How to Produce Wells Steadily and Sustainably
A Paradigm Shift in the Oil and Gas Industry

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Outline

> Unconventional Oil and Gas Production

> Well Factory Approach: The Need to Produce Wells Steadily
  > Struggling with Productivity Decline Curves
  > Unconventionals’ Supply Chain Design and Well Development Planning

> Sustainability Issues: Frac Water Management
  > Freshwater Consumption, Water Treatment and Disposal
  > Optimal Design and Operation of Water Pipeline Networks
  > Coordinate Operations to Simplify Water Management

> Summary and Final Remarks
Unconventional Oil and Gas Production

- Shale well development involves **vertical drilling**, **horizontal drilling**, and **hydraulic fracturing**

- Hydraulic fracturing: injection of a fracturing fluid (typically water) into a formation under high pressure

- The well stimulation creates fractures in the reservoir that allow trapped gas to flow into the wellbore

- Producers have the ability to drill **multiple wells** (up to 40) from a single well pad

- Multi-well pads increase gas extraction while greatly reducing the surface disruption
Unconventionals’ Development Operations

**Challenge**
- Economies of Scale, Productivity Curves, Oil and Gas composition
- Acreage Position, Permitting, Seasonal Constraints
- Rig & Crew Availability, Logistical Coordination
- Water Sourcing, Water Blending, Water Storage
- Gathering System Capacity, Wells Shut-in (Curtailment)
- Gas Quality Specifications, Impaired Water Production
- Price Uncertainty, Well Performance Uncertainty

**Opportunity**
- Network Design, Pipeline Sizing, Compressor Sizing
- Number of Wells, Water Impoundments (e.g. pits vs. ASTs)
- Drilling Schedule, “Return-to-Pad” Operations
- Fracturing Schedule, Water Blending Strategies
- Turn-in-Line Schedule, Well and Line Pressure Management
- Blending & Processing Strategies, Impaired Water Management
- Artificial Lift & Maintenance Scheduling, Refracture Frequency and Timing

**Steps**
1. **Gathering System Construction**
2. **Well Pad Construction**
3. **Vertical & Horizontal Drilling**
4. **Hydraulic Fracturing & Completions**
5. **Turn-In-Line Operations**
6. **Gas Production**
7. **Well Maintenance & Restimulations**
Unconventionals’ Challenges: Need for Well Factory Approach

Steep Productivity Decline Curves

- Some shale gas wells produce half of their total resources within the first year of operation.
- Decline rates are more rapid than conventional wells due to the ultralow permeability.

- Producers aim to maximize utilization of their production & gathering equipment.
- They are also contractually obligated to provide steady gas deliveries over time.
- The timing of turning a well in-line is critical for well development profitability.
Unconventionals’ Challenges: Need for Well Factory Approach

Space-Time Variability

Different Productivity Decline Curves
(from reservoir simulation models)

Different Shale Gas Compositions
(wet gas vs. dry gas)

Cafaro & Grossmann, 2014
Optimal Design of Unconventionals’ Supply Chain Network
+ Well Development Planning

Goal

Determine the optimal network of pipelines, compressors and processing plants together with the well development plan, to maximize the NPV of the shale gas project, subject to water availability (among other) constraints.

\[
\text{NPV} = \sum_{t=0}^{\infty} \left( 1 + \left( \frac{c}{4} \right) \right)^{-t} \left( \sum_{j \in J} \sum_{k \in K} g_{j,k} \cdot n_{j,k} \cdot T_{P,j,k} - \sum_{p \in P} \sum_{k \in K} e_{p,k} \cdot n_{p,k} \cdot P_{p,k} + \sum_{p \in P} \sum_{k \in K} l_{p,k} \cdot n_{p,k} \cdot N_{p,k} \right) \\
- \sum_{i \in I} \sum_{j \in J} s_{i,j} \cdot n_{i,j} \cdot F_{i,j} \\
- \sum_{i \in I} \sum_{a = 1}^{A} \sum_{n = 1}^{N} \sum_{j \in J} k_{d} \cdot n_{m} \cdot \text{WellExp}_{i,j,a,n} \\
- \sum_{j \in J} \sum_{p \in P} s_{q} \cdot \text{SepIn}_{p,q} \\
- \sum_{j \in J} \sum_{p \in P} i_{p,j} \cdot \text{DFT}_{i,j} - \text{GasPipeExp}_{j} - \sum_{p \in P} \sum_{k \in K} i_{p,k} \cdot \text{DG}_{p,k} - \text{GasPipeExp}_{j} \\
- \sum_{j \in J} \sum_{p \in P} i_{p,j} \cdot \text{DFT}_{j} - \text{LiqPipeExp}_{j} - \sum_{j \in J} \sum_{p \in P} \sum_{k \in K} i_{p,k} \cdot \text{DFT}_{j} - \text{LiqPipeExp}_{j} \\
- \sum_{j \in J} \sum_{p \in P} k_{j} \cdot \text{ICInst}_{j,p} - \text{CompExp}_{j,p} - \sum_{j \in J} \sum_{p \in P} k_{j} \cdot \text{ICInst}_{j,p} - \text{CompExp}_{j,p} \\
- \sum_{j \in J} \sum_{i \in I} \left( \text{fix}_{i} + \text{var}_{j,i} \right) \cdot W_{i,j} + \left( 1 + \left( \frac{c}{4} \right) \right)^{-T} \sum_{t=0}^{\infty} \sum_{i \in I} k_{i,j} \cdot N_{i,j} 
\]
Optimal Design of Unconventionals’ Supply Chain Network
+ Well Development Planning

