Technical-Economic Modeling of CO_2 Sequestration - EOR

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Ana Teresa F. S. Gaspar

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Outline

1) Motivation / Objective

2) Introduction: CO_2 Sequestration

3) Costs of CO_2 Sequestration

4) Methodology:
- CO_2 Life Cycle
- Economic Analysis

5) Case Study: Mature Oilfield

6) Results

7) Conclusions

Motivation

Wikepedia:

Carbon dioxide emissions for the top 40 countries by total emissions in 2013, given as totals and per capita. Data from EU Edgar database

1) Motivation

- Avoiding CO_2 emissions
  increase oil production in a mature oil
  reservoir through gas injection.

- Recovering residual oil
  prolonging the lifetime
  extending benefits to local communities.

1) Goal

- Development of a methodology to evaluate the technical-economic feasibility of CO_2 Sequestration in EOR operations.

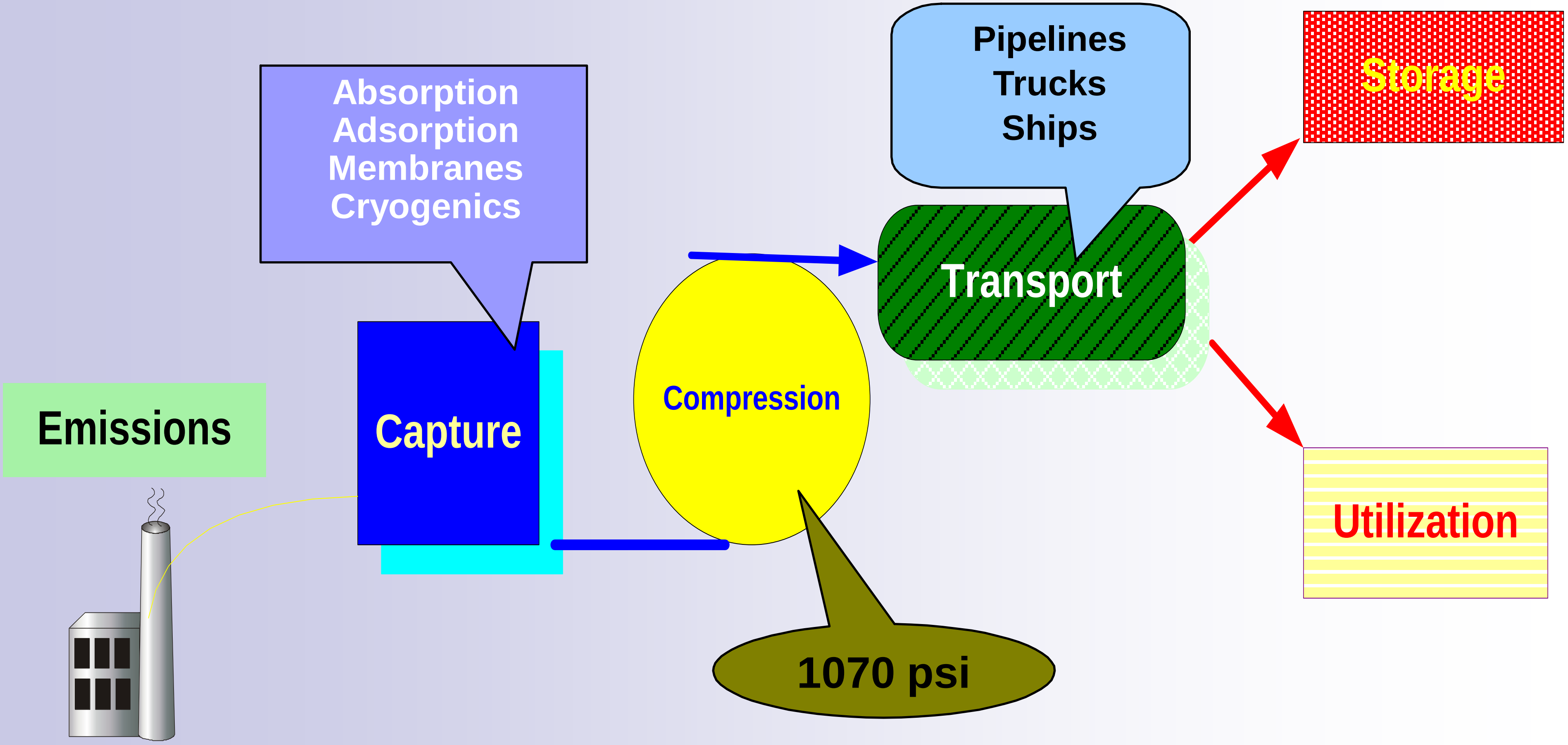
2) CO_2 Sequestration

"Capture and Safe Storage"

Sites of CO_2 Storage:

- Depleted Oil and Gas Reservoirs
- Deep Saline Formations
- Oceans
- Forests
- Utilization: EOR and ECBM

2) Steps of CO_2 Sequestration



3) Costs of CO_2 Sequestration

Source of Emissions	Costs of Capture and Recompression (US$/t$CO_2$)
Fertilizer	4
Hydrogen Production	4
Power Plants	32 - 53
Petrochemical	40 - 45
Iron Steel	36

Hendriks et al., 2004

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Hendriks et al., 2004

Transportation	US$/t$CO_2$ per 250 km
Pipeline	1 - 8

IPCC, 2005

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Hendriks et al., 2004

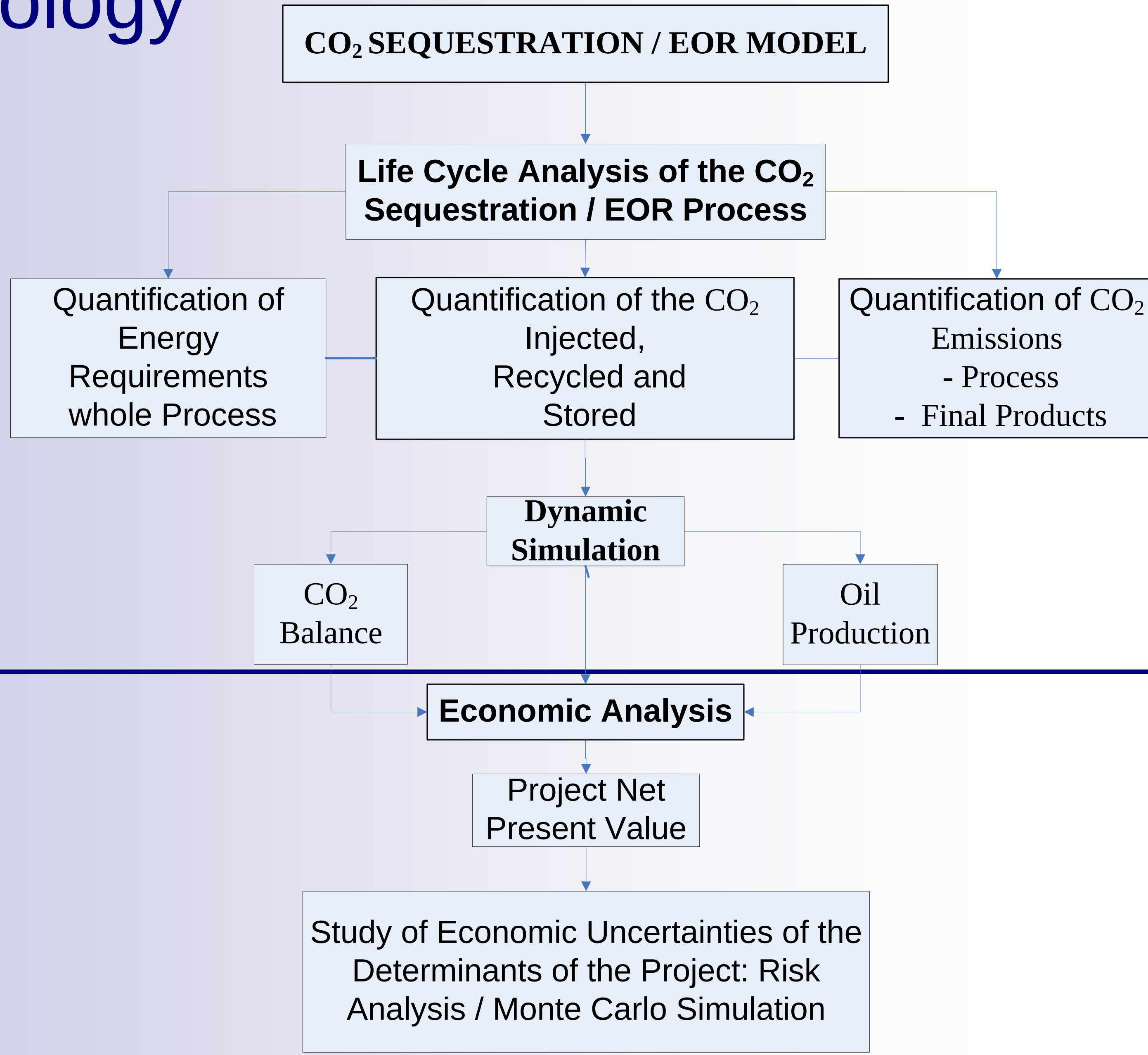
Transportation	US$/t$CO_2$ per 250 km
Pipeline	1 - 8

