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Exergy analysis of polymer flooding in clastic reservoirs

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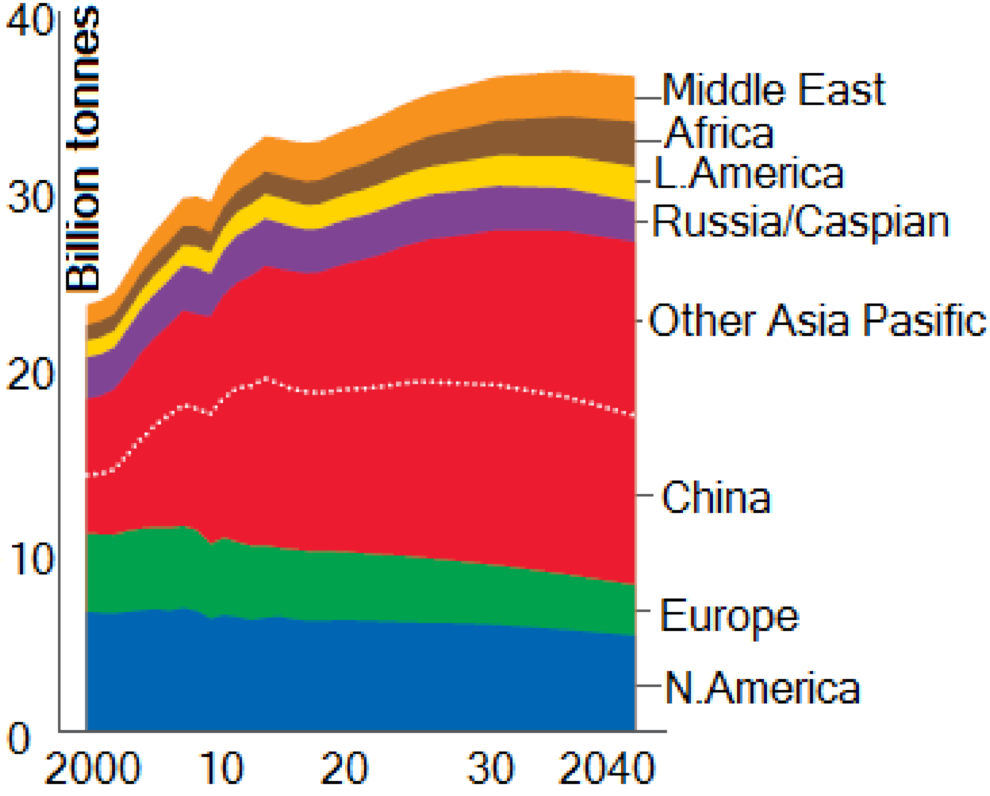
Challenge the future

جامعة السودان للعلوم والتكنولوجيا

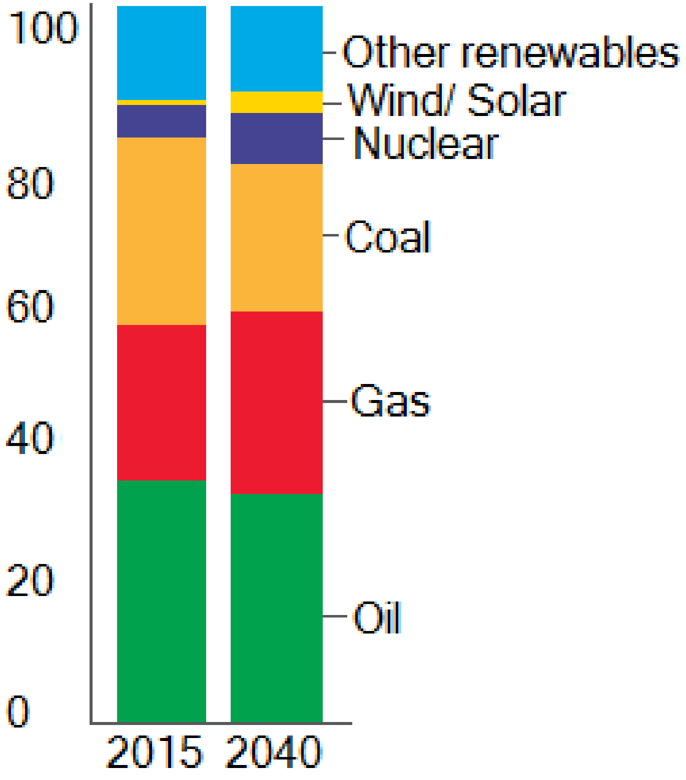
Agenda – Contents

- Introduction
  - Energy outlook (view to 2040)
  - What can be done?
- Objective/ scope of the project
- EOR-polymer flooding
- Why exergy analysis?
- Bio-polymer model(s) results
- Conclusions

Energy Outlook - view to 2040



Energy-related CO_2 emissions peak



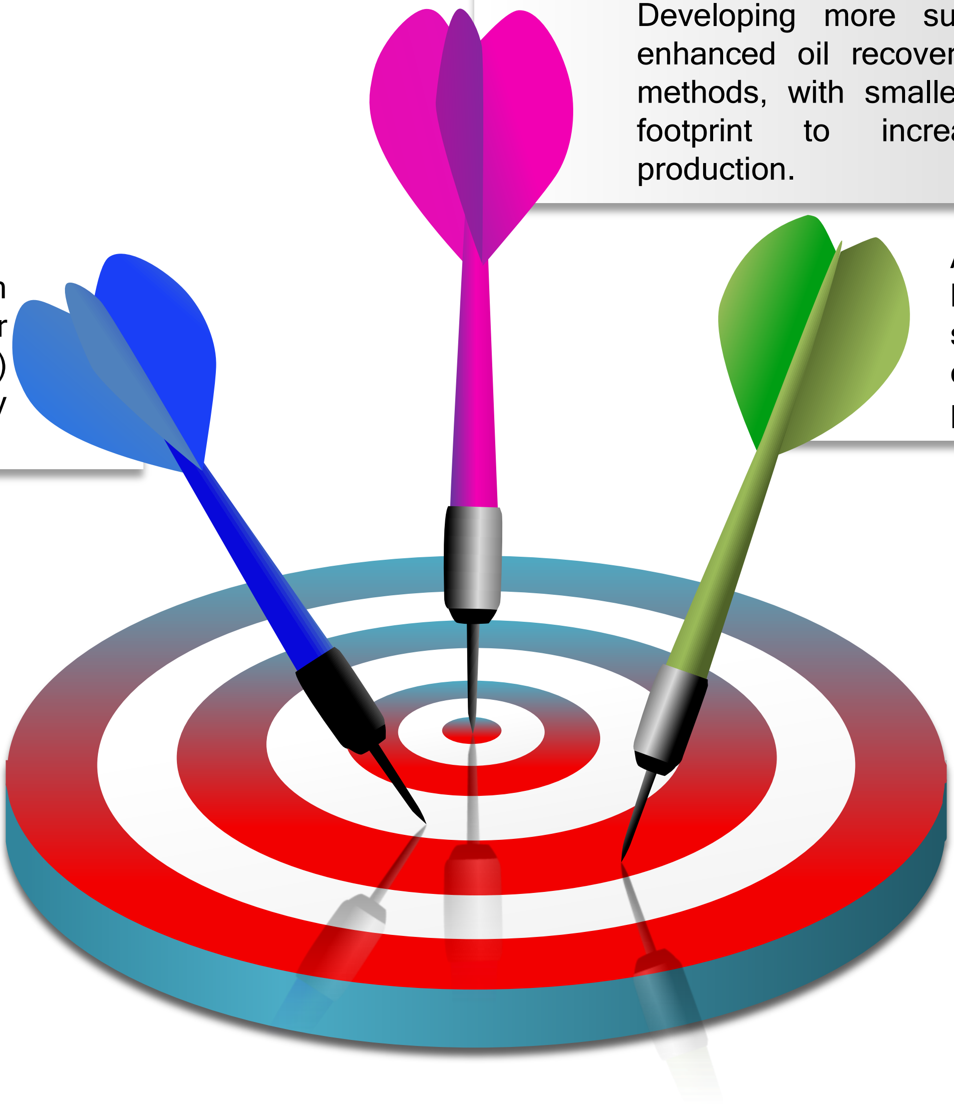
Global share of primary energy

(Source: United nation, ExxonMobil estimates, 2017)

To which extend can the oil and gas industry contribute to this transition (ERoEI)?

- Exergy can be used to determine whether improved oil recovery is more efficient than conventional oil recovery and therefore reduce the carbon footprint by $\sim$ 1%
- The possibility to compare energy invested to realize recovery for enhanced and conventional recovery.
- To define marking point (exergy-zero time recovery) when the exergy invested and exergy recovered become the same.

Objective / scope

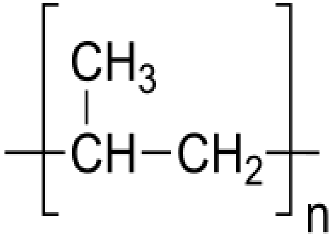


Developing more sustainable enhanced oil recovery (EOR) methods, with smaller carbon footprint to increase oil production.

