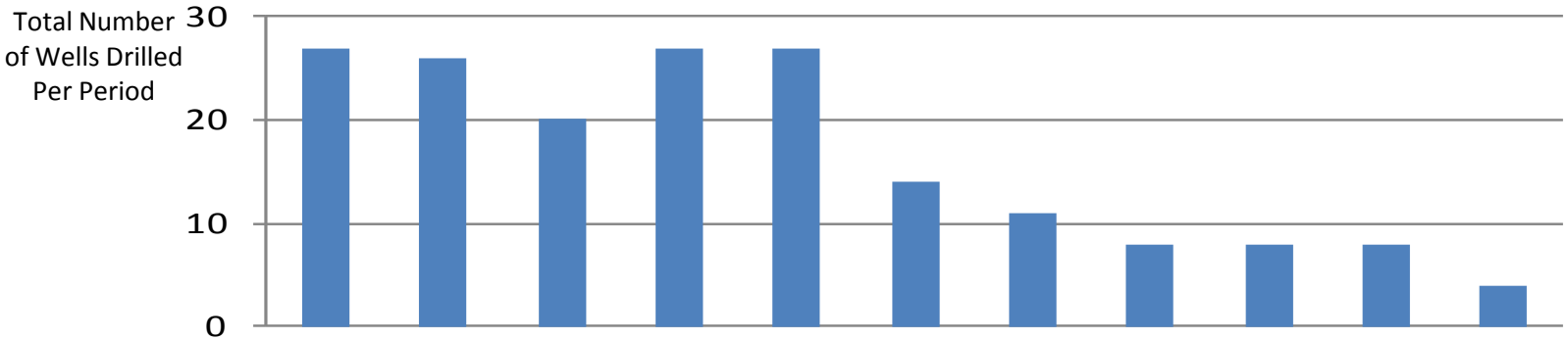
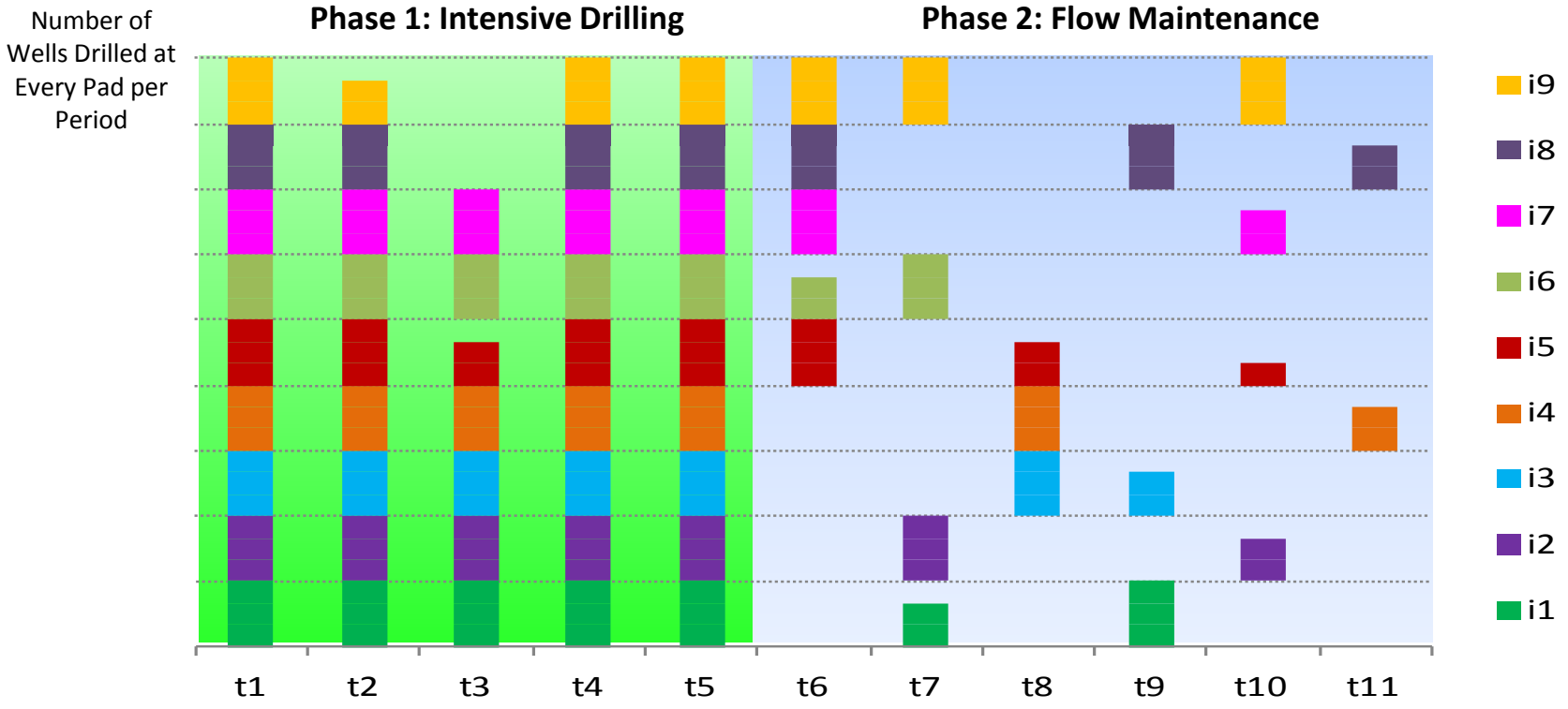