IPCC, 2005

Storage Site	Storage Costs (US$/ t$CO_2$)
Geological Reservoir	5 - 20
Ocean	5.53 -17.64

Nguyen and Allinson, 2002
Herzog and Golomb, 2004

4) Methodology

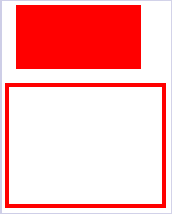


Technical Stage

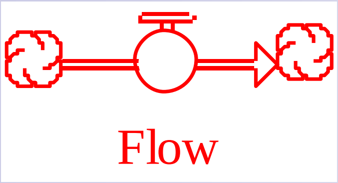
Economic Stage

4) Methodology: Dynamic Systems (I)

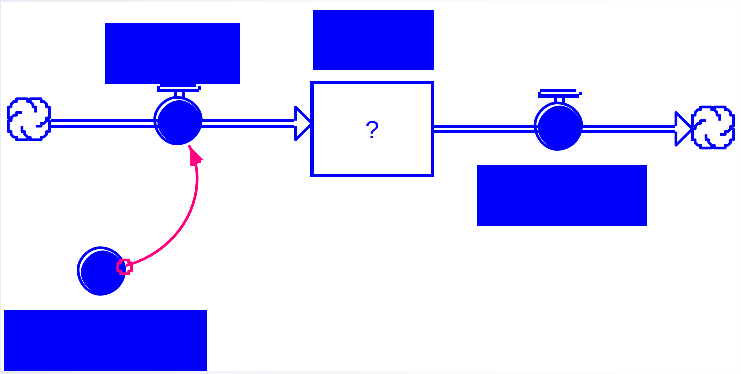
Stock = Accumulations



Flows = Rate of Change



Tools of System Dynamics

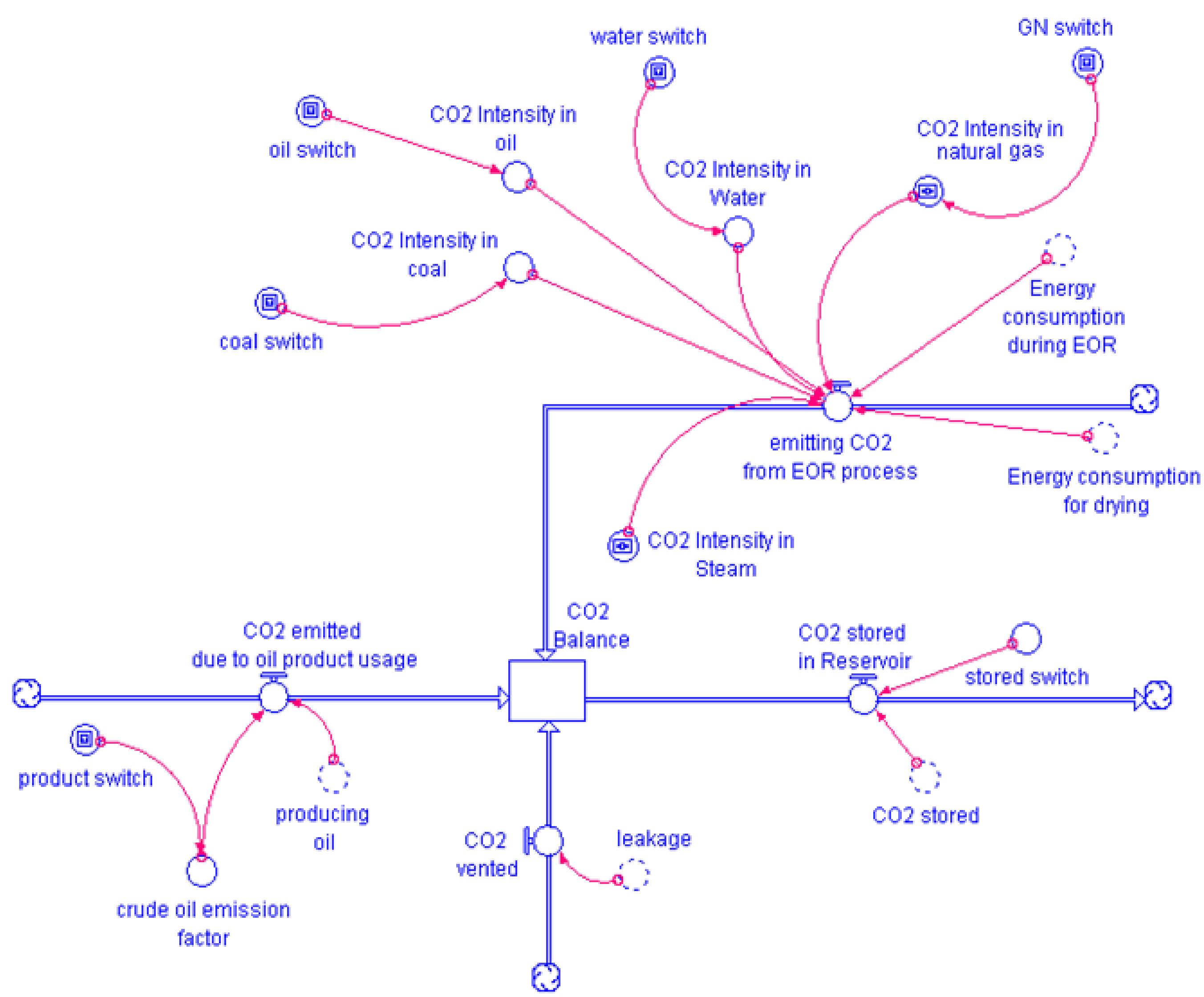


STELLA® : Systems Thinking Educational Learning Laboratory with Animation

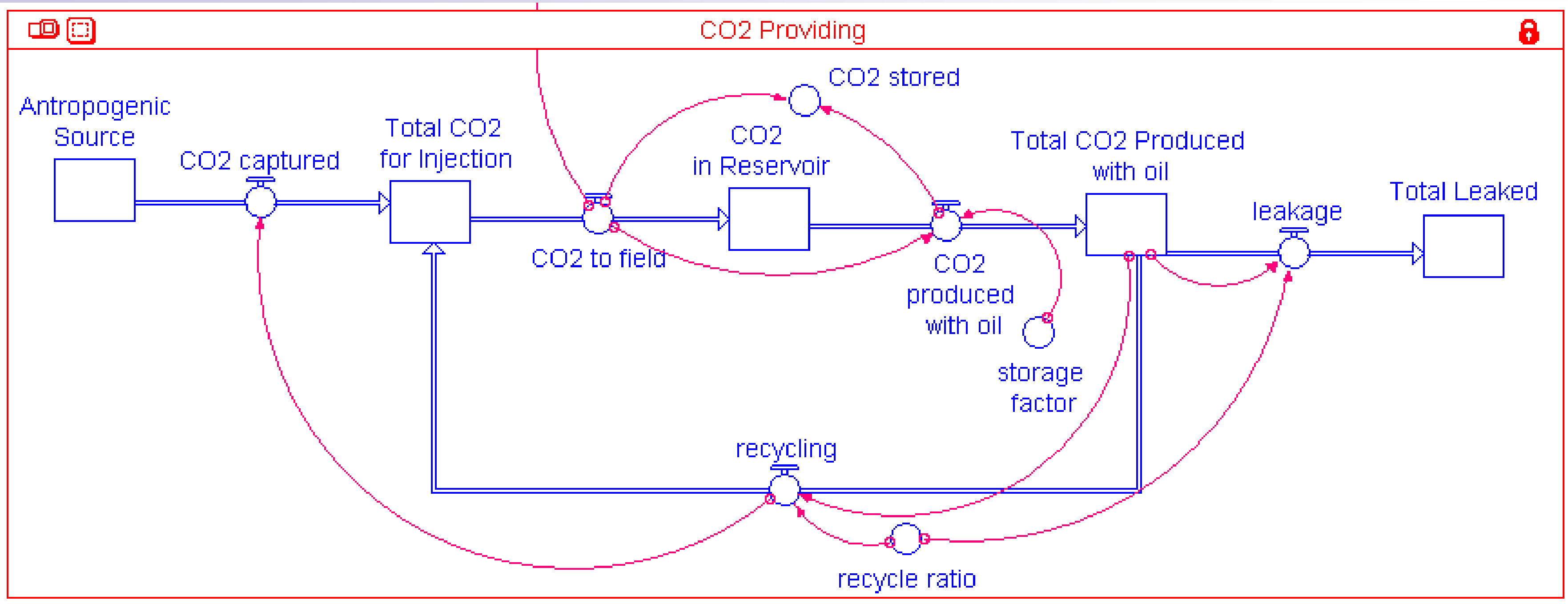
4) Methodology: Life Cycle (I)

