Advanced CO_2 capture technology: Current development and Outlook

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Annual ATPAC-MOST-OHEC-IPST Conference

January 27th 2017

What is RTI International?

RTI is an independent, nonprofit institute that provides research, development, and technical services to government and commercial clients worldwide.

Our mission is to improve the human condition by turning knowledge into practice.

Global Presence – Workforce

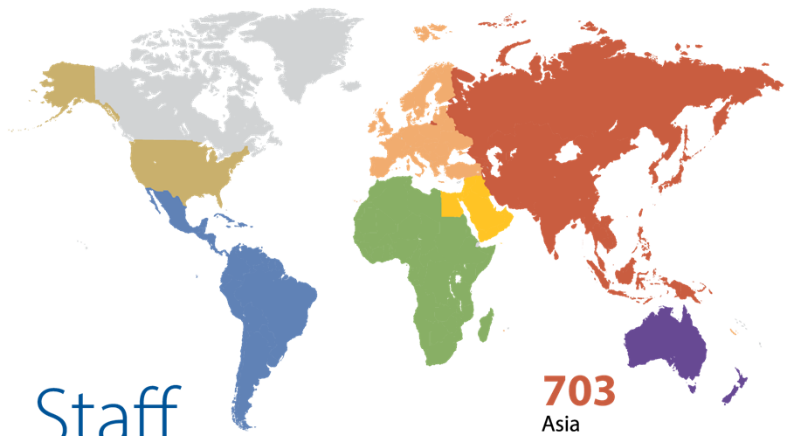
32 Fellows

250 Degree Fields

90 Languages

105 Nationalities

4,723 Staff Members Worldwide



Staff By Region

3,036 United States

101 Latin America and the Caribbean

754 Africa

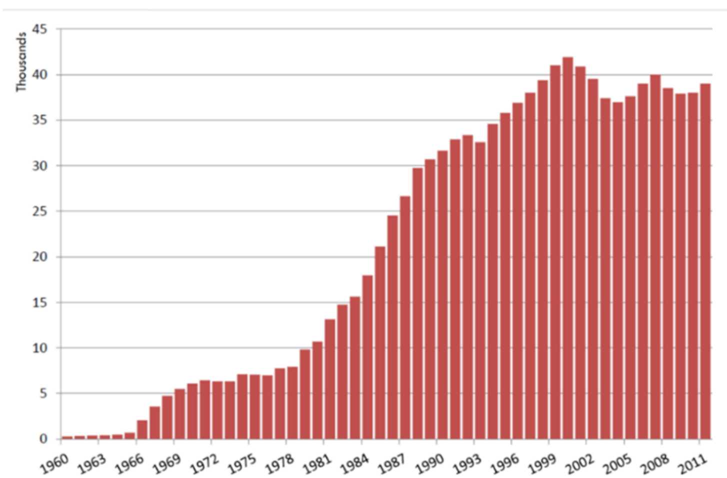
703 Asia

75 Europe

52 Middle East

2 Australia

RTP’s Economic Transformation: Critical Success Factors



Job Growth in RTP 1960 - 2011

- Three tier 1 research universities
- Largest research park and innovation ecosystem in the US
- A history and culture of effective collaboration
- An early adopter approach and culture
- Flexibility to encourage industry growth at convergence points
- A steady pipeline of talent
- Stable government policies and business climate

How to Build an Innovation Ecosystem

How do we create a culture of entrepreneurship that increases chances of long-term success?
Foster Effective Entrepreneurship Programs

How can a government strengthen its policy tools to effectively foster growth in its innovation economy?
Creating Policy Infrastructure for Innovation

How do we better align university output with industry needs to produce market-ready technologies and job-ready graduates?
Strengthen University-Industry Alignment

How do we match our innovation assets with sectors primed for rapid and sustained growth in global markets?
Identify Industry Sectors for Growth