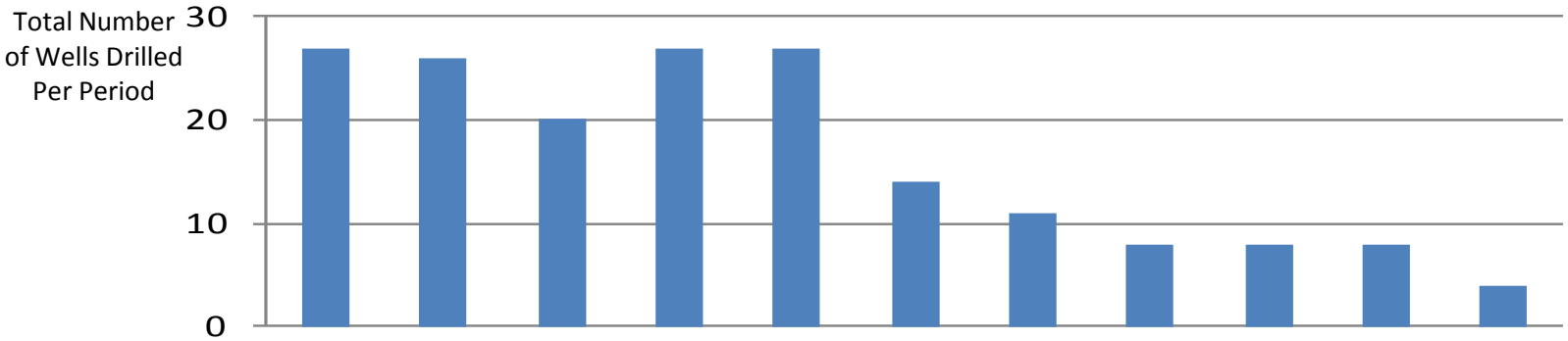
# Optimal Drilling Strategy