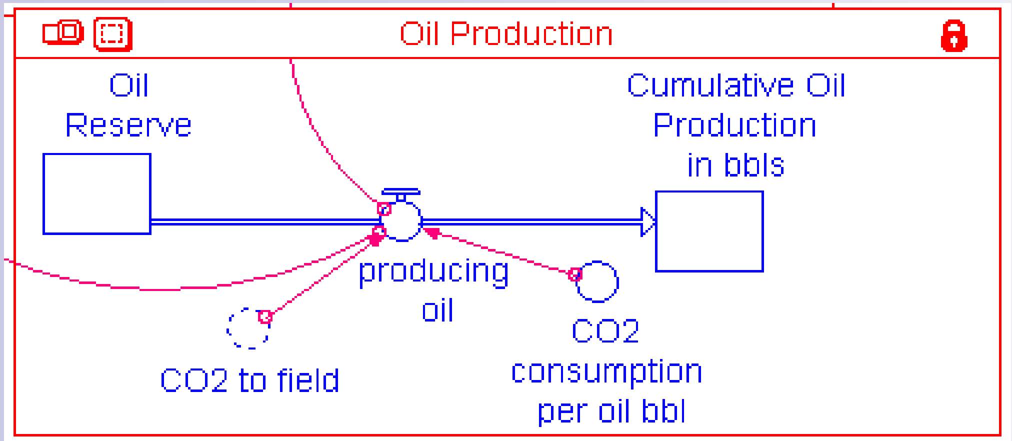
Map/

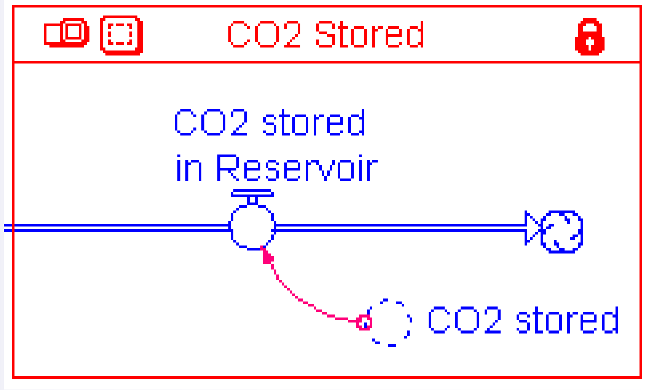
Model Level



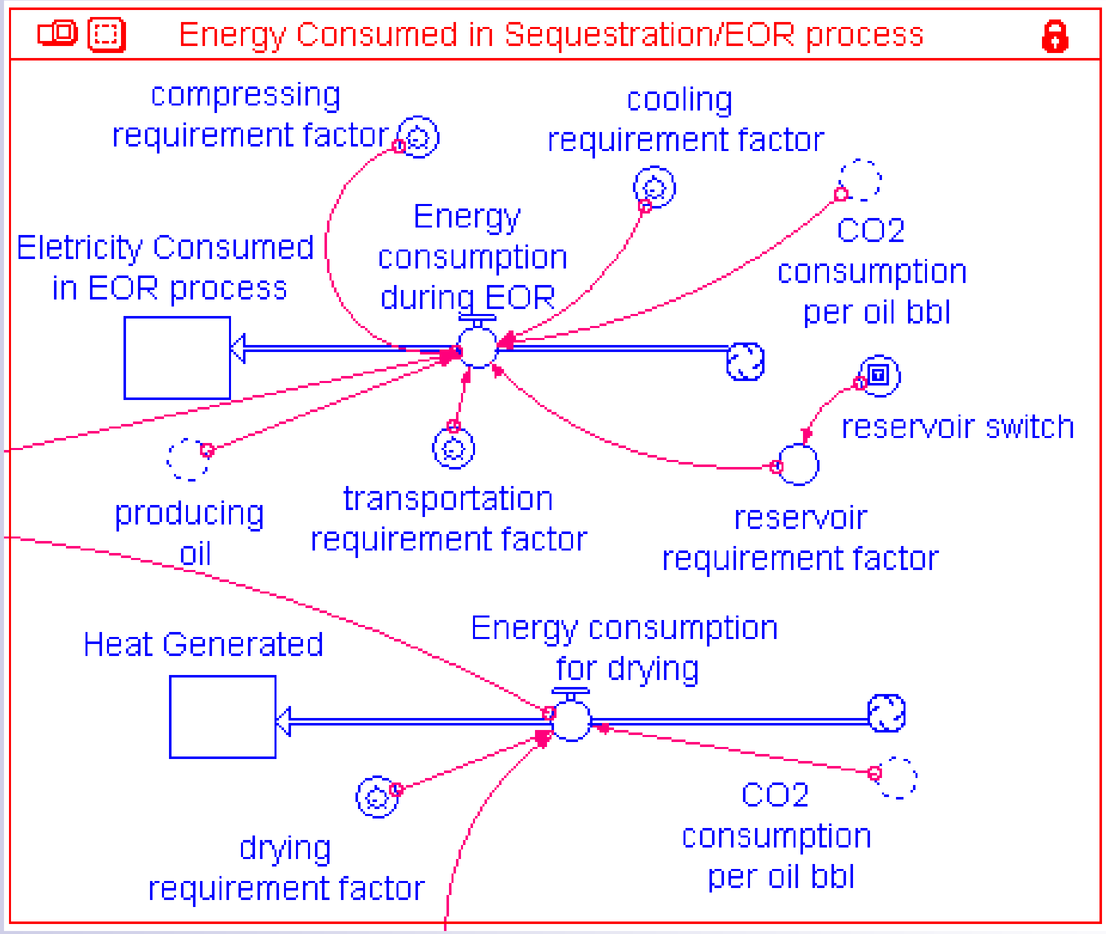
4) Methodology: Life Cycle (II)







4) Methodology: Energy Requirements



Compression

3 Stages

$P_o = 40$ / $P_1 = 127.6$ / $P_2 = 407$ / $P_3 = 1{,}300$ psi

T = 50°C

(Stationary, Adiabatic, Reversible state)

4) Methodology: Energy for Transportation

- Fluid Velocity
- Reynolds Number
- Pressure Drop
- Bernoulli Equation

4) Methodology: Energy for EOR

- Separation of CO_2 from produced gases
- Breakthrough
- Pumping the oil to the market