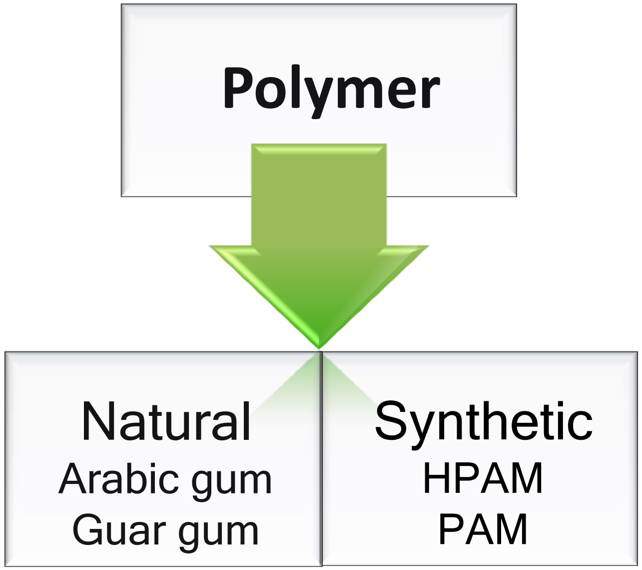
The focus would be is on injecting natural polymer (Arabic gum / Guar gum) to enhance the recovery behavior.

Analyzing the exergy balance of Arabic gum and showing how such analysis can be done to quantify process efficiency.

Polymer flooding



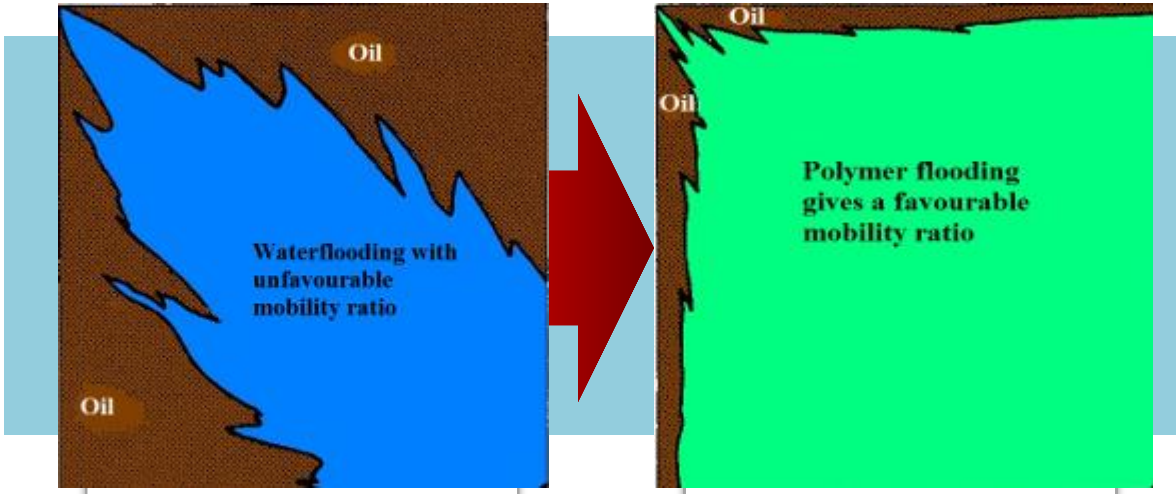
$$\left[\begin{array}{c} CH_3 \\ | \\ CH - CH_2 \end{array}\right]_n$$



Polymer

Natural
Arabic gum
Guar gum

Synthetic
HPAM
PAM



M > 1
(Fingering)
Before Polymer Flooding

M < 1
(Favorable)
After Polymer Flooding

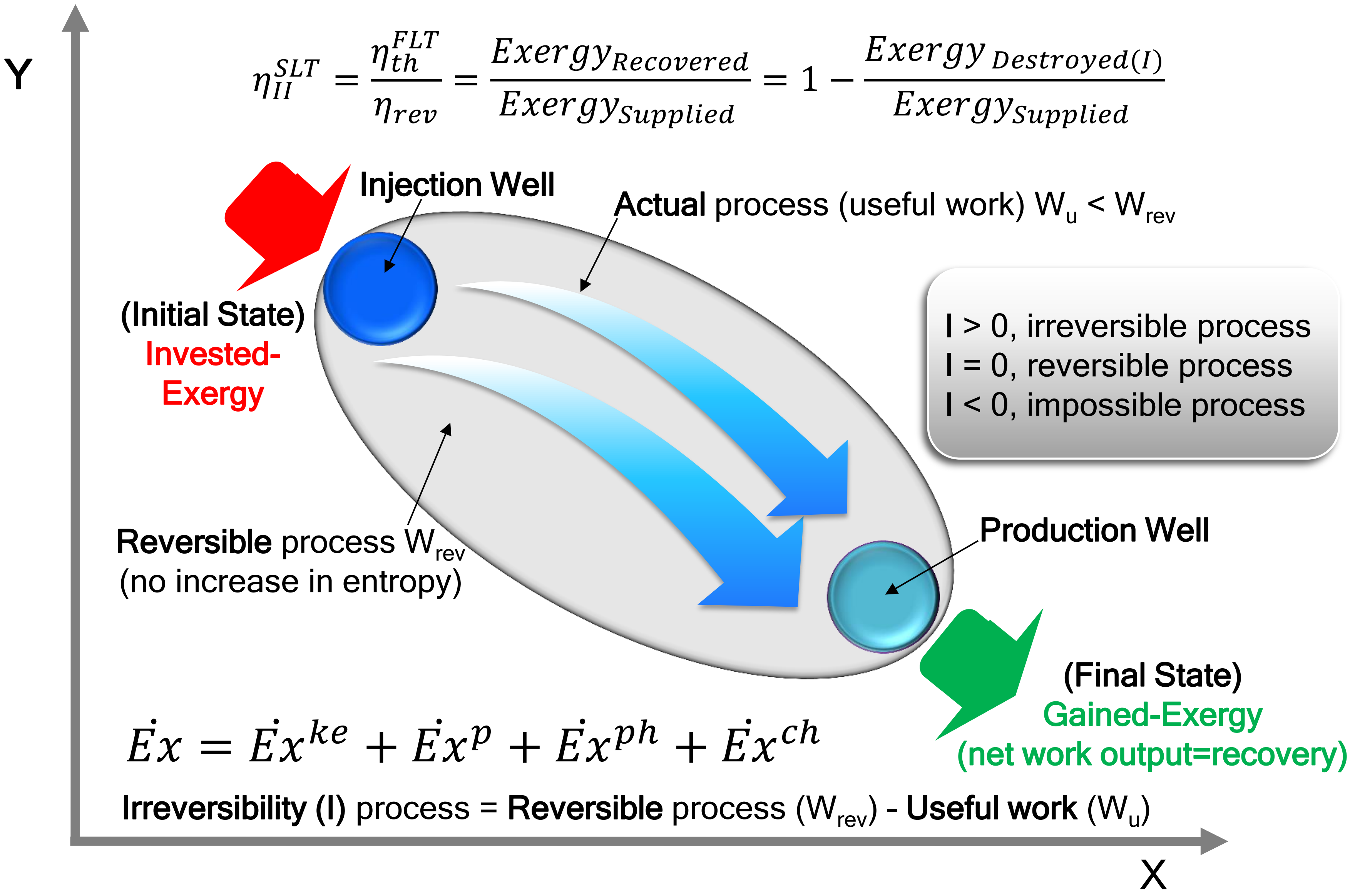
Benefits:

- Enhanced oil recovery up to 30%.
- Decreasing the mobility ratio (M)
- Sweep efficiency (no fingring).
- Less water reqiured for injection.
- Where: κ = permeability; λ = mobility;
  μ = viscosity.

$$M = \frac{\lambda_{water}}{\lambda_{oil}} = \frac{\kappa_{water} \,/\, \mu_{water}}{\kappa_{oil} \,/\, \mu_{oil}}$$

Exergy Analysis

$$\eta_{II}^{SLT} = \frac{\eta_{th}^{FLT}}{\eta_{rev}} = \frac{Exergy_{Recovered}}{Exergy_{Supplied}} = 1 - \frac{Exergy_{\,Destroyed(I)}}{Exergy_{Supplied}}$$



Injection Well

Actual process (useful work) $W_u < W_{rev}$

(Initial State)
Invested-Exergy

- I > 0, irreversible process
- I = 0, reversible process
- I < 0, impossible process

Reversible process W_{rev}
(no increase in entropy)