# Optimal Drilling Strategy



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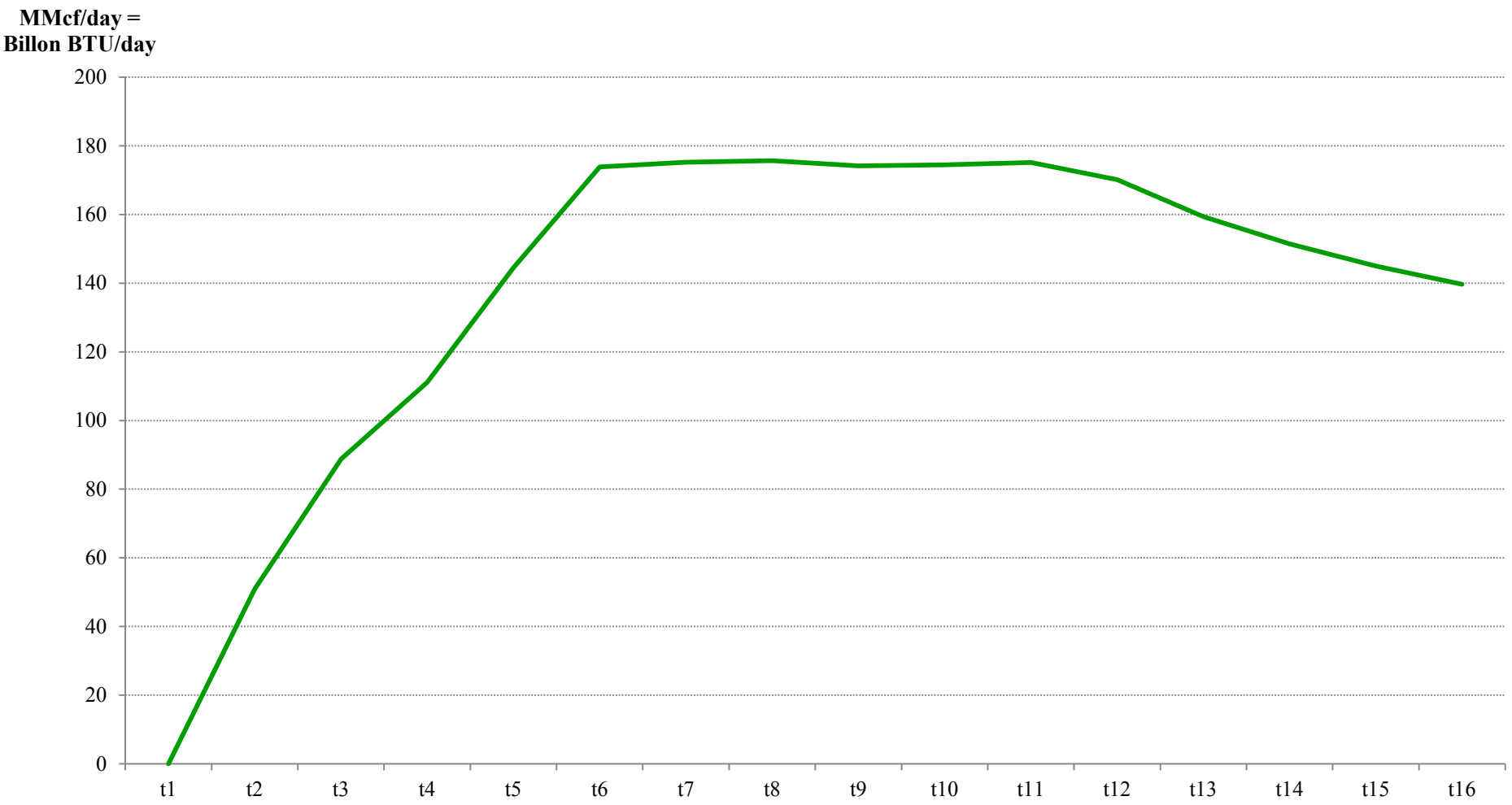
# Optimal Production Profile