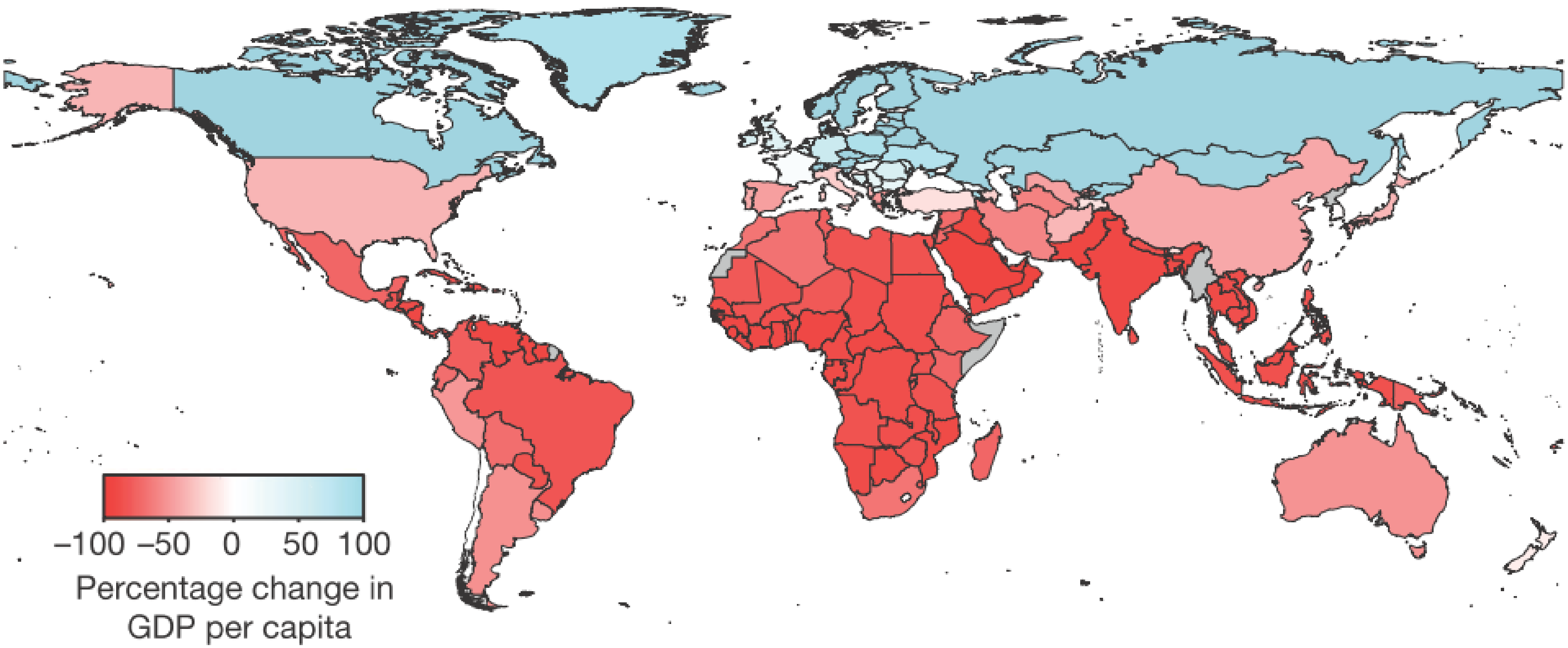
How do Small & Medium Enterprises with limited resources find and adopt technologies and processes so that they can grow and thrive?
Drive Technology Adoption in SMEs

How do we know what's working? How do we build on success? What should we invest in next?
Assess Initiatives for Effectiveness & Impact

How do we produce a skilled workforce in in the right numbers and with the right qualifications to propel high-value industries?
Develop an Innovation-Ready Workforce

How do we convert R&D investments into commercially valuable new products, processes and services?
Accelerate Technology Commercialization