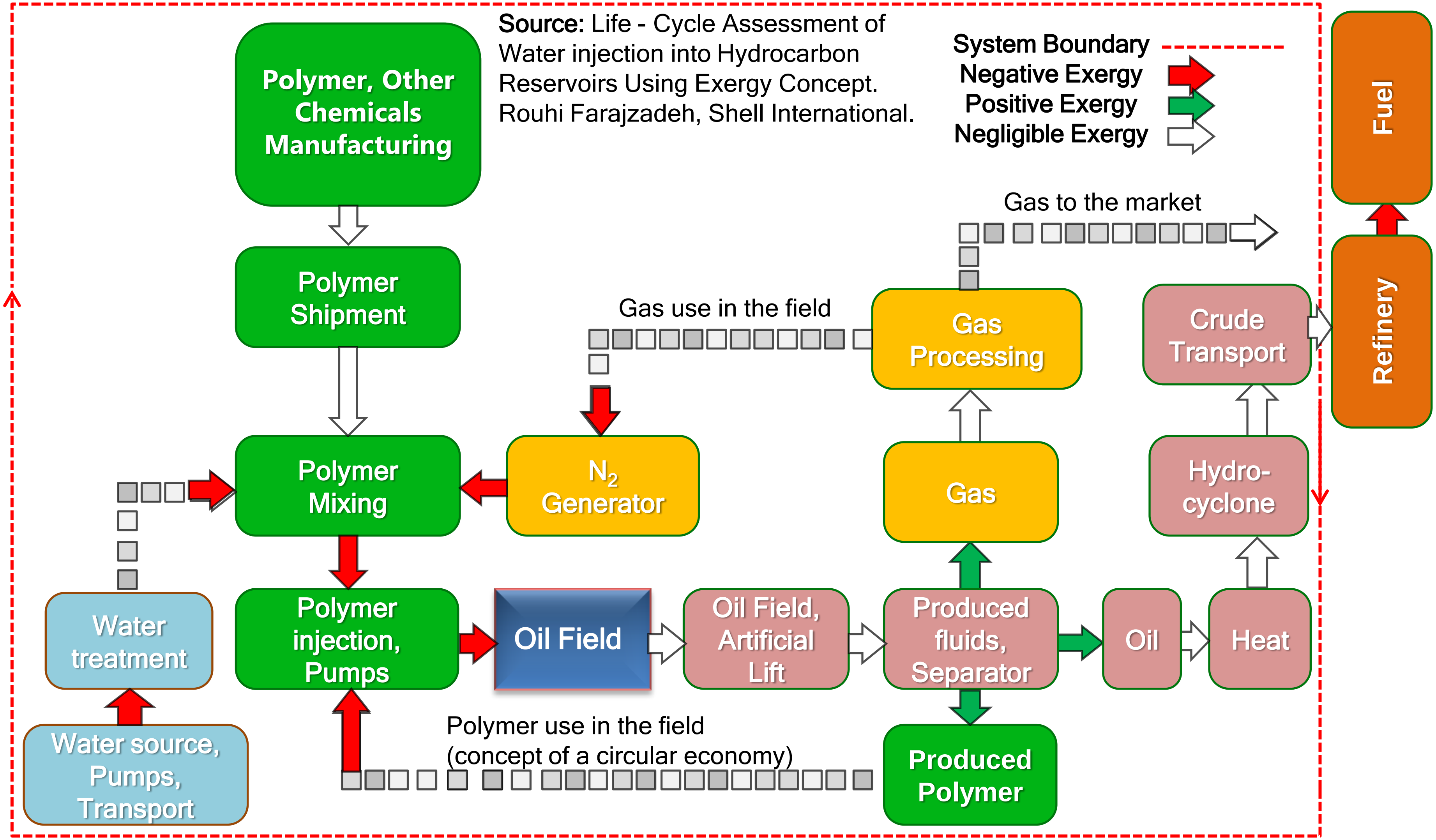
Production Well

(Final State)
Gained-Exergy
(net work output=recovery)

$$\dot{Ex} = \dot{Ex}^{ke} + \dot{Ex}^{p} + \dot{Ex}^{ph} + \dot{Ex}^{ch}$$

Irreversibility (I) process = **Reversible** process (W_{rev}) - **Useful work** (W_u)

EOR-polymer based system (PBS)



Source: Life - Cycle Assessment of Water injection into Hydrocarbon Reservoirs Using Exergy Concept. Rouhi Farajzadeh, Shell International.

System Boundary
Negative Exergy 🟥
Positive Exergy 🟩
Negligible Exergy ⇨

Polymer, Other Chemicals Manufacturing

Polymer Shipment

Polymer Mixing

N_2 Generator

Gas use in the field

Gas Processing

Gas to the market

Gas

Crude Transport

Hydro-cyclone

Fuel

Refinery

Water treatment

Water source, Pumps, Transport

Polymer injection, Pumps

Oil Field

Oil Field, Artificial Lift

Produced fluids, Separator

Oil

Heat

Polymer use in the field (concept of a circular economy)

Produced Polymer

Main exergy contributors of PBS

Drilling exergy

Crushing energy 116 [MJ/m] (PM)

Tubing / Casing

35.8 [GJ/ton-steel] (PM)

Recovery exergy

u_{inj} [m/s] × 10.7 × 10^3 [kWh/m^3-oil] × (1-f_w) [-] = u_{inj} × 3.85 × 10^{10} [J/m^3] × (1-f_w) [W/m^2]

Gained-exergy

Polymer exergy

Manufacturing costs: neglect

$c \leq 1200$ [ppm]

Circulation exergy

$$3\times\int_0^{length} dxuinj[\mathrm{m/s}]\Delta P[\mathrm{J/m^3}]$$

[W/m^2]

Invested-exergy

Labour cost

0.215 [€/kWh] ≈ 59.7 [€/GJ] (Mackay, 2008)

≈ 80% of Total

Enhanced Oil Recovery (EOR)

Scenario 1

Water Injection

- Water injection during the entire process
  - c = 0

Scenario 2

Polymer Injection

- Constant natural polymer injection during the entire process
  - $c = c_{bound} = 0.001$

Scenario 3

Slug Injection

- Time dependent slug injection
- C_{bound} × [tannh(t - tijd1) - tnnh(t - tijd2)] where, tannh(x) (0.5+0.5) × tannh(x/δ) where, δ = 0.1
- tijd2= 3x10 [s] & tijd2= 6x10 [s]

COMSOL MODEL- architecture

$$\varphi\partial_t S_w + \partial_x(uinjfw) = 0$$

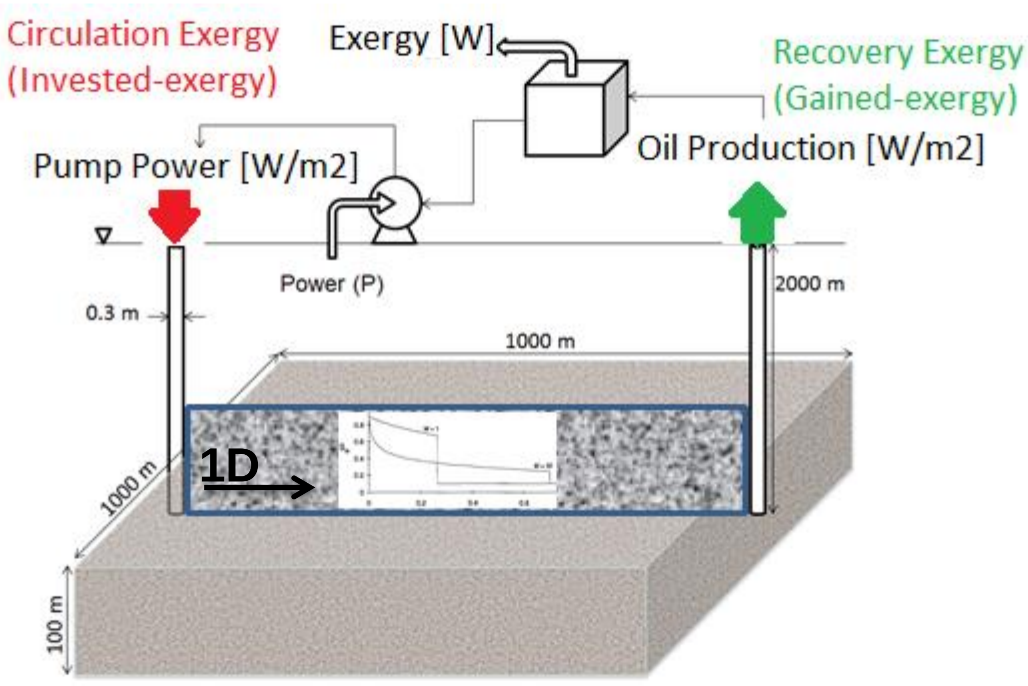
$$\varphi\partial_t(cS_w) + \partial_x(uinjcfw) = 0$$

where:φ= porosity, S_w= water saturation, c= polymer-Concentration, u_{inj}= injection velocity, f_w= fractional flow function;

$$f^{\gamma}{}_w(Sw,c) = \frac{k_{rw}(Sw)/\mu_w(c;\gamma)}{\frac{k_{rw}(Sw)}{\mu_w(c;\gamma)}+\frac{k_{ro}}{\mu_o}},$$