CAPD CENTER

- **Methane Sales Flow**



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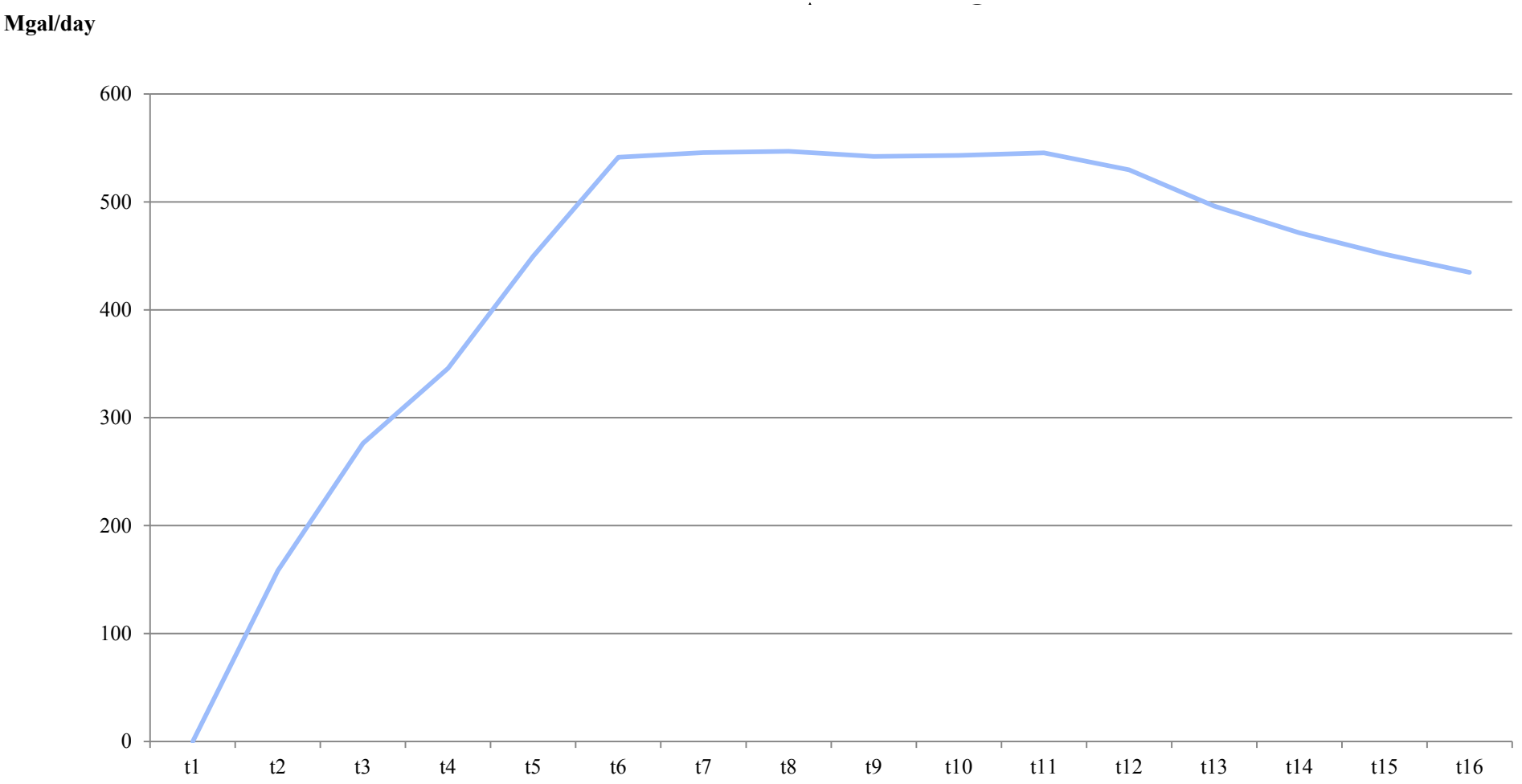
# Optimal Production Profile