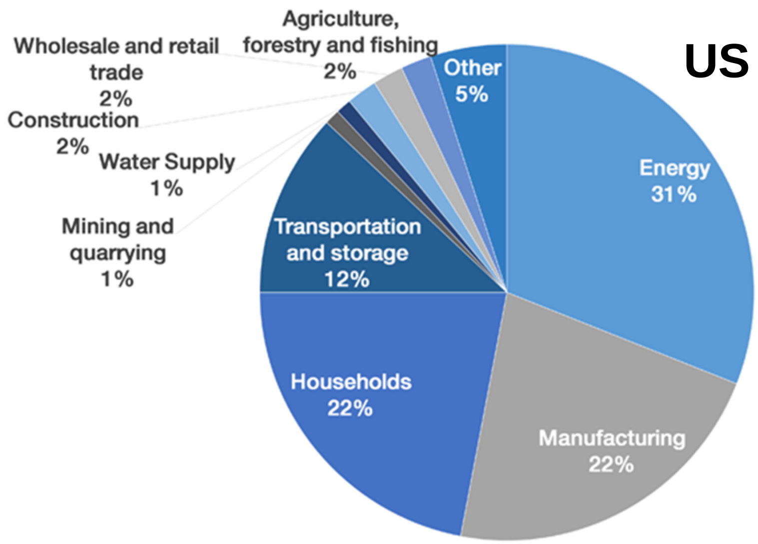
Driving force: Economic Impact



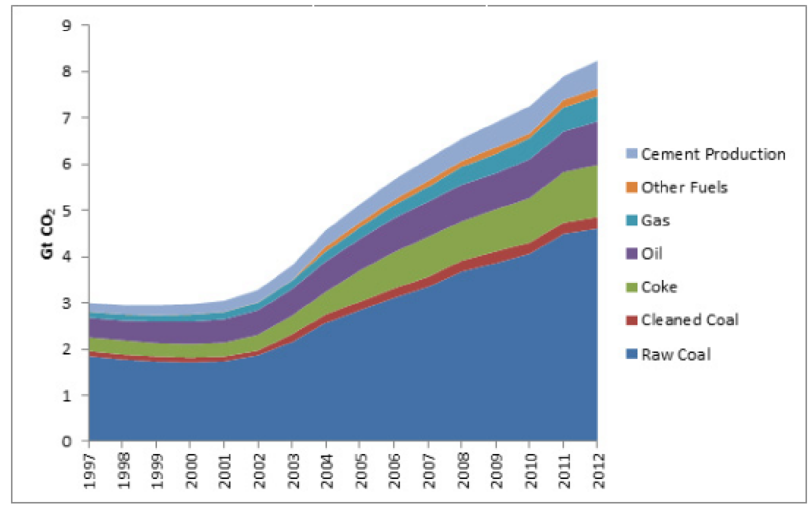
www.nature.com/nature/journal/v527/n7577/full/nature15725.html

Emission Data by Sources/Sectors

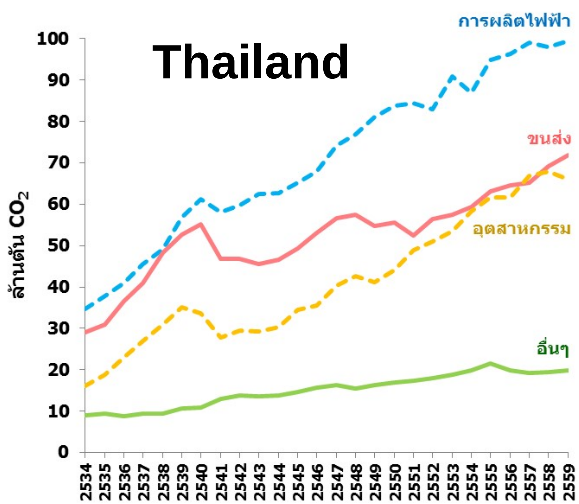
US



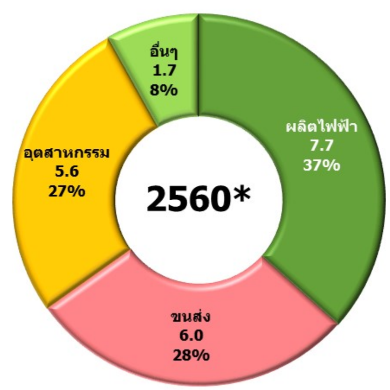
China



Thailand



สัดส่วนการปล่อยก๊าซ CO_2
จากการใช้พลังงาน รายสาขาเศรษฐกิจ



รวมทั้งสิ้น 21.0 ล้านตัน CO_2

* เดือน ม.ค.

Focused sectors:
- Power production
- Cement and Iron production
- Petrochemicals