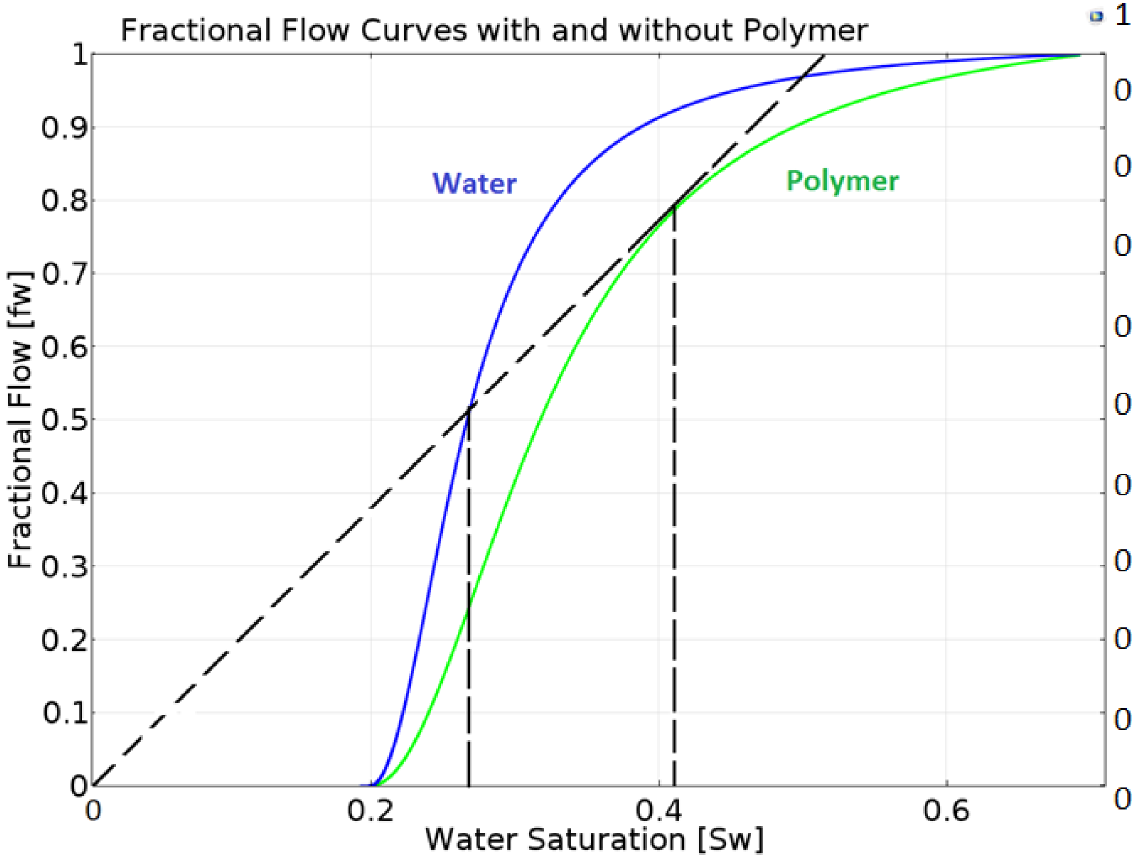
where: k_r=relative permeability, μ= viscosity

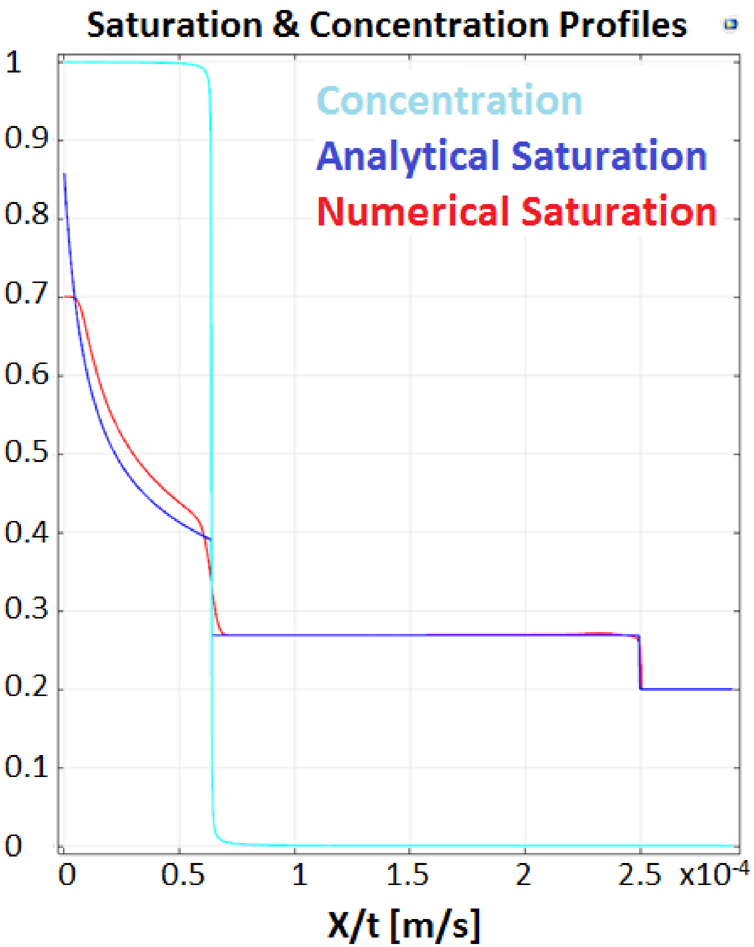
Accumulation, **Convection**, **Diffusion**



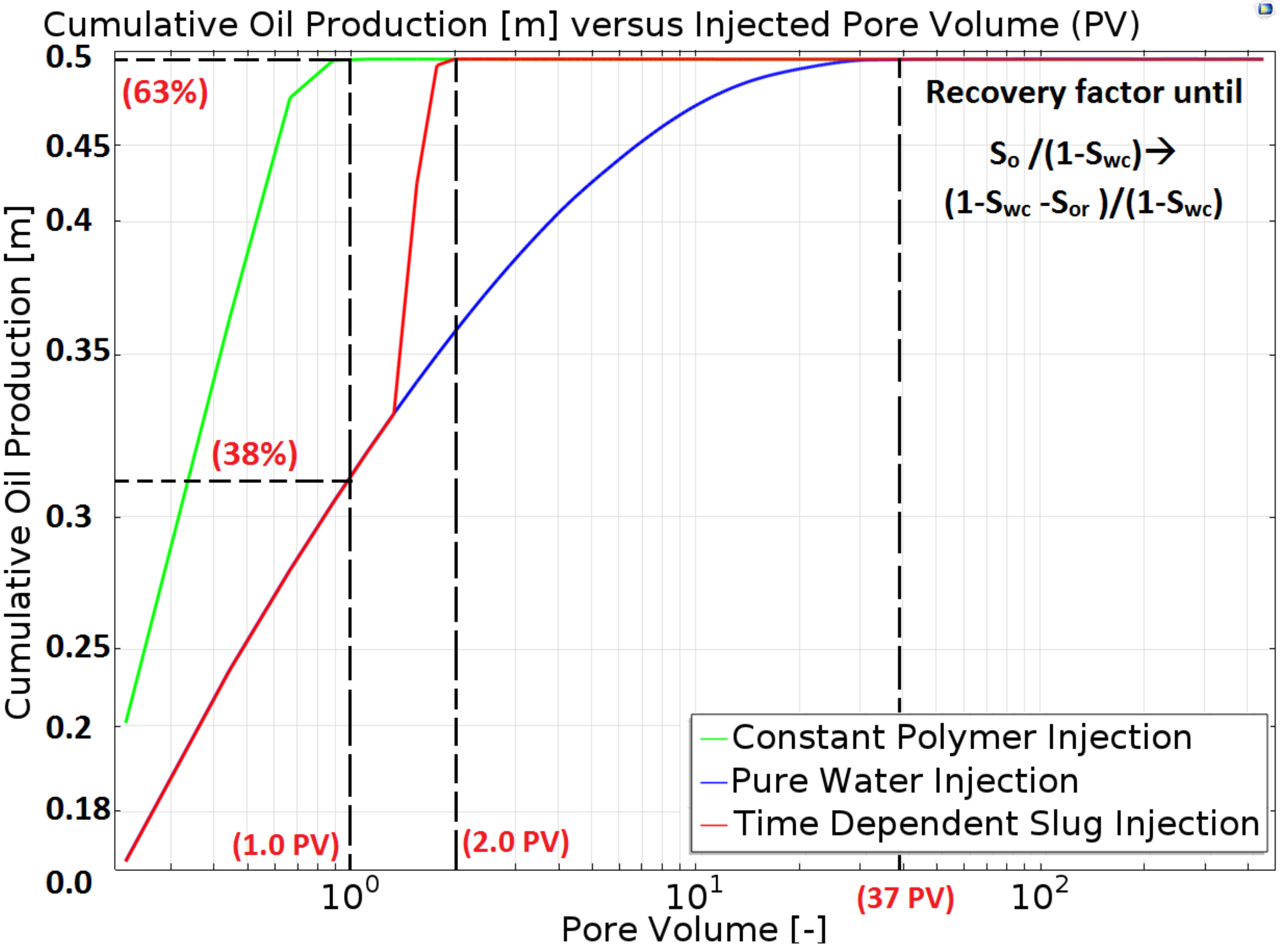
- $\boldsymbol{Weak\ Form1\ (Water)}$: $\overbrace{\varphi\partial(S,t)\times test(S)} - \overbrace{u_{inj}\times fw(S,c)\times test(Sx)} + \overbrace{\left(\frac{1}{Pe}\right)\times(S_x)\times test(Sx)}$
- $\boldsymbol{Weak\ Form2\ (Polymer)}$: $\underbrace{\varphi\partial(cS,t)\times test(c)} - \underbrace{ui_{nj}\times cfw(S,c)\times test(cx)} + \underbrace{\left(\frac{1}{Pe}\right)\times(Sc_x)\times test(cx)}$