CAPD CENTER

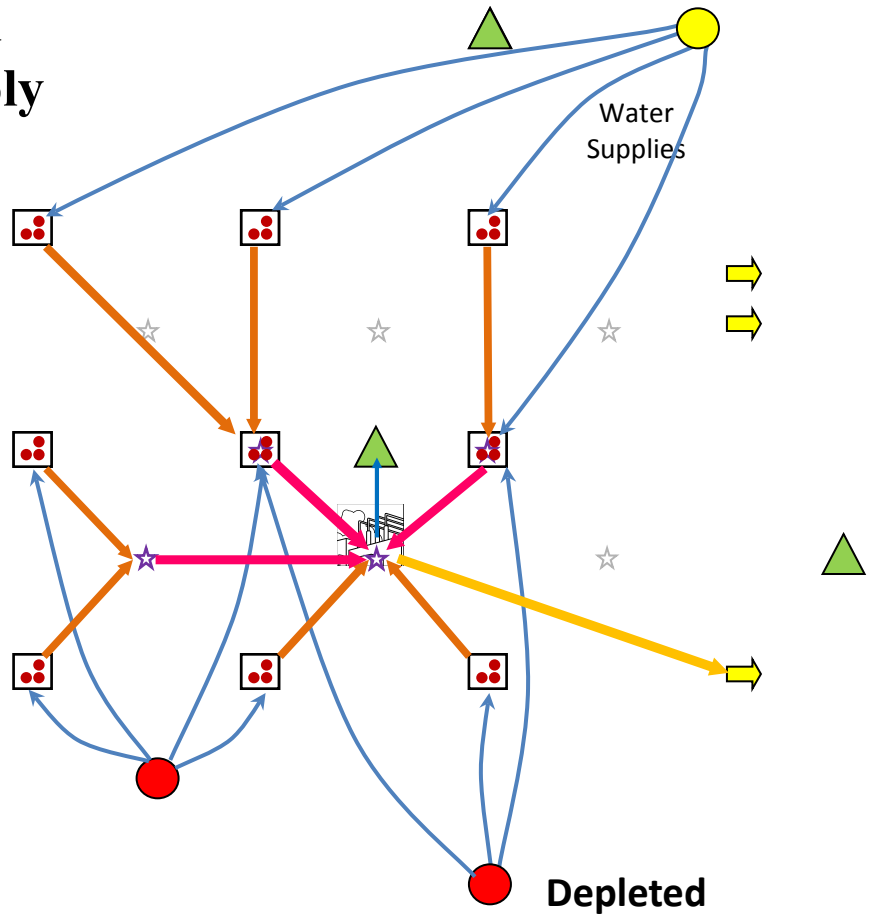
- **Ethane Sales Flow**



# Optimal Operation



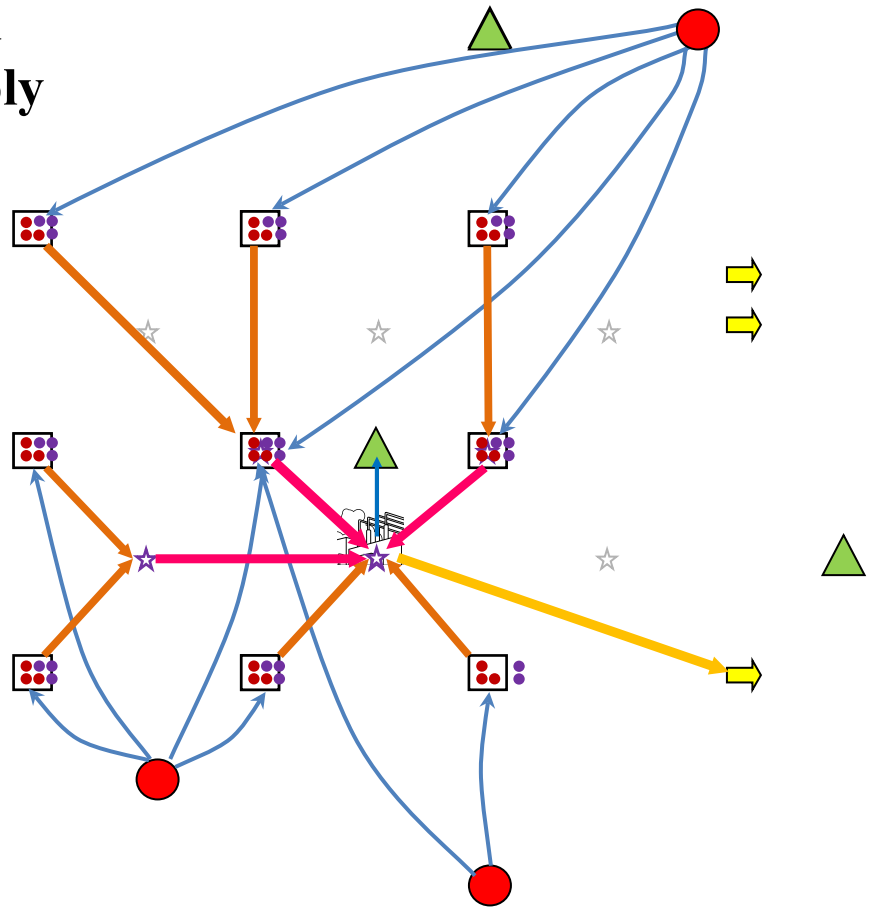
- **Quarter 1**
  - **Drilling and Water Supply**