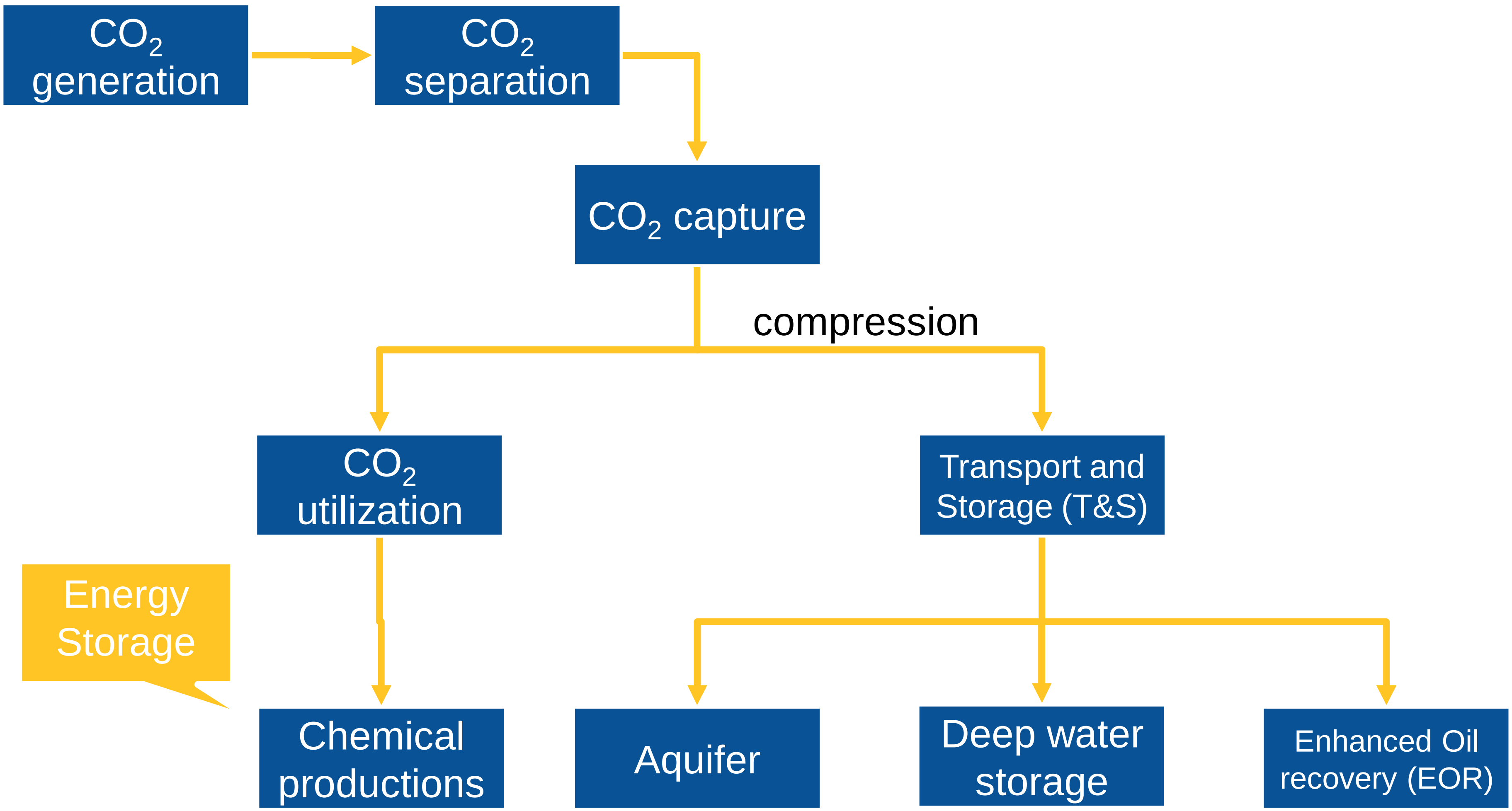
https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf

http://www.belfercenter.org/sites/default/files/legacy/files/carbon-emissions-report-2015-final.pdf

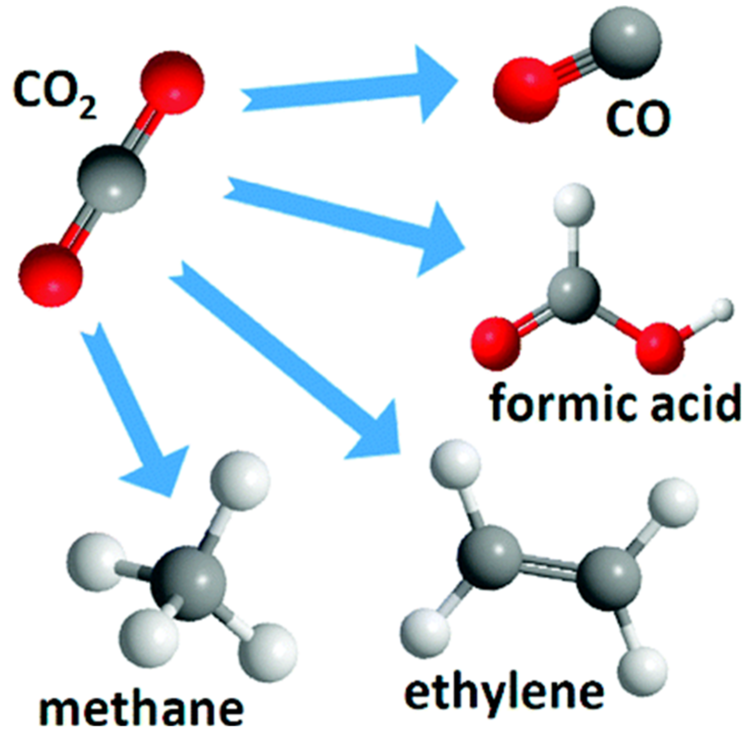
http://www.eppo.go.th/index.php/en/en-energystatistics/co2-statistic?orders[publishUp]=publishUp&issearch=1