Results - analytical vs numerical

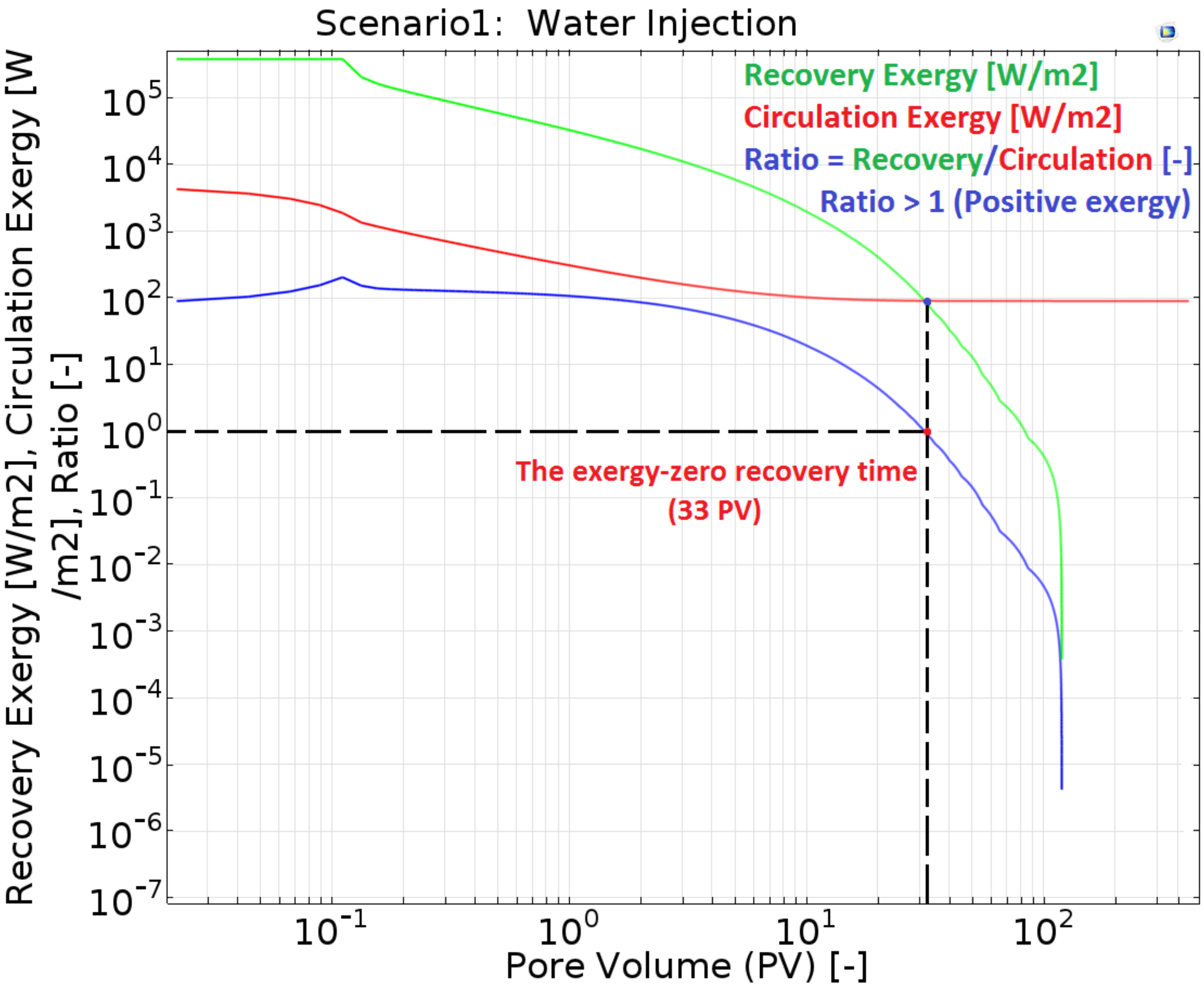




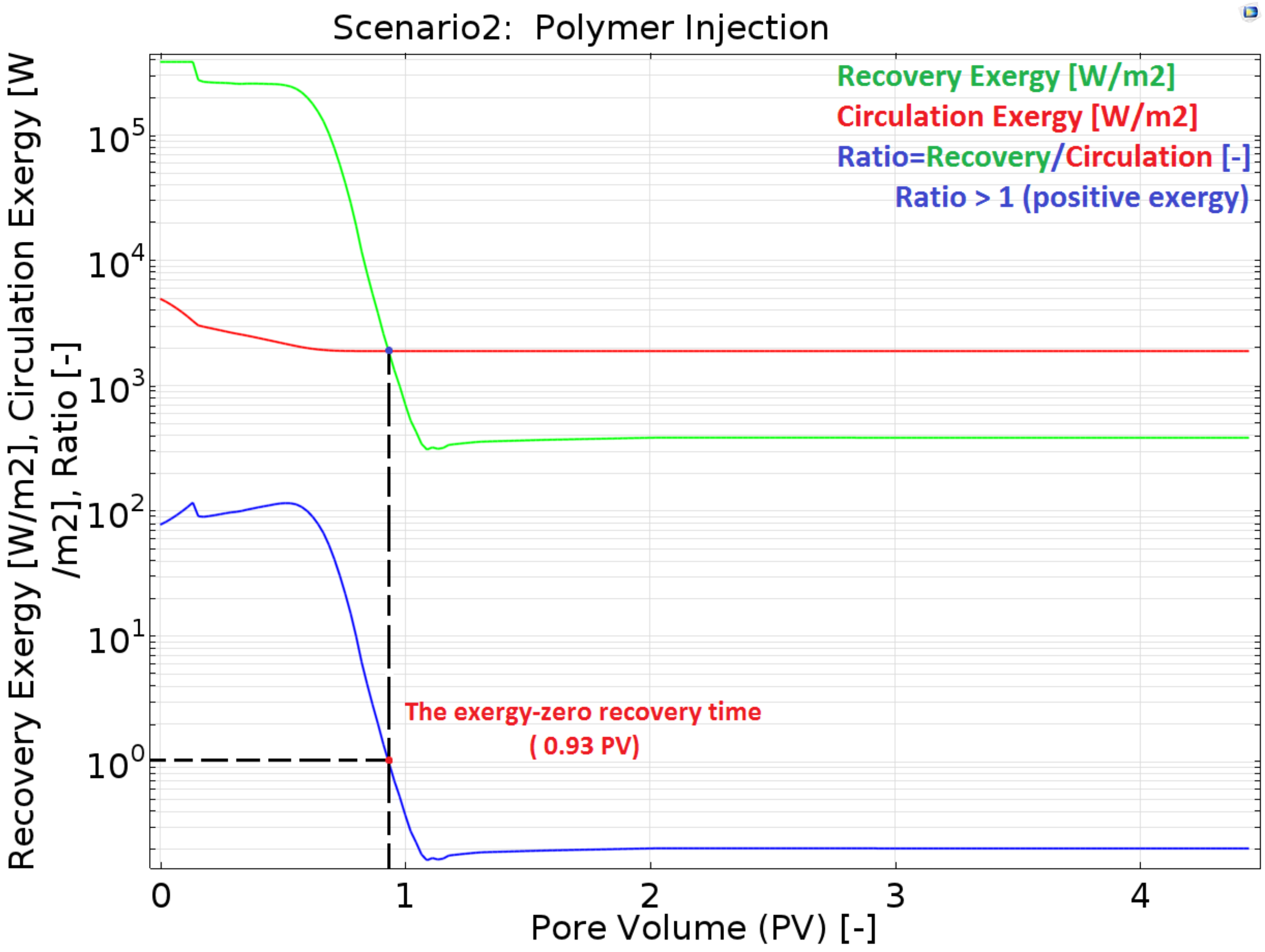
Results - Recovery Exergy (RF)