# Optimal Operation



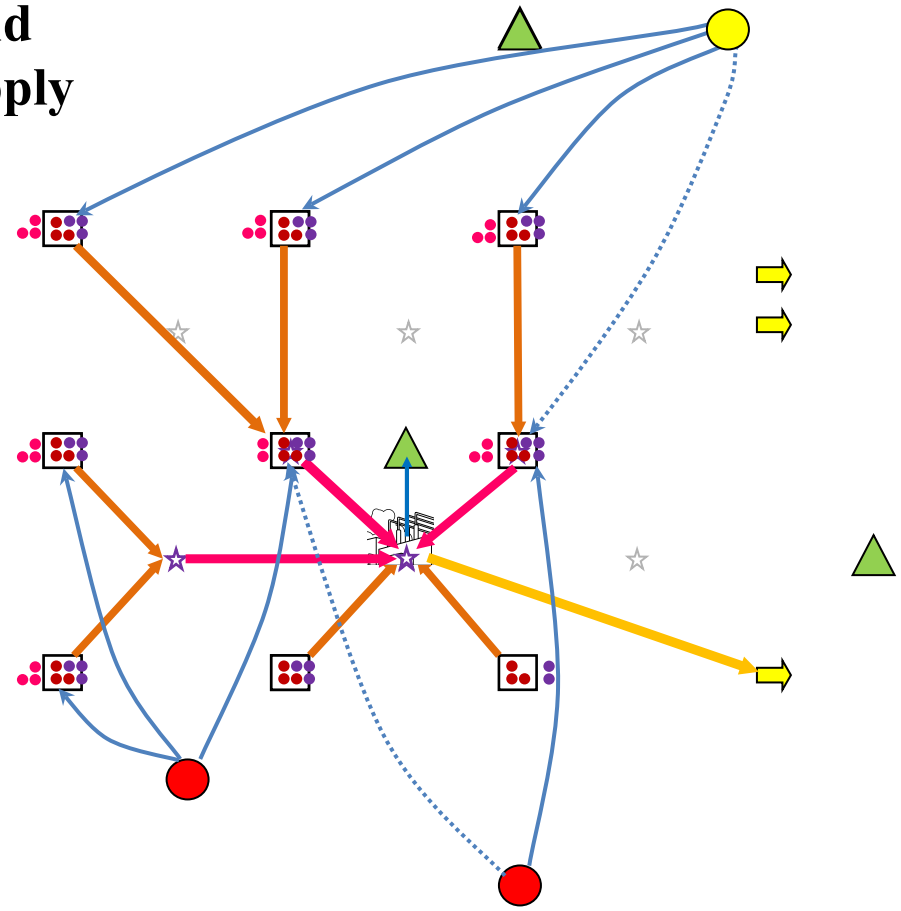
- **Quarter 2**
  - **Drilling and Water Supply**



# Optimal Operation



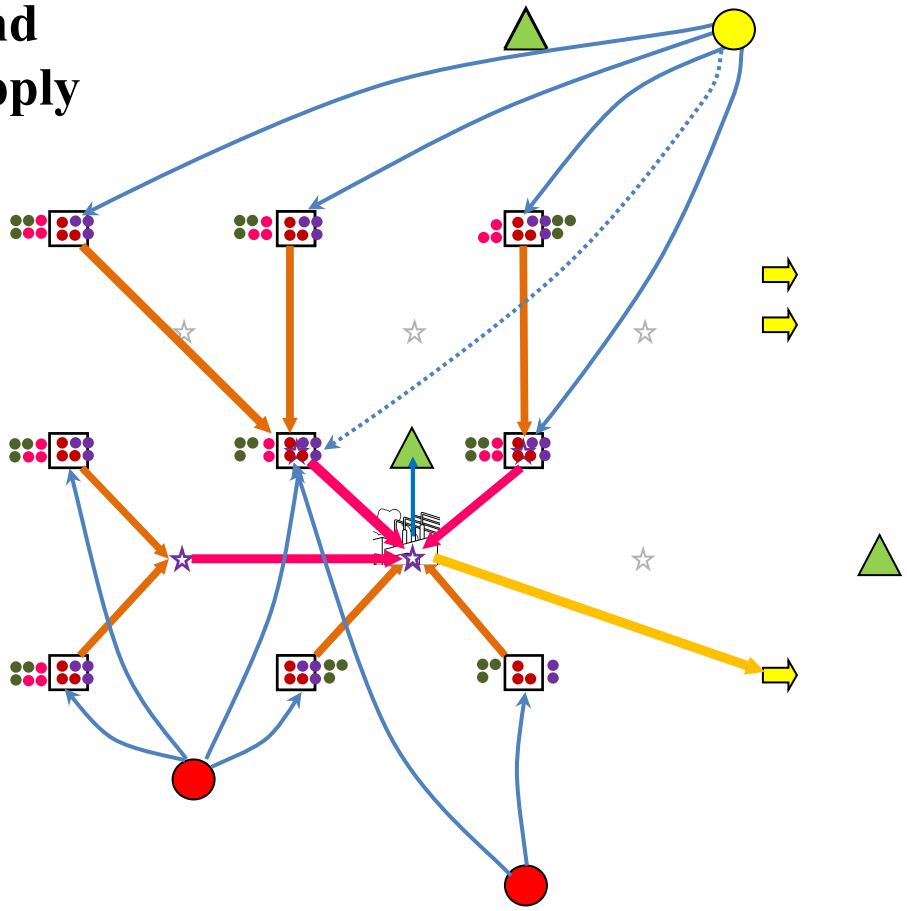
- **Quarter 3**
  - **Drilling and Water Supply**