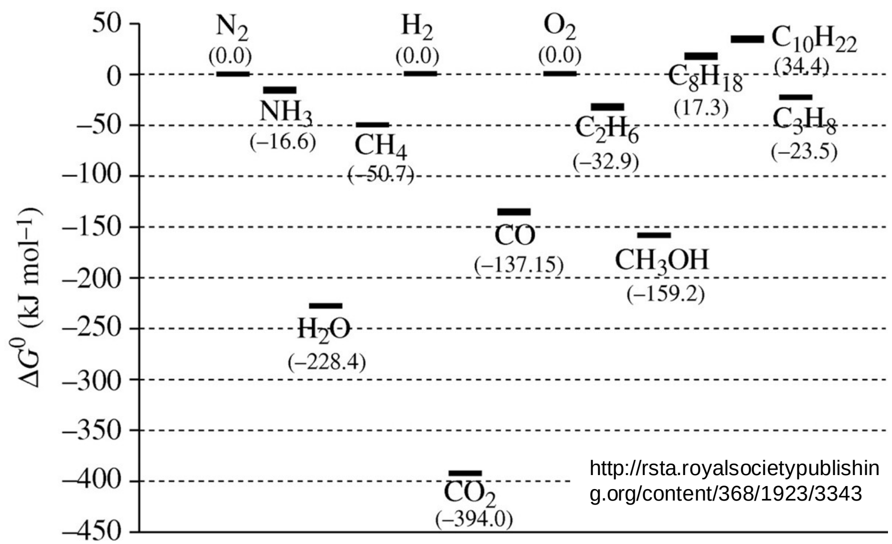
A Solution

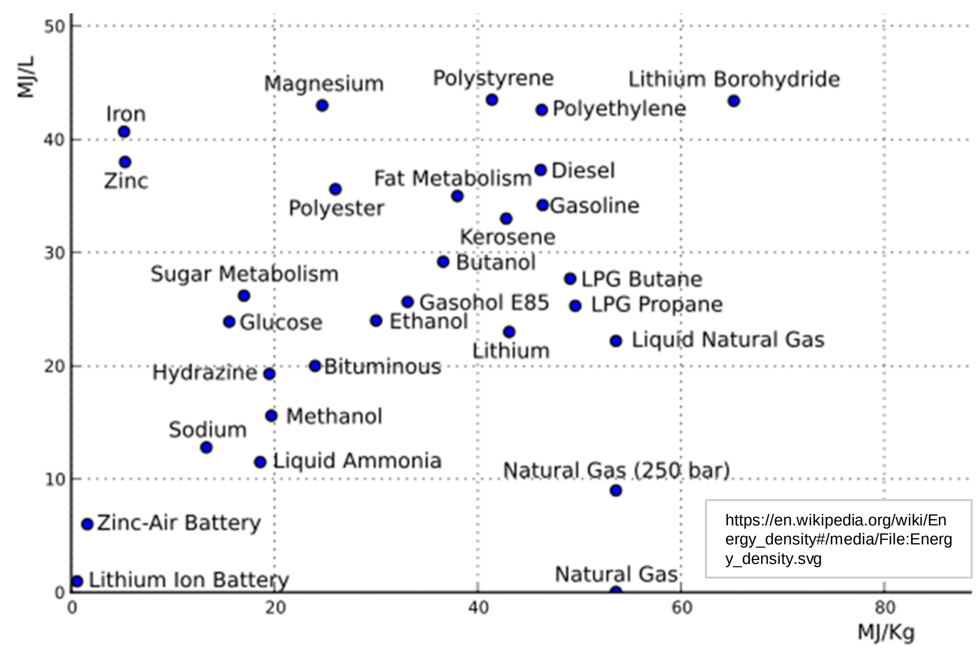
Current solution for static point sources