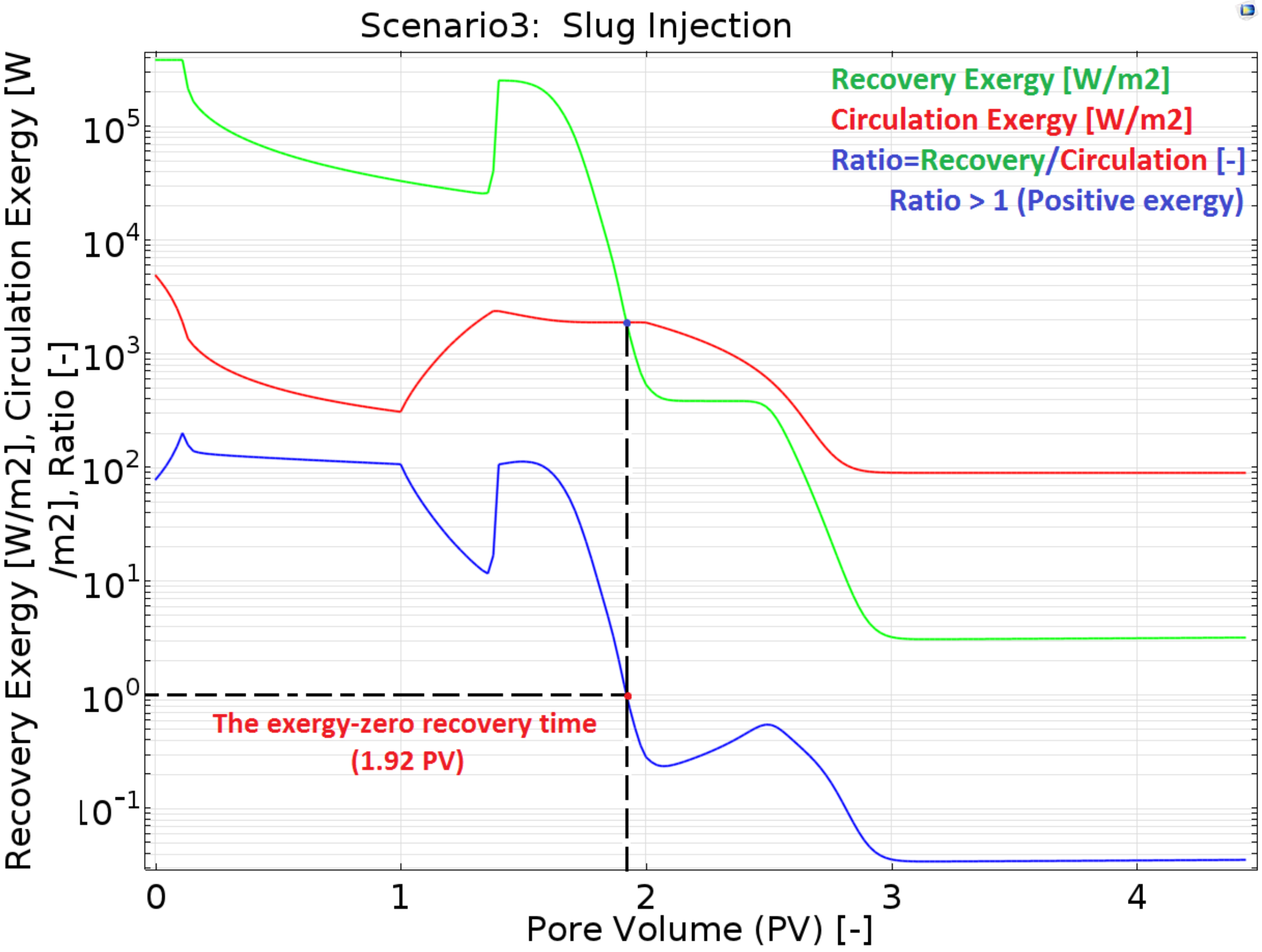
Results - Scenario 1



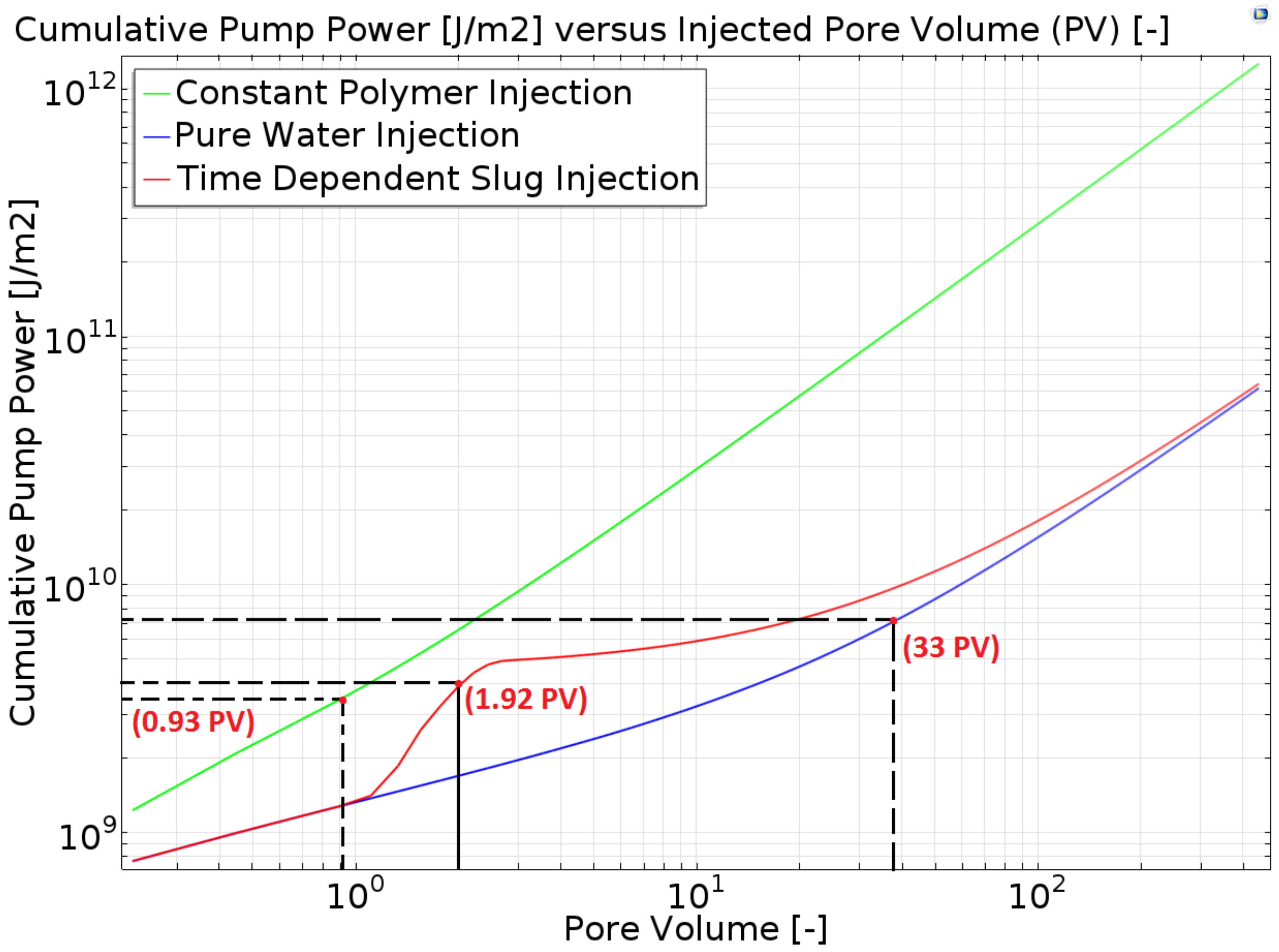
Results - Scenario 2



Results - Scenario 3



Results - Invested Exergy



Conclusions

1. Using a 1-D model of polymer displacement it is possible to analyze the exergy (maximum attainable work) balance of viscosified water injection.
2. The circulation exergy is the major contributor, i.e. it exceeds the exergy costs for drilling, casing, tubing and cleaning.
3. The analysis shows that (bio)-polymer injection leads to slightly higher exergy costs for circulation of the fluids, but can for the conditions considered accelerate the production.
4. A consideration for more cases is necessary to decide whether permanent polymer injection can compete with optimized slug injection.
5. The analysis shows that at the end of the project (concept of exergy-zero recovery time), for each scenario the termination point is reached when circulation exergy equal the recovery exergy.

Questions?

Backup slides

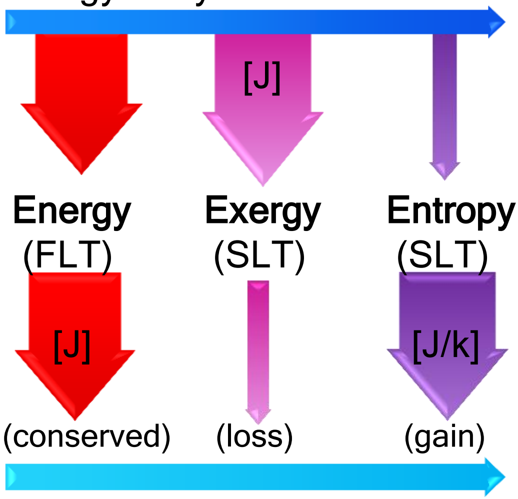
Energy Outlook – view to 2040

- Modern energy is one of most complex endeavors
- World demographic shift (from 7.3 to **9.1** billion in 2040)
- World economy doubles over the next 20 years (**3.4%**)
    - Global productivity will effectively double (GDP per person)
    - Growth in number of middle class families (2 billion)
    - Emerging economy powers (i.e., China, India)
- Global demand (700 quadrillion BTUs in 2040 ~ **25%**)
- Oil remains the primary fuel ~ **60%** (transport, industry)
- Global CO_2 emissions
    - Global CO_2 emissions rose close to 40% from 2000 to 2015
    - Global CO2 emissions are likely to peak (2015 to 2040)