# Optimal Operation



- **Quarter 4**
  - **Drilling and Water Supply**



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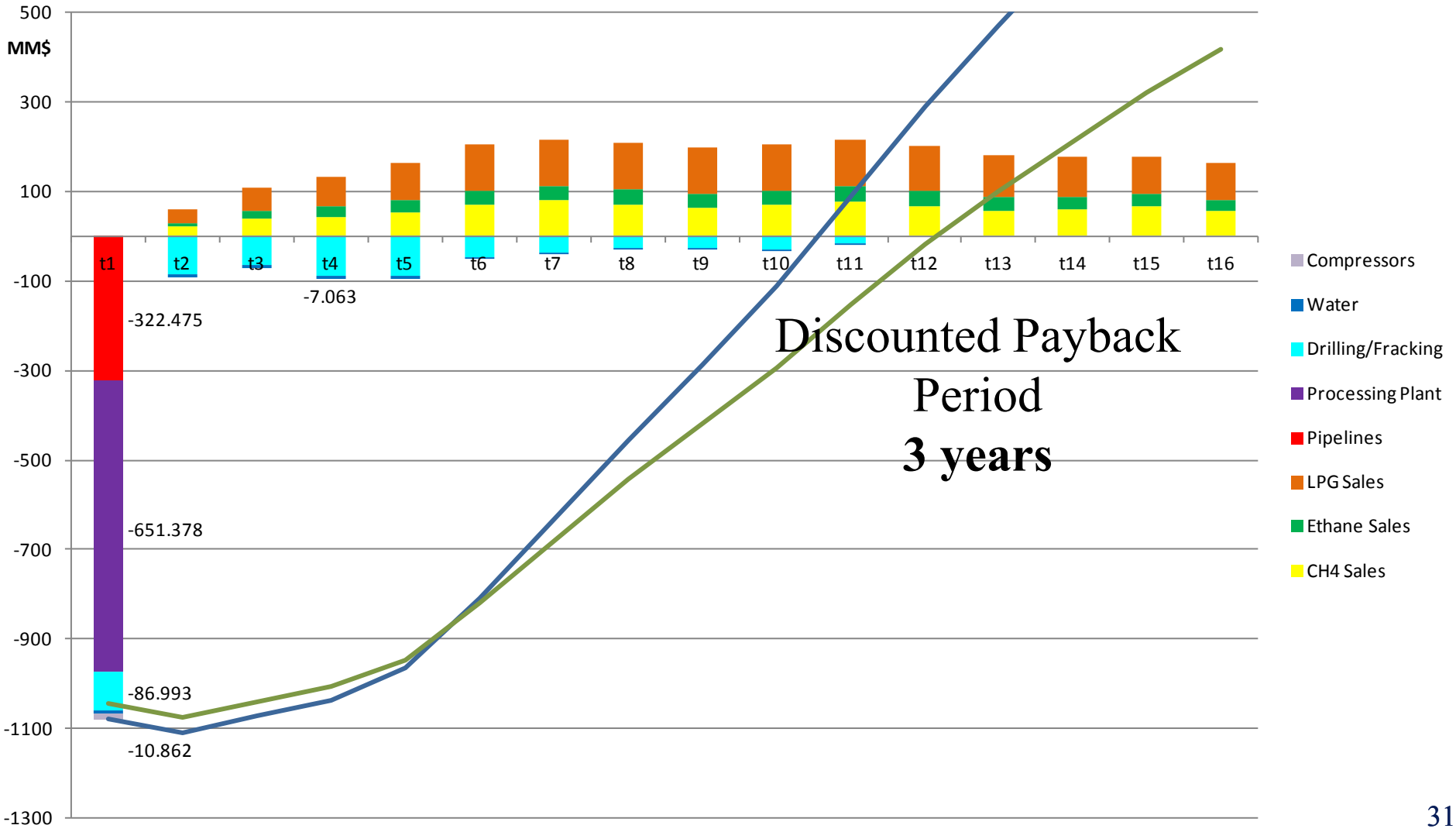
# Economic Analysis

- **Cash Flow**



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# Real World Case Study

CAPD CENTER

150 well pads
4 wells per pad
Dry gas *(95% methane)*
10 years (40 time periods)
No gas plants

MINLP Model
4,815 discrete variables
12,226 continuous variables
16,815 constraints
*20 hours CPU-time*
*8% Gap*