CO_2 Utilization: Energy Storage



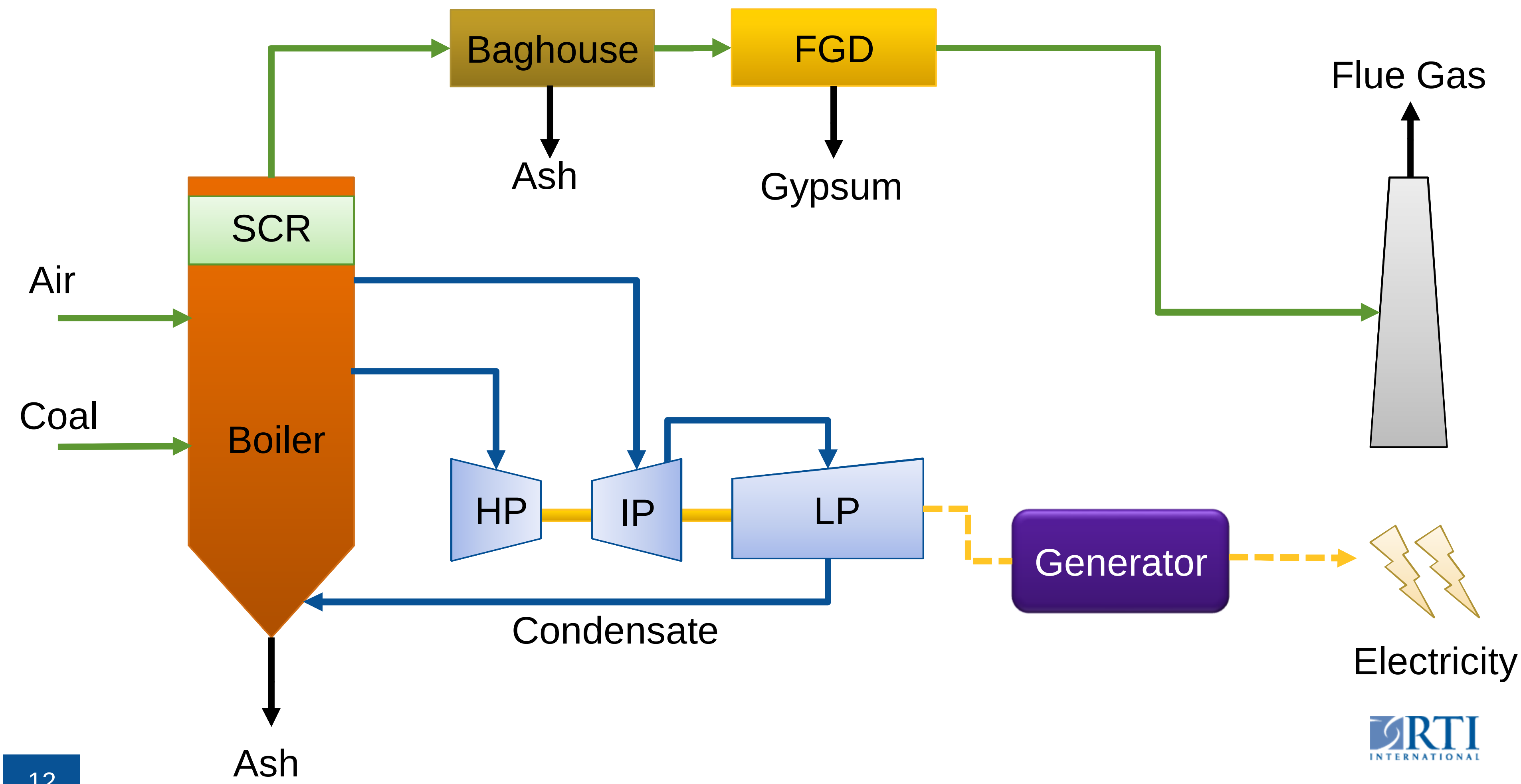




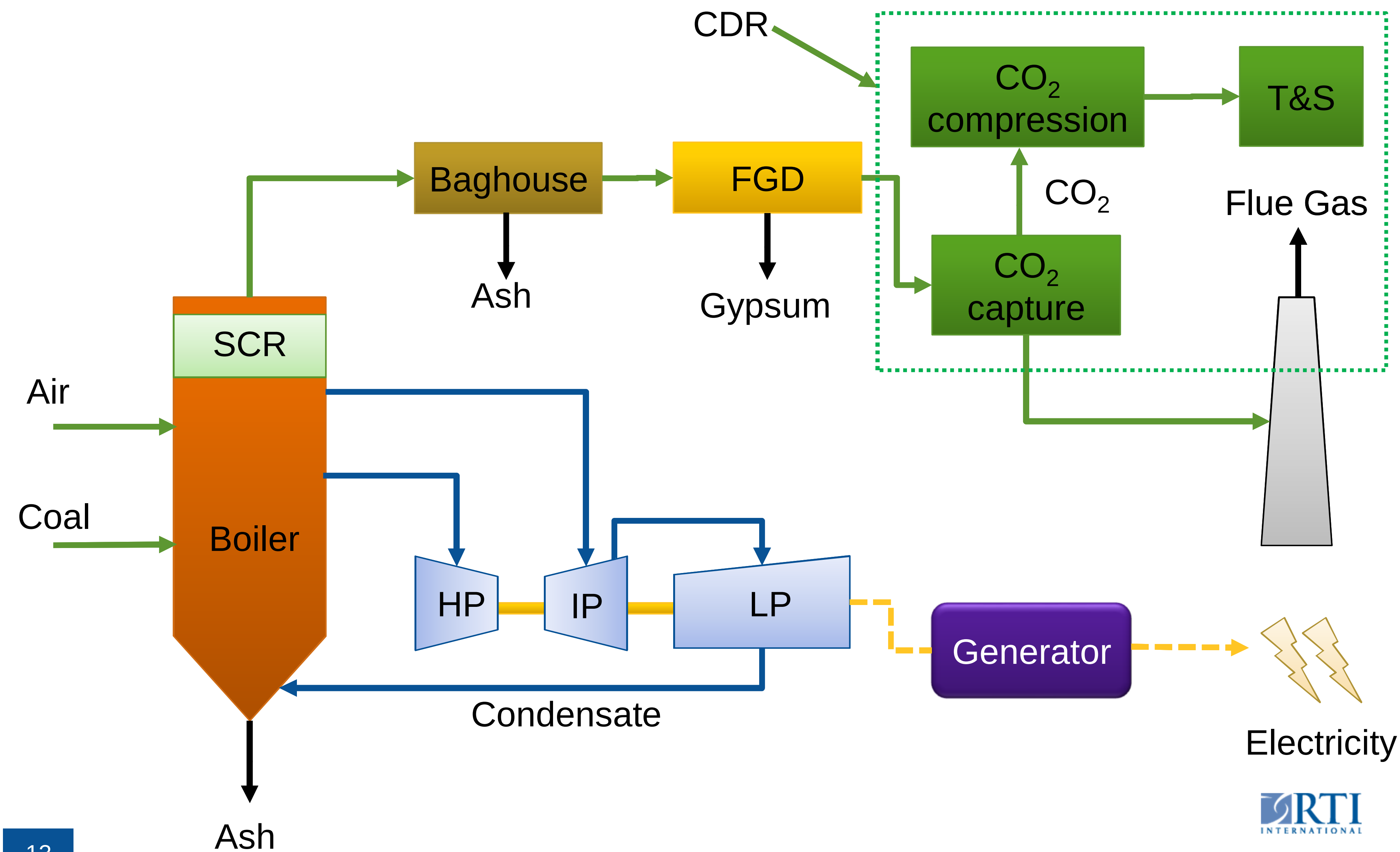
- Electricity from alternative energy sources (wind, solar, hydro)
- Assist in balancing power plant load
- More flexibility in usage:
  - Chemical production
  - Fuel/additive
  - Energy Storage