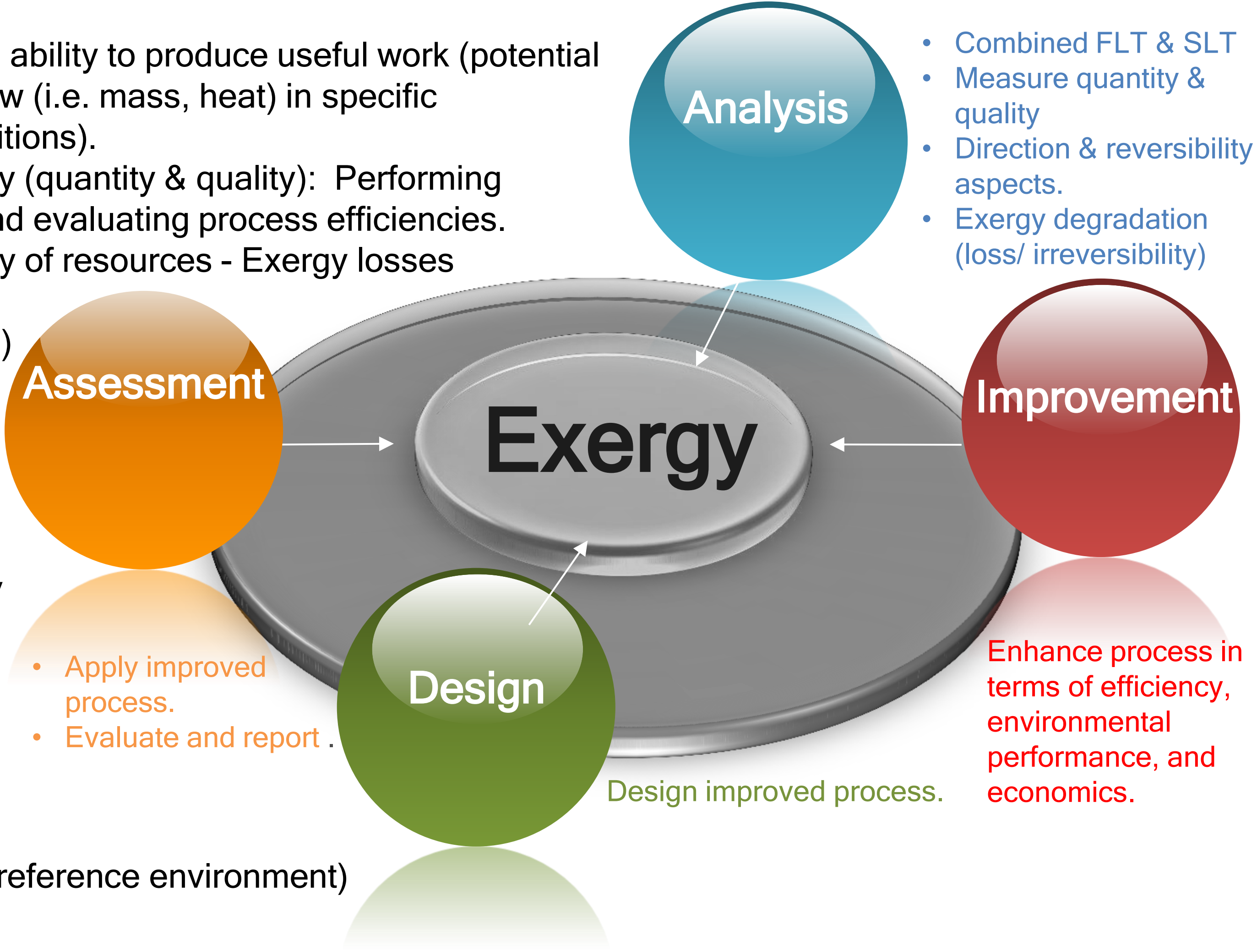
Why exergy analysis?

- **Exergy** is a measure of the ability to produce useful work (potential work) from a quantity or flow (i.e. mass, heat) in specific environment (T, P, compositions).
- Energy (quantity) vs. Exergy (quantity & quality): Performing energy/ exergy balances and evaluating process efficiencies.
- Exergy of products = Exergy of resources - Exergy losses

Non-equilibrium State (T_1, P_1, x_1)
Exergy of System > 0.



Equilibrium State $(T_0 P_0, x_0) \rightarrow$ (reference environment)
Exergy of System = 0.



- Combined FLT & SLT
- Measure quantity & quality
- Direction & reversibility aspects.
- Exergy degradation (loss/ irreversibility)

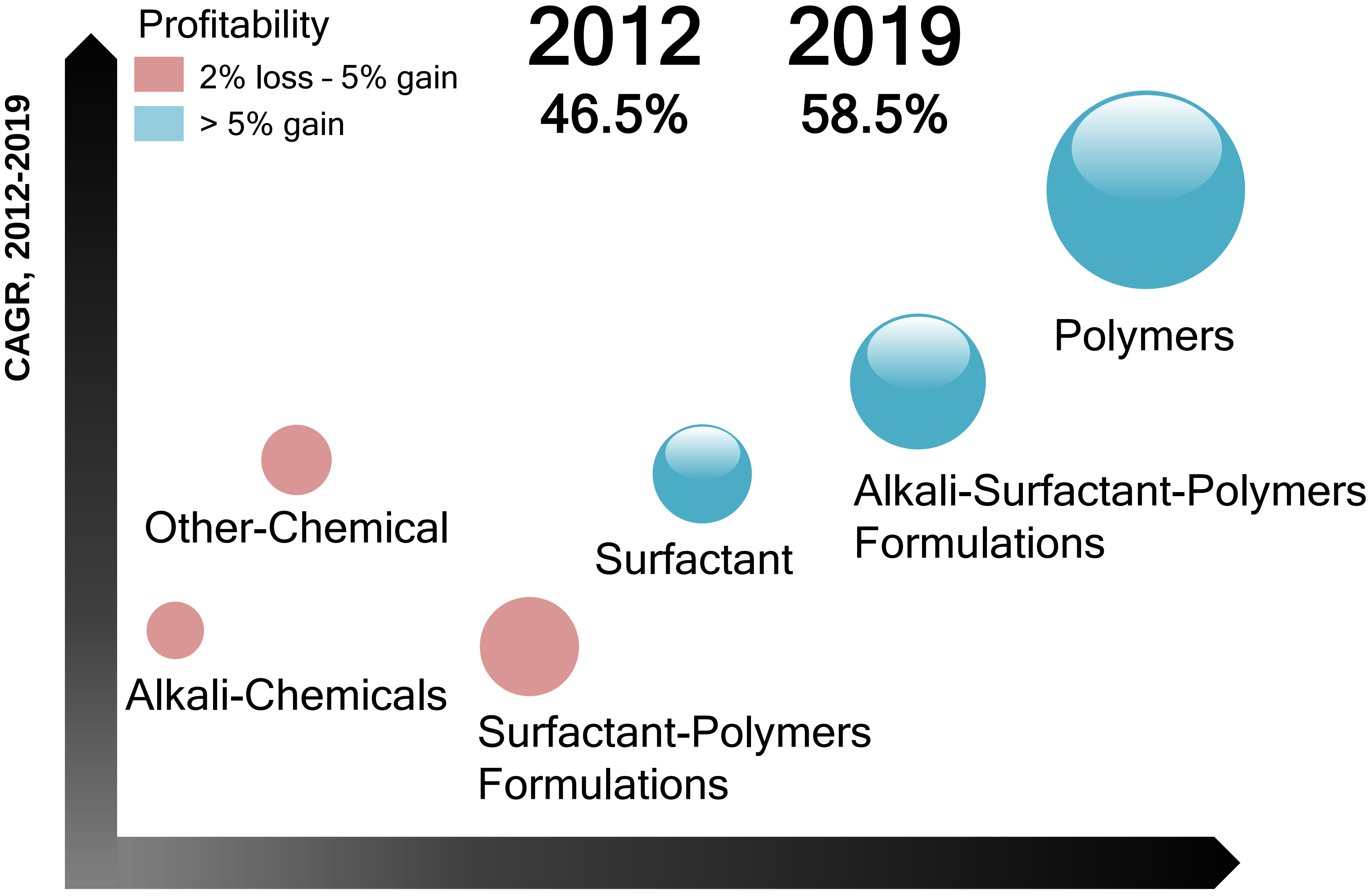
- Apply improved process.
- Evaluate and report .

Design improved process.

Enhance process in terms of efficiency, environmental performance, and economics.

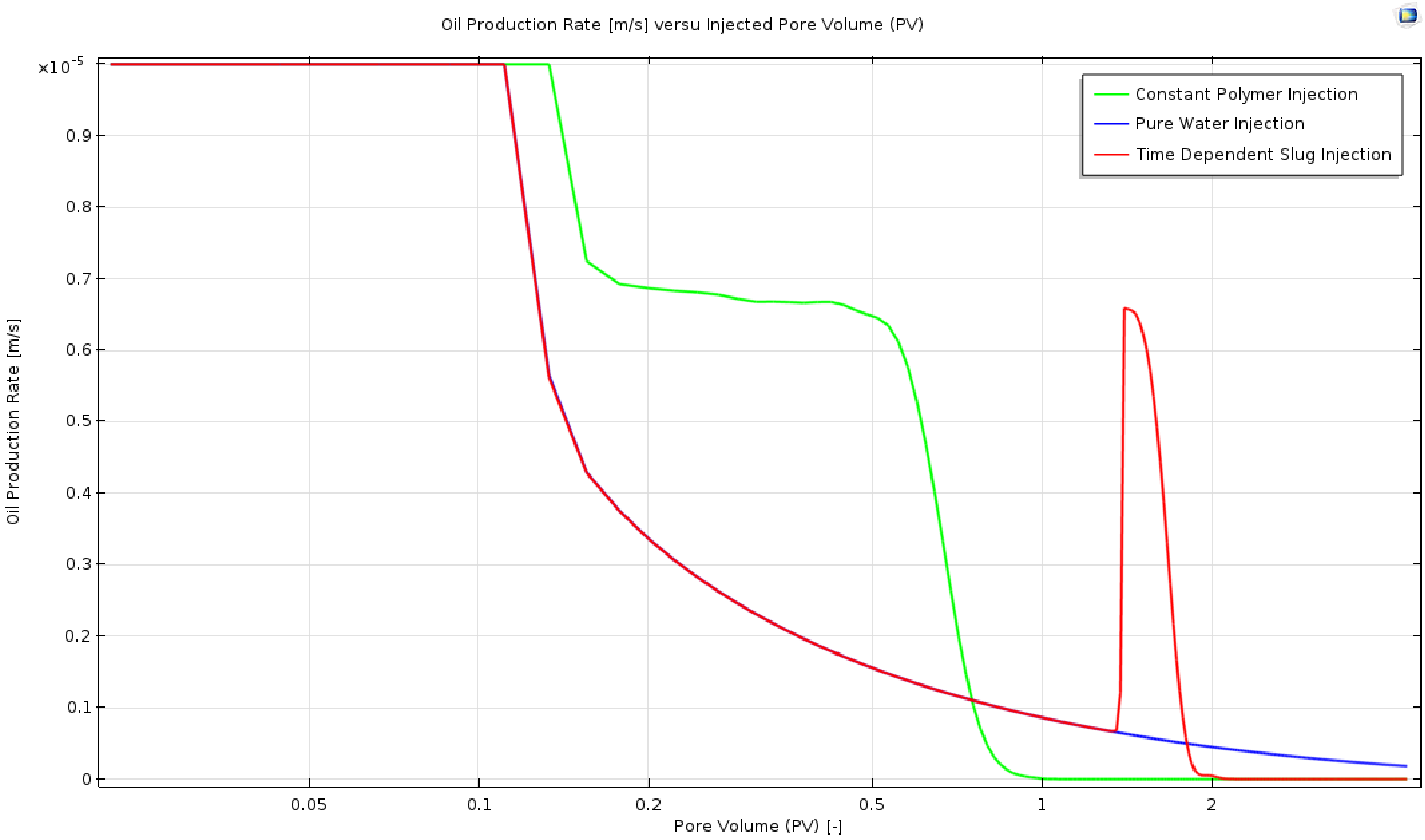
$$\dot{E}x = \dot{E}x^{ke} + \dot{E}x^{p} + \dot{E}x^{ph} + \dot{E}x^{ch}\ ;\ Ex_{RF} = \frac{(Ex_{gained} - Ex_{invested})}{Ex_{gained}}$$