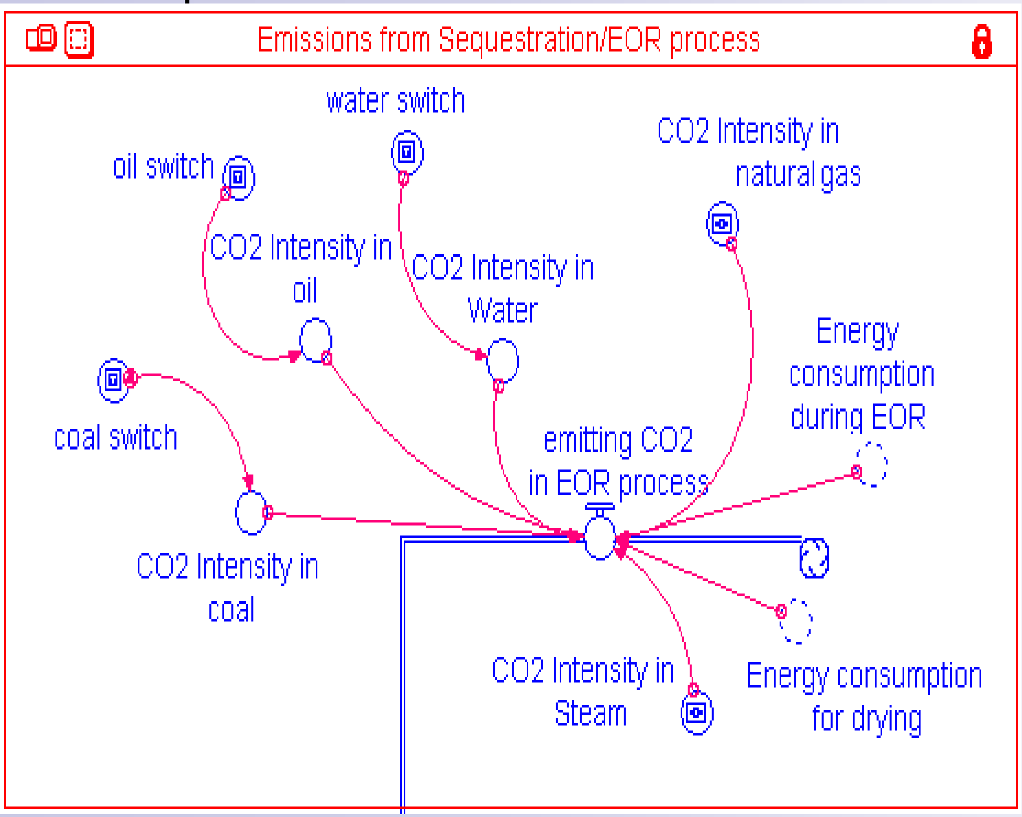
Power = 5 Hp/bopd (CO$_2$EOR)
0.75 Hp/bopd (thermal EOR)

Source: EPRI, 1999

4) Methodology: CO_2 Emissions

INDIRECT

Sequestration/EOR Process



Emissions (electricity) =
Specific emission x Energy consumed

DIRECT

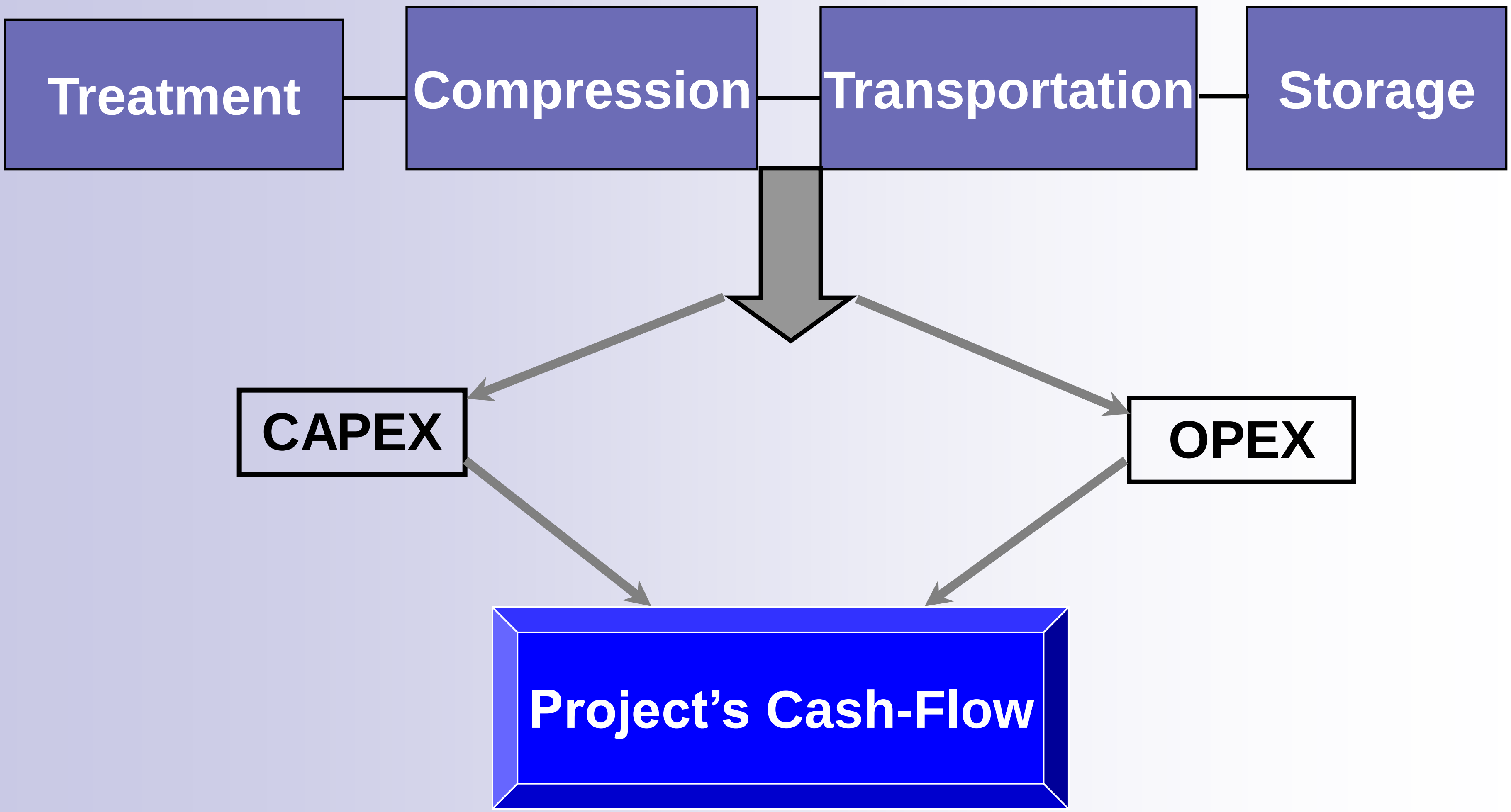
Leakage

Emissions =
0.005 x Total CO_2 Injected

Product Usage

Emissions =
Crude oil emission factor x Oil produced

4) Methodology: Economic Analysis (I)



4) Methodology: Economic Analysis (II)

Annual Net Cash Flow

$$NCF = (R + C_{CO2} - Roy - PIS - OpEX - IW - D)*(1-T) + D - CapEX$$

5) Case Study

Mature Onshore Oilfield

Source: Ammonia Production

Source – Storage site: 75 km

5) Fiscal and Economic Assumptions

Economic Characteristics

Investments (MMUS$)	
Treatment,	6.00
Compression	5.00
Transportation	9.00
Storage	1.00
OpEx (US$/t)	
Compression	7.50
Transportation	0.50
Storage	3.00
CO_2 Purchase	12.0
Costs of Abandonment (MMUS$)	1.10

5) Fiscal and Economic Assumptions

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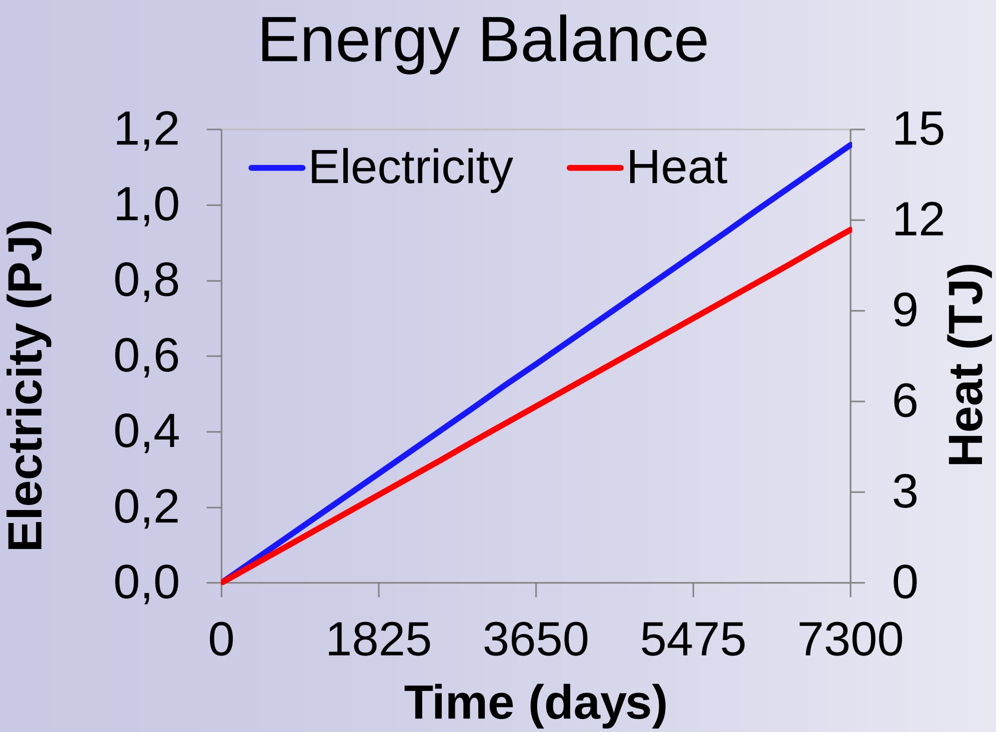
Costs of Abandonment (MMUS$)	1.10

Fiscal and Economic Assumptions

Useful Life (years)	20
Oil Price (US$/bbl)	35
Discount Rate (%)	12
Corporate Tax (%)	25
PIS/PASEP + COFINS (%)	3.65
Royalties (%)	5
Area Rental (US$/$km^2$)	300

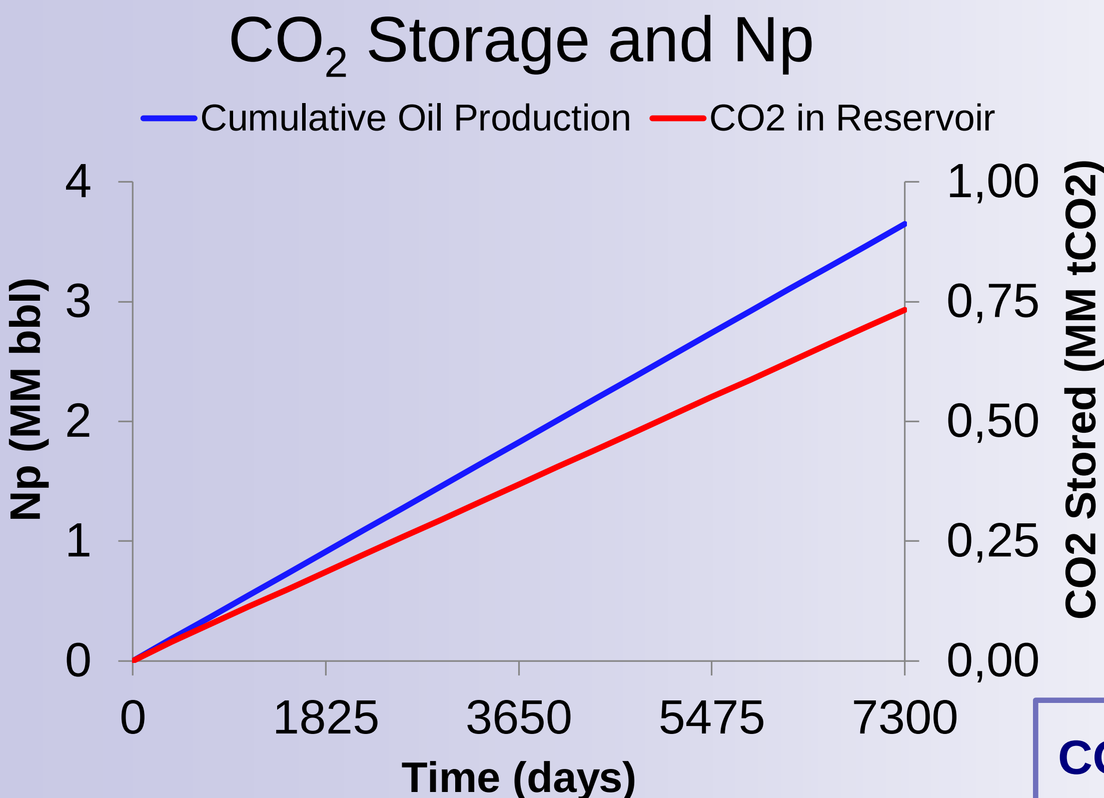
6) Results: Life-Cycle



Electricity /Heat Requirements

Compression	270.5
Cooling	8.0
Drying	8.0
Transportation	10.2
EOR	508.2
Total	**804.9 MJ/tCO_2**

6) Results: Life-Cycle

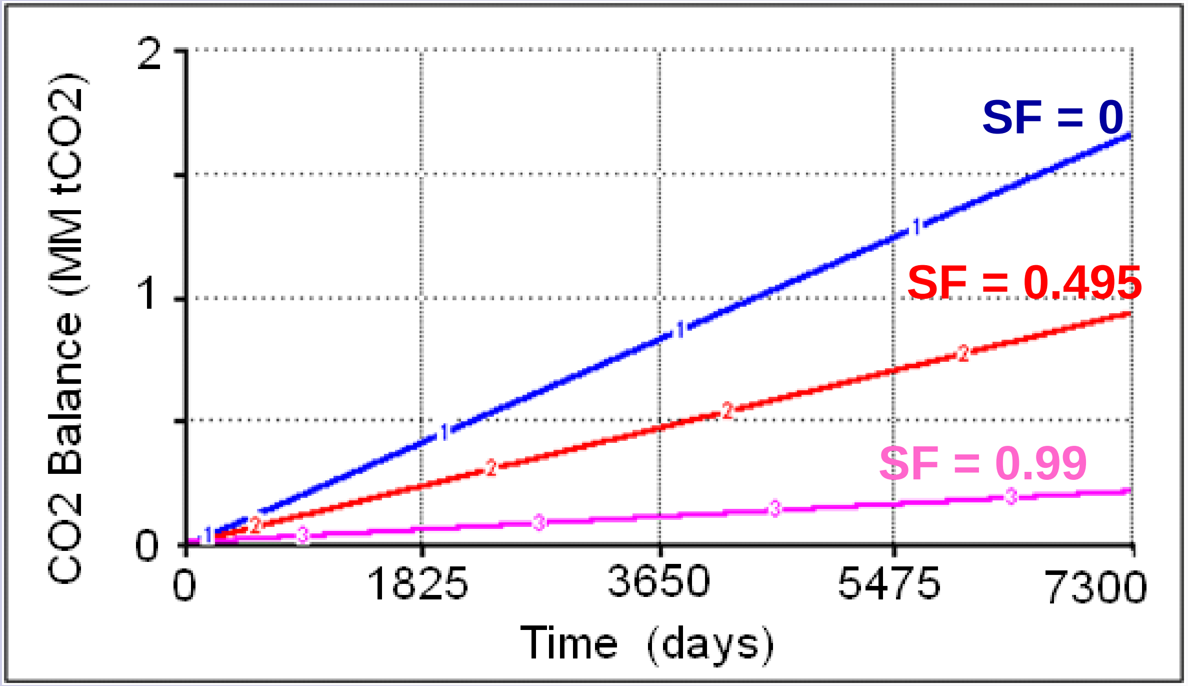


Mass Balance

	CO_2 Sequestration	$MMtCO_2$
	Total Injection	1.46
50% →	Storage	0.733
0.5% →	Emissions (Leaks)	0.0073
4% →	Emissions (Electricity)	0.0599
	Np	**3.65 MMbbl**