The Power Plants

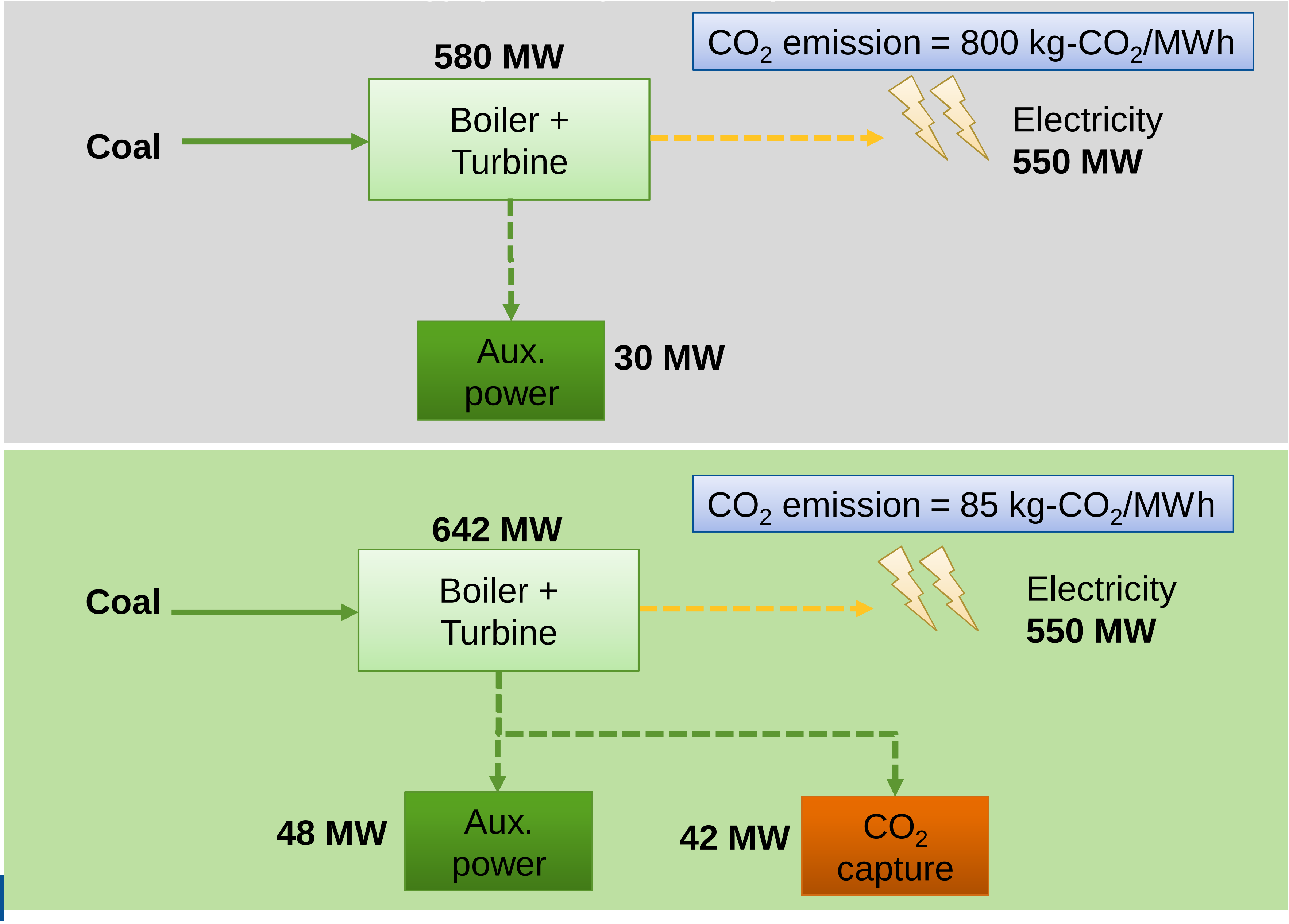
Pulverized-coal power plant process diagram (PCCC)