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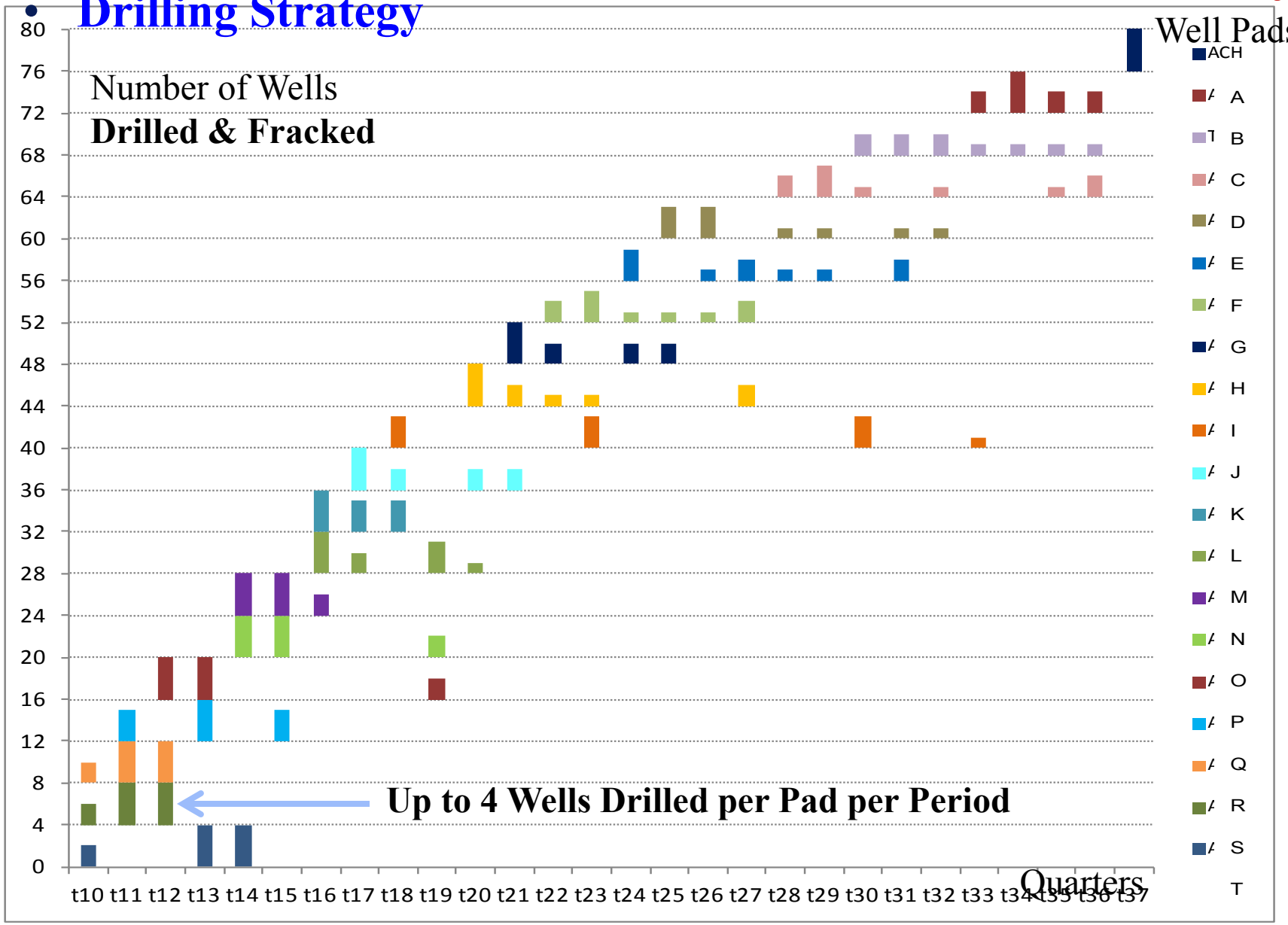
# Real World Case Study

CAPD CENTER

- **Drilling Strategy**



# Conclusions

1. Proposed Multiperiod MINLP Model for Shale Gas Production

2. Model determines:
   a) Structure of supply chain:
   - Plants of Natural Gas
   - Pipelines and Compressors
   b) Operation supply chain:
   - Drilling strategy
   - Supply of water

3. Branch-Refine-Optimize Algorithm for Large-scale Nonconvex MINLP

4. MINLP model leads to systematic optimization of Shale Gas Production Systems