Growth Opportunities for EOR-polymer Demand

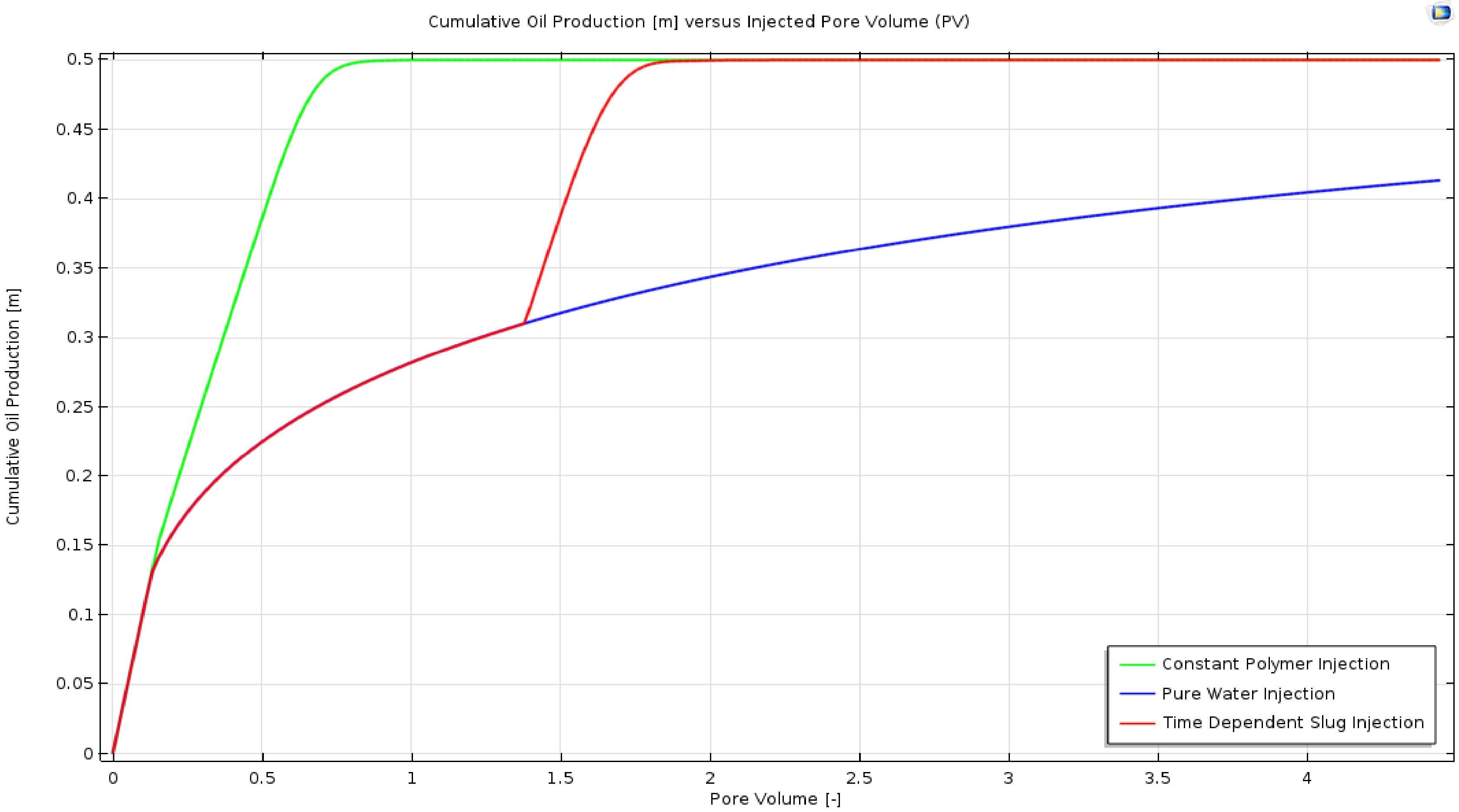


Source: Forst & Sullivan, 2012.
Analysis of Enhanced Oil Recovery Chemical Market in The United States and Europa.

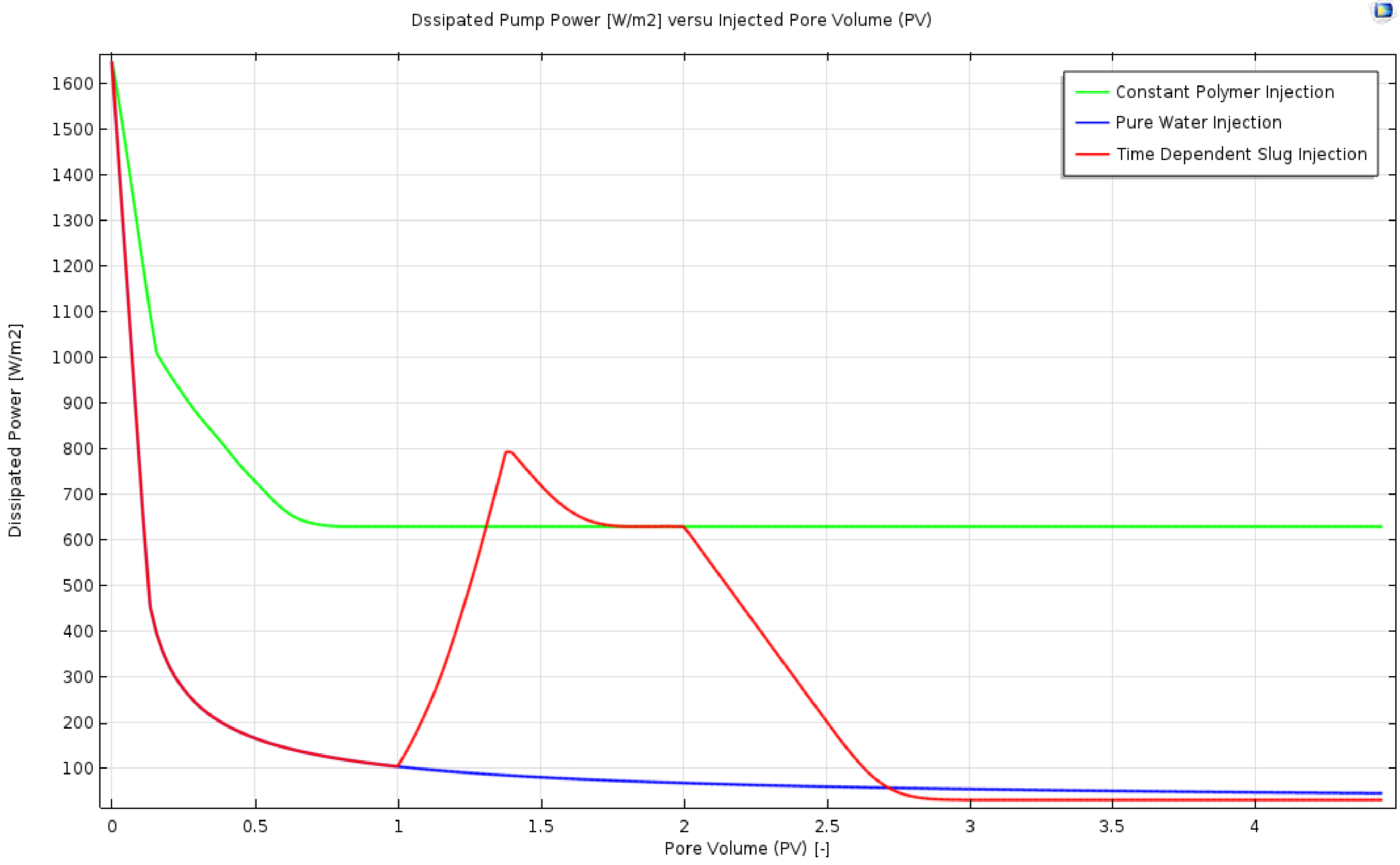
Results - Oil production rate



Results - Cumulative oil production



Results - Dissipated pump power



Results - Ratio [-]