Time Horizon: 10 years

Optimal Design of the Supply Chain

1.6 billion NPV

236 MMcf/day
Shale Gas Processing Plant

Cafaro & Grossmann, 2014
Optimal Design of Unconventionals’ Supply Chain Network
+ Well Development Planning

Key Decision
Return-to-pad Operations

Cafaro & Grossmann, 2014
Optimal Design of Unconventionals’ Supply Chain Network

+ Well Development Planning

Number of Wells Drilled per Pad

Phase 1

Phase 2

Water Scarcity

Shale Gas Production [MMcf/day]

PAD A
PAD B
PAD C
PAD D
PAD E
PAD F
PAD G
PAD H
PAD I

0 50 100 150 200

t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 t14 t15 t16
Optimal Design of Unconventionals’ Supply Chain Network
+ Well Development Planning

### Main Results

- **1.6 billion NPV** (3 years payback period)
- **1 billion Investment** (60% processing plant, 30% pipelines)
- **Input Data:**
  - 4 USD/MMBTU NatGas (37% of the total income)
  - 300 USD/ton Ethane (50% of the total income)
  - 3 MMUSD Development Cost per Well

**MINLP:** 2,343 0-1 variables, 14,252 constraints, 16,912 cont. variables

*Branch-Refine-Optimize (BRO) solution algorithm – DICOPT Solver*

**Total CPU time** = 8.5 hours (<3% optimality gap)

*Cafaro & Grossmann, 2014*
Optimal Design of Unconventionals’ Supply Chain Network

Real World Case Study

Number of Wells Drilled

<table>
<thead>
<tr>
<th>Number of Wells Drilled</th>
<th>MMcf/d</th>
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<tr>
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<td>t3</td>
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<tr>
<td>2</td>
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<td>4</td>
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<td>32</td>
<td>t35</td>
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<tr>
<td>34</td>
<td>t37</td>
</tr>
</tbody>
</table>

Gas Flow in Pipelines

<table>
<thead>
<tr>
<th>Gas Flow in Pipelines</th>
<th>PA-4</th>
<th>PA-7</th>
<th>NFG-DTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>200</td>
<td>150</td>
</tr>
</tbody>
</table>

Optimal Network Design

- **PA-4**
- **PA-7**
- **Water Source 10**
- **Water Source 13**
- **Water Source 6**
- **NFG (200 MMcf/d)**
- **DTI (100 MMcf/d)**
- **TGP (100 MMcf/d)**
- **4 x 10,000 HP**

Quarters

- **12”**
- **24”**
- **24”**
- **18”**

Number of Wells Drilled

- **0**
- **2**
- **4**
- **6**
- **8**
- **10**
- **12**

MMcf/d

- **0**
- **200**
- **400**
- **600**
- **800**
- **1000**
- **1200**

- **PA-4**
- **PA-7**
- **Water Source 10**
- **Water Source 13**
- **Water Source 6**
- **NFG (200 MMcf/d)**
- **DTI (100 MMcf/d)**
- **TGP (100 MMcf/d)**
- **4 x 10,000 HP**

- **12”**
- **24”**
- **24”**
- **18”**

EQT

Where energy meets innovation.
Unconventionals’ Sustainability Issues

Frac Water Management

- Site Preparation (3 weeks)
- Drilling (4-6 weeks)
- Completion (1-3 months)
- Production (20-40 years)

Water acquisition

Fracuring

Flowback water

Produced water

Yang, Manno, Grossmann, 2014
Unconventionals’ Sustainability Issues

Frac Water Management

- **Site Preparation**
  - 3 weeks
- **Drilling**
  - 4-6 weeks
- **Completion**
  - 1-3 months
- **Production**
  - 20-40 years

- 1,000 to 2,000 trucks required for every single well
- 90% associated with fracturing operations
Unconventionals’ Sustainability Issues

Frac Water Management

- **Site Preparation**
  - 3 weeks
  - 4-6 weeks
  - 1-3 months
  - 20-40 years

- **Drilling**

- **Completion**
  - 1-3 months

- **Production**
  - 20-40 years

- **Water acquisition**

- **Flowback water**

- **Produced water**

- **Operations**
  - Top Setting
  - Horizontal Drilling

- **Fracturing**

- **Gas Production**
  - Turning-in-Line

- **Water Consumption**
  - Flowback + Water Production

- **Horizontal Drilling**

- **Time**

- **Unconventionals’ Sustainability Issues**
Unconventionals’ Sustainability Issues