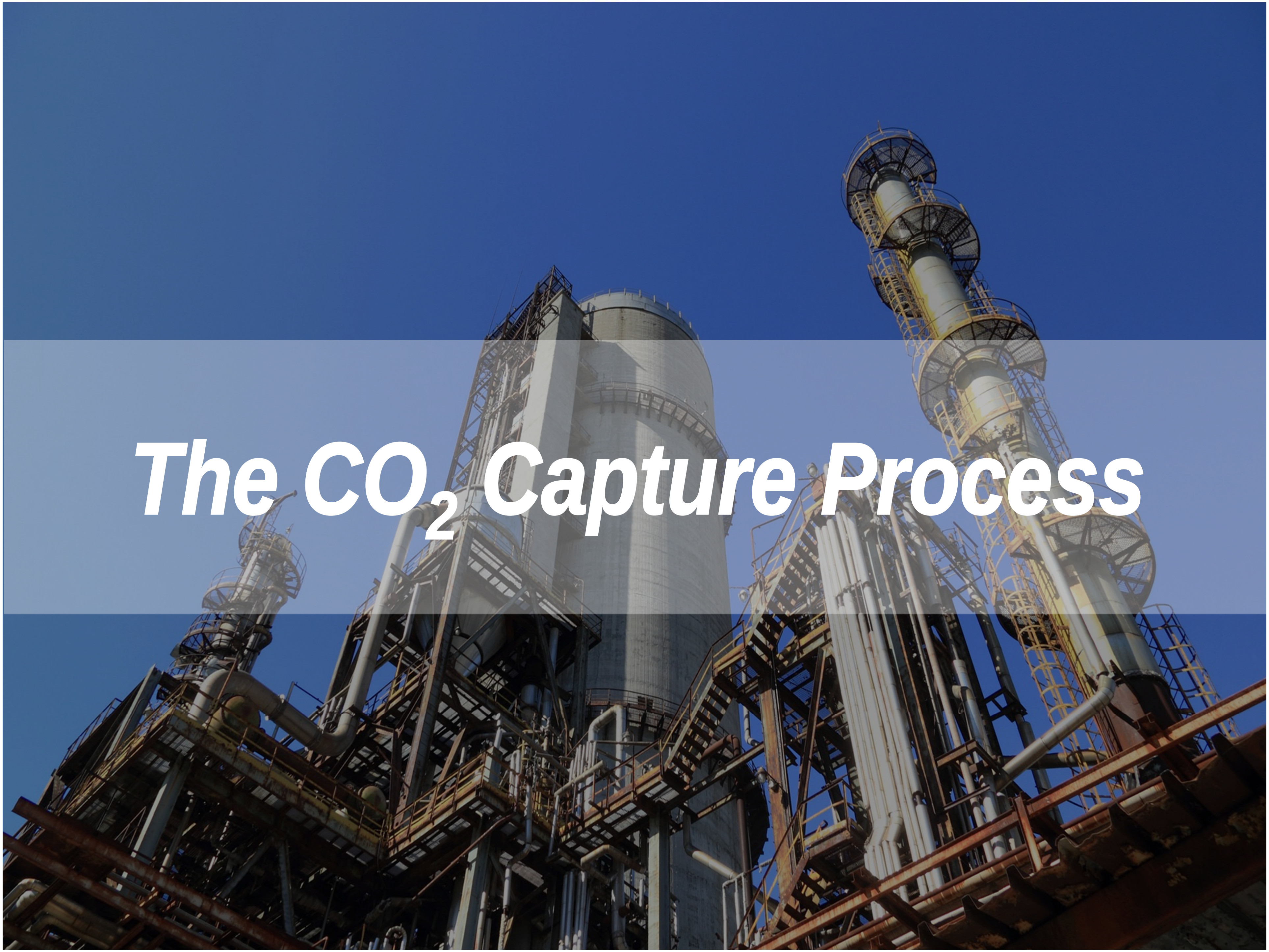
Pulverized-coal power plant process diagram (PCCC)