6) Results: Life Cycle

CO_2 Balance as function of Storage Factor



1.664 $MMtCO_2$

0.925 $MMtCO_2$

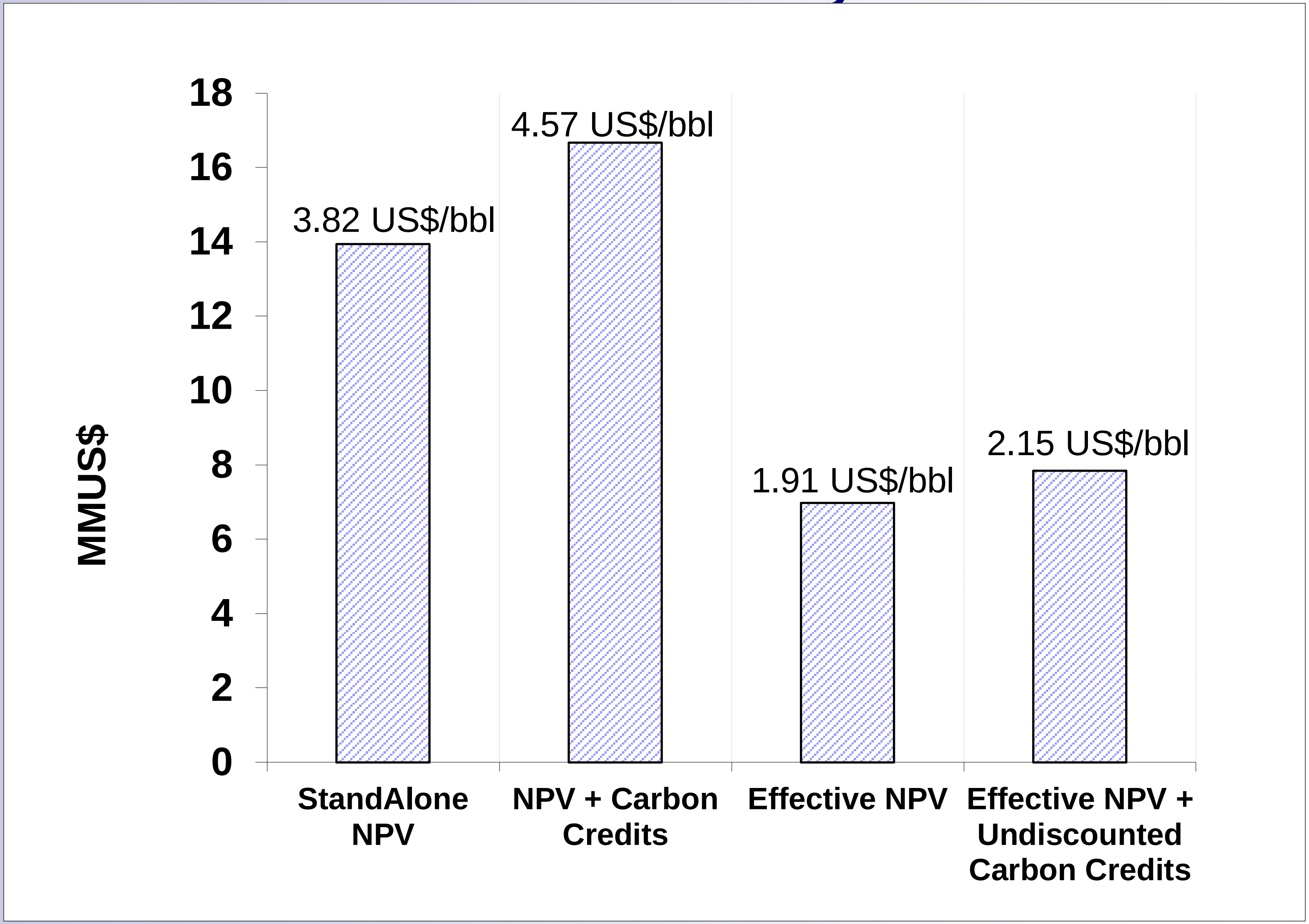
0.350 $MMtCO_2$

		CO_2 Balance
No Storage	**(SF = 0)**	**Increase 14%**
Storage	**SF = 0.495**	**Decrease 37%**
	SF = 0.990	**Decrease 86%**

6) Results: Life Cycle

Storage Efficiency (tCO_2/ bbl)	Reference
0.18	Result of this research
0.15	Wilson *et al.* (2000)
0.30	Espie (2000)
0.18 – 0.78	Stalkup (1984)

6) Results: Economic Analysis



13.95 MMUS$ 16.67 MMUS$ 6.98 MMUS$ 7.84 MMUS$

6) Results: Sensitivity Analysis

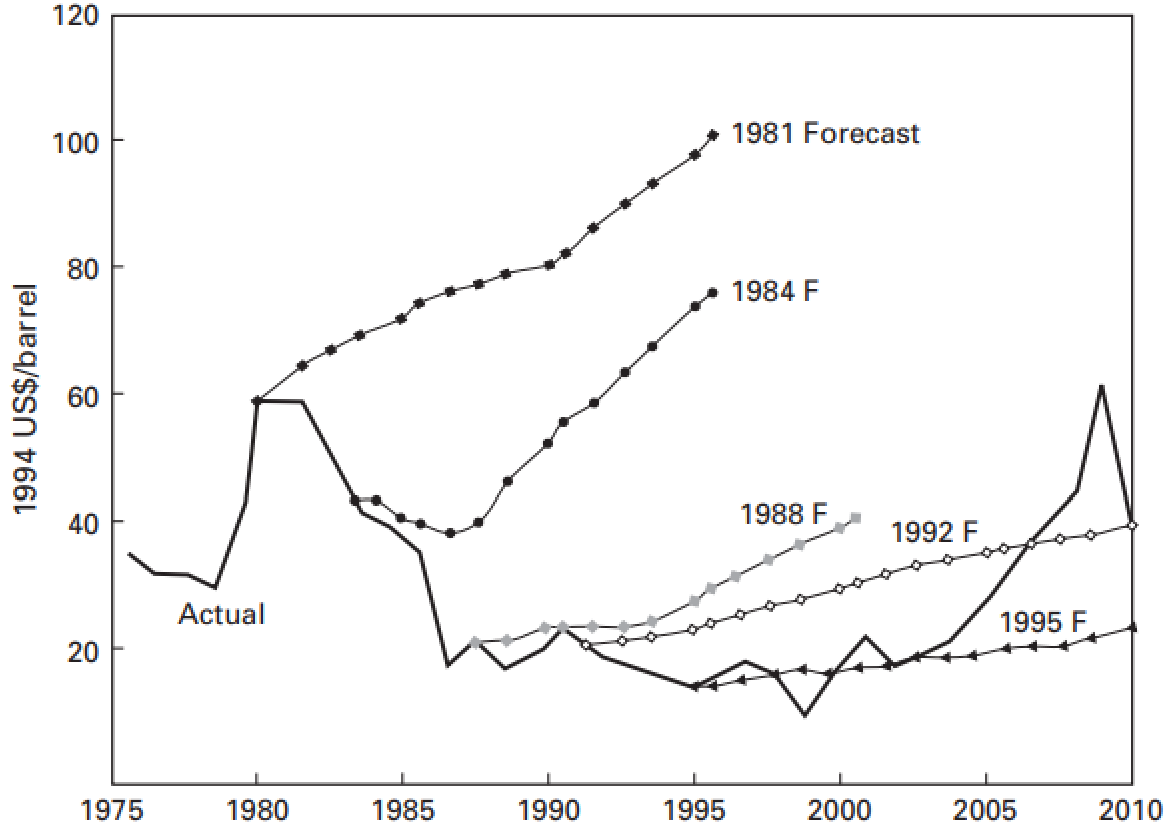
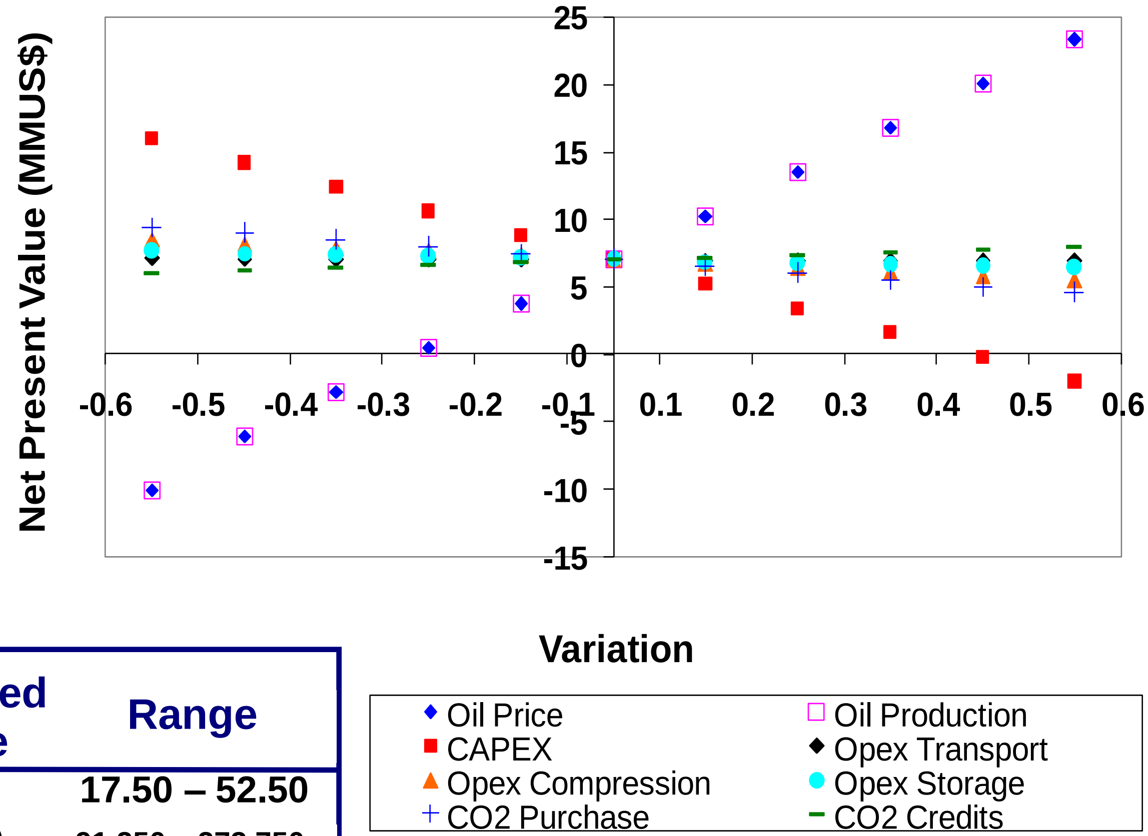


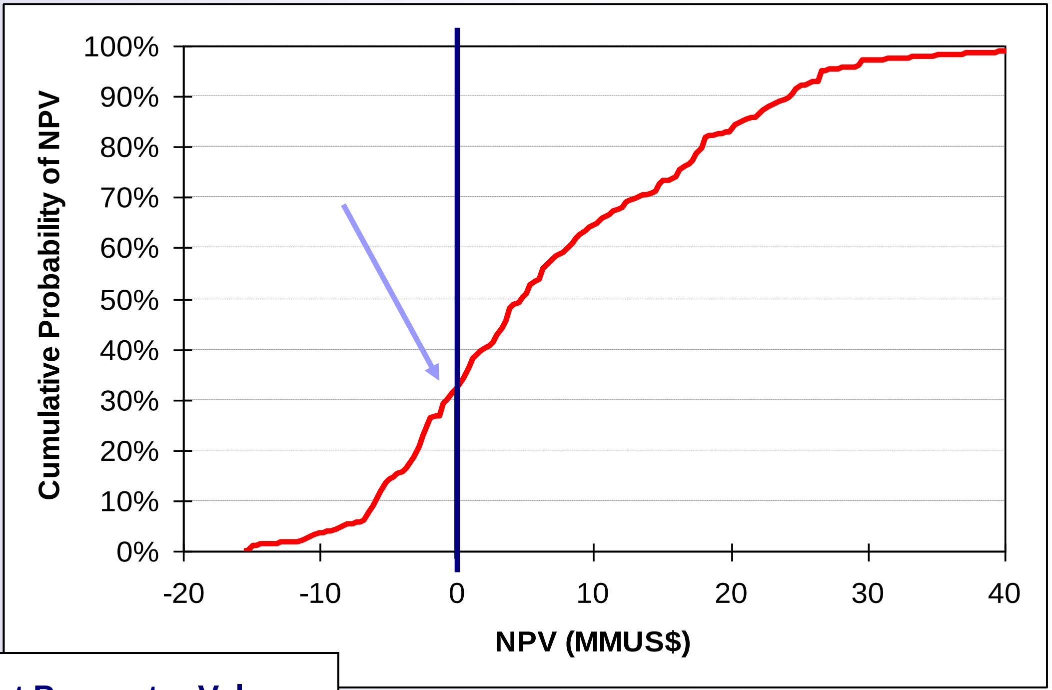
Figure 1.2
Forecasts of oil prices compared with actual prices. Notice how expert estimates failed to anticipate reality, even in the short run.
Source: U.S. Department of Energy, compiled by M. Lynch.

6) Results: Sensitivity Analysis



Uncertain Variables	Assumed Value	Range
Oil Price (US$/bbl)	35.00	17.50 – 52.50
Oil Production (bbl/year)	182,500	91,250 – 273,750
CapEX (MMUS$/t$CO_2$)	21.00	10.50 – 31.50
CO_2 Purchase (US$/t$CO_2$)	12.00	6.00 – 18.00
OpEx Compression (US$/t$CO_2$)	7.50	3.75 – 11.25
OpEx Transportation (US$/ t$CO_2$	0.50	0.25 – 0.75
OpEx Storage (US$/t$CO_2$)	3.00	1.50 – 4.50
Credits (US$/ t$CO_2$)	10.00	5.00 – 15.00

6) Results - Risk Analysis



Uncertainties

Uncertain Variables	Distribution	Input Parameter Values
Oil Price (US$/bbl)	lognormal	mean = 35; sd= 10%
Amount of CO_2 Injected (t)	triangular	150; 200; 250
Storage factor (%)	normal	mean = 50%; sd= 10%
Discount rate (%)	lognormal	mean = 12%; sd = 4%
CO_2 Credits (US$/t)	lognormal	mean =10; sd = 5%
Opex Transp. (US$/t)	triangular	0.3; 0.5; 1.5
Opex Compression (US$/t)	triangular	6; 7.5; 9
Opex Storage (US$/t)	triangular	1.5; 3; 4.5
Opex Treatment (US$/t)	triangular	10; 12; 18

7) Conclusions (I)

- CO_2 sequestration ⟹ efficient tool to control greenhouse gas emissions into the atmosphere.

- Costs and CO_2 LCA.

- Some variables minimize the energy usage.

- EOR highly energy intensive

- Optimize strategies to maximize CO_2 storage with the same or even increased oil production.

7) Conclusions (II)

- ↑ Oil prices stimulate investments in CO_2 sequestration with EOR.

  ↓ CO_2 credits ⇒ do not influence the NPV strongly.

  EOR, even without credits, CO_2 sequestration is economical.

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Technical-Economic Modeling of CO_2 Sequestration considering Injection in Mature Oilfields

Ana Teresa F. S. Gaspar Ravagnani

4) Methodology: Energy for Transportation

Fluid Velocity

$$v = \frac{Q}{A \times \rho}$$

Reynolds Number

$$\mathrm{Re} = \frac{\rho \cdot v \cdot d}{\mu}$$

Re < 2,1*10^3 → laminar flow
Re > 2,1*10^3 → turbulent flow

f

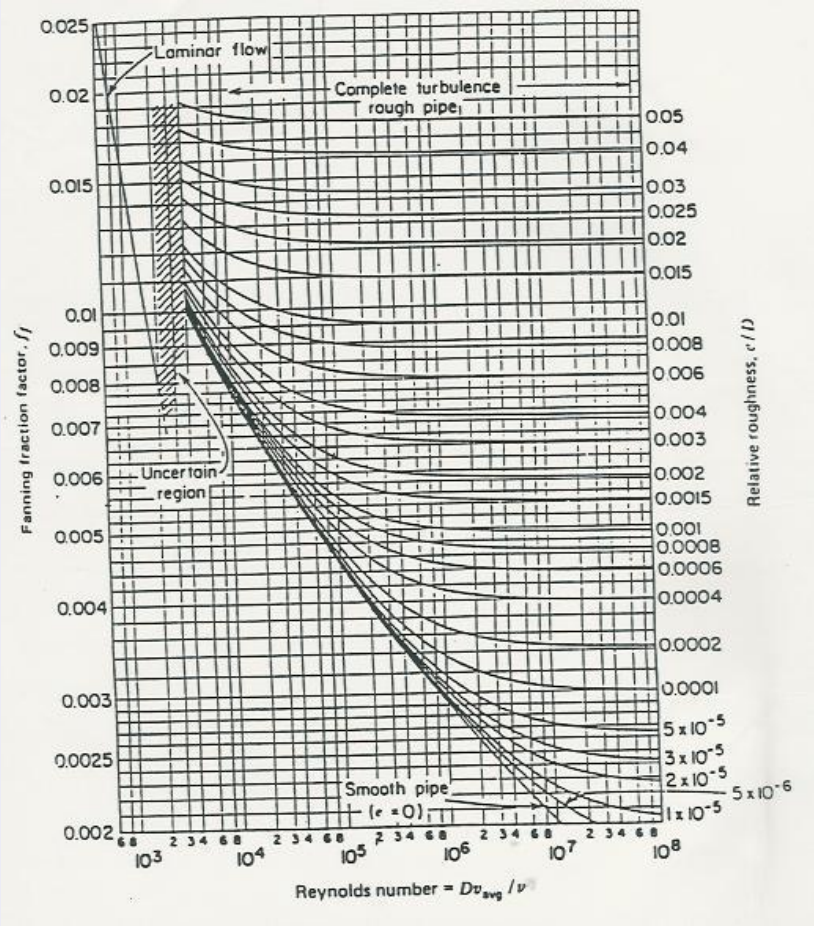
Pressure Drop

$$\Delta P = 2 * f * \rho * v^2 * \frac{L}{d}$$

Bernoulli Equation

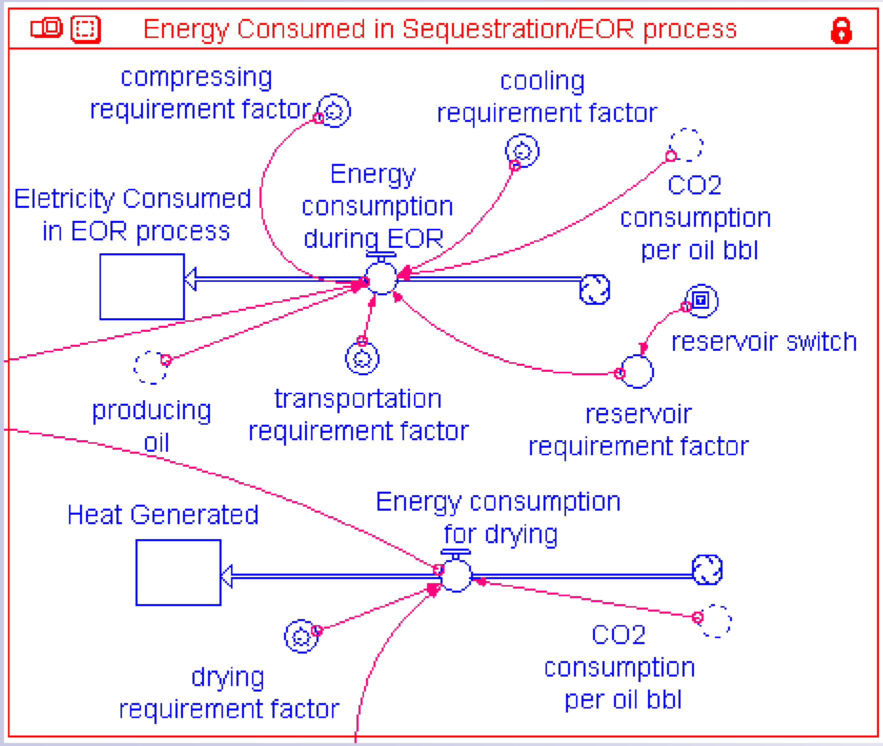
$$W = \frac{\Delta P}{\rho}$$

Fanning friction factor diagram



Source: Welty et al, 1984

4) Methodology: Energy Requirements



Compression Ratio

$$\frac{P_i}{P_{i-1}} = \left(\left(\frac{P_n}{P_0}\right)^{\frac{1}{n}} \right)$$

3 Stages

P_o = 40 / P_1 = 127.6 / P_2 = 407 / P_3 = 1,300 psi

T = 50ºC

(Stationary, Adiabatic, Reversible state)

Each Stage

Mass Balance

$$\dot{M}_{in} + \dot{M}_{out} = 0$$

$$\dot{M}_{in} = -\dot{M}_{out} = -\dot{M}$$

Energy Balance

$$\dot{M}_{in}\hat{H}_{in} + \dot{M}_{out}\hat{H}_{out} + \dot{W} = 0$$

$$\dot{W} = \dot{M}(\hat{H}_{out} - \hat{H}_{in})$$

Entropy Balance

$$\dot{M}_{in}\hat{S}_{in} + \dot{M}_{out}\hat{S}_{out} = 0$$

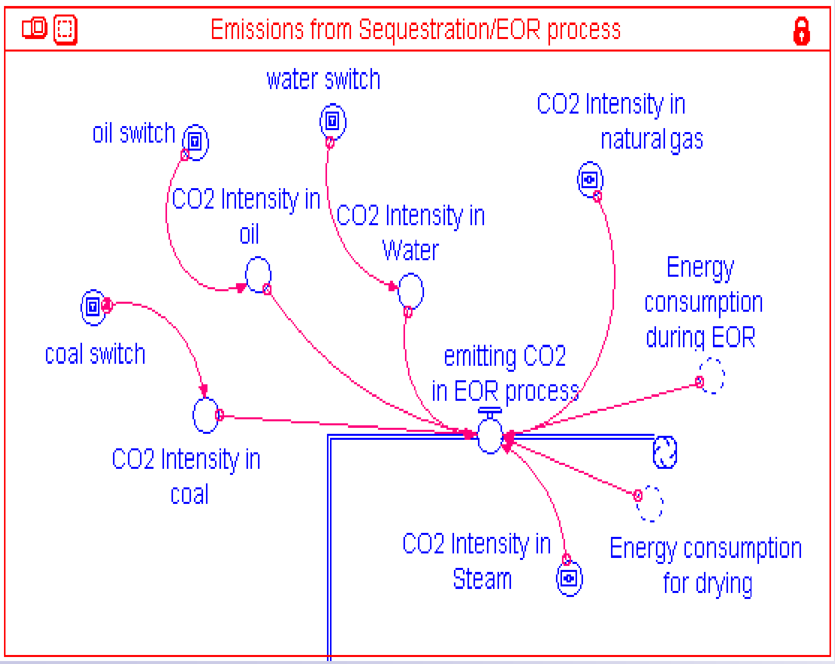
$$\hat{S}_{out} = \hat{S}_{in}$$

CO_2 Pressure-Enthalpy Diagram (Mollier)

4) Methodology: CO_2 Emissions

INDIRECT

Sequestration/EOR Process

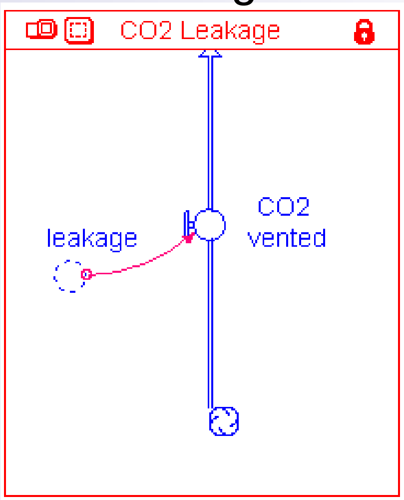


Emissions (electricity) =
Specific emission x Energy consumed

	Emission Factor
Electricity	**51 kg-CO_2/GJ (natural gas)**
Heat	**62 kg-CO_2/GJ (steam)**

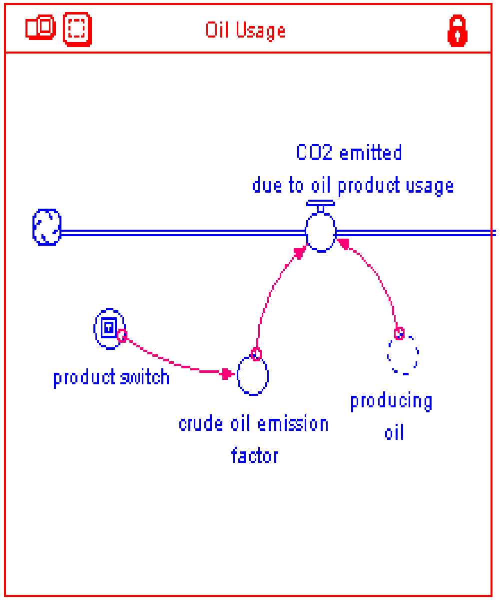
DIRECT

Leakage



Emissions =
0.005 x Total CO_2 Injected

Product Usage



Emissions =
Crude oil emission factor
x
Oil produced

CO_2 content in Oil	**73.3 t/TJ**
Energetic Content	**5.95 GJ/bbl**
Emission Factor	**0.436 tCO_2/bbl**