Water Supplies and Treatment Alternatives

Focus on Water Recycling

Carrero-Parreño et al., 2019
Optimal Design and Operation of Water Pipeline Networks

Problem Definition

Given:

- **One year** time horizon divided into **weeks**
- A set of **wellpads** (no. of wells, productivity curves, water consumption, flowback/water production, **land permits issuing dates**).
- A set of **operations** to develop every well: 
  - TS -> HZ -> FRAC -> TIL
- A set of **resources** (rigs, crews, equipment)
- A set of **freshwater sources** for fracturing
- A set of **disposal wells** for impaired water
Optimal Design and Operation of Water Pipeline Networks

Problem Definition

Challenges

How to Reduce Freshwater Consumption

How to Track Water Composition

How to Manage Uncertain Land Permits Issuing Dates

Goal
Determine the optimal design for the network of water pipelines together with the well development plan.

Cafaro, Li & Grossmann, 2020
Carnegie Mellon University
Wilton E. Scott Institute
for Energy Innovation
Optimal Design and Operation of Water Pipeline Networks

Unconventionals’ industry is driven by drilling as many wells as possible, and turning them in line as quickly as possible.
Optimal Design and Operation of Water Pipeline Networks

Water Distribution Network may Become Unnecessarily Complex

Bidirectional Pipelines Operation

Tracking Water Storage and Composition

Cafaro, Li & Grossmann, 2020
Coordinate Operations to Simplify Water Management

Myopic Development Strategy

NPV from Shale Gas Production

137.15 MMUSD

NPV of Water Management Costs

38.87 MMUSD

Natural Gas Production

Weeks

Weeks

Pad

1
2
3
4
5
6

3
2.5
2
1.5
1
0.5
0

1
3
5
7
9
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43
45
47
49
51

TS
HZ
FRAC
TIL

208x47 210x210 195x183 312x183 368x183

Æ 8˝
Æ 4˝
Ø 8˝
Ø 4˝

0 4 8 12 16 20 24 28 32 36 40 44 48 52

0 2 4 6 8 10 12
Coordinate Operations to Simplify Water Management

Smart Development Strategy

NPV from Shale Gas Production

135.79 MMUSD (-1 %)

NPV of Water Management Costs

28.56 MMUSD (-26.5 %)

Net savings: 6 MMUSD

90+ MM gallons/year freshwater savings
Sustainable Development of Shale Gas Resources

Results from MILP Model

- **No water disposal after one year of operation**
  
  Avoid 94 million gallons disposal  
  (one truck every 15 min)
- **Less freshwater consumption**
  
  320 → 230 million gallons per year  
  (30% reduction)
- **Less Truck Transportation Emissions**
  
  11 MM ton-miles for water acquisition  
  22 MM ton-miles for interpad transportation  
  5400 metric tons of CO₂ / year
- **Less road damage**
  
  Pipelines avoid 100,000 trips per year

**MILP:** 7,500 0-1 variables, 38,000 cont. variables, 40,000 constraints,  
**Total CPU time** = 3 hours (1% optimality gap) – CPLEX Solver
Well Factory Approach: Material and Service Supplies

Optimal Design of Material and Service Supply Chains

Modelling Challenges

Large Number of Nodes (wells)

Different types of services required during the lifespan of each well

Goal

Determine the optimal number, size and location of facilities to fulfill service demands from wellpads, at minimum total cost, accounting for the network responsiveness to unexpected events (avoid well production losses).

Montagna & Cafaro, 2019
Modelling Challenge

Permeability depends on the particle size distribution

\[ K = 5.1 \times 10^{-6} \phi^{5.1} d_5^{2} e^{-1.385\psi} \]
Goal
Determine the optimal amount of sand (natural proppant) to supply from different sources to meet fracturing requirements, at minimum production, transportation and processing cost.
Summary and Final Remarks

- Shale gas is playing a key role in **decarbonizing energy systems**
  
  (US CO₂ emissions cut by **2% annually**)

- Discussion is still open: Will shale gas serve as a **bridge fuel**? For how long?
  
  What is the **breakeven** price for **shale gas** investment?

- By 2050, **36%** of electricity generation in the US is expected to come from **natural gas**
  
  **92%** of natural gas will be **shale gas**

- Unconventionals’ development is largely driven by drilling new wells, **intensively:**
  
  **Well Factory Approach**

- Results from **optimization models** prove that **myopic strategies** may yield
  
  unnecessarily high **water management costs**
Summary and Final Remarks

> **Math programming** shows the way to **smarter** and **more sustainable strategies**

> By resigning **1%** of the NPV of the shale gas production, **water management** costs reduce by more than **26%**

> Pipeline transportation avoids more than **100,000 trips** of water trucks **per year**, over an area with **20 pads** with about **100 wells**

> This implies **30 MM ton-miles / year**, reducing **CO₂ emissions by 5,000 metric tons**

> **Coordinate** well development strategies permit to recycle **100% of the flowback water** to fracture new wells

> Freshwater consumption is reduced by **90 MM gallon/year (up to 30% reduction)**
Thanks for your attention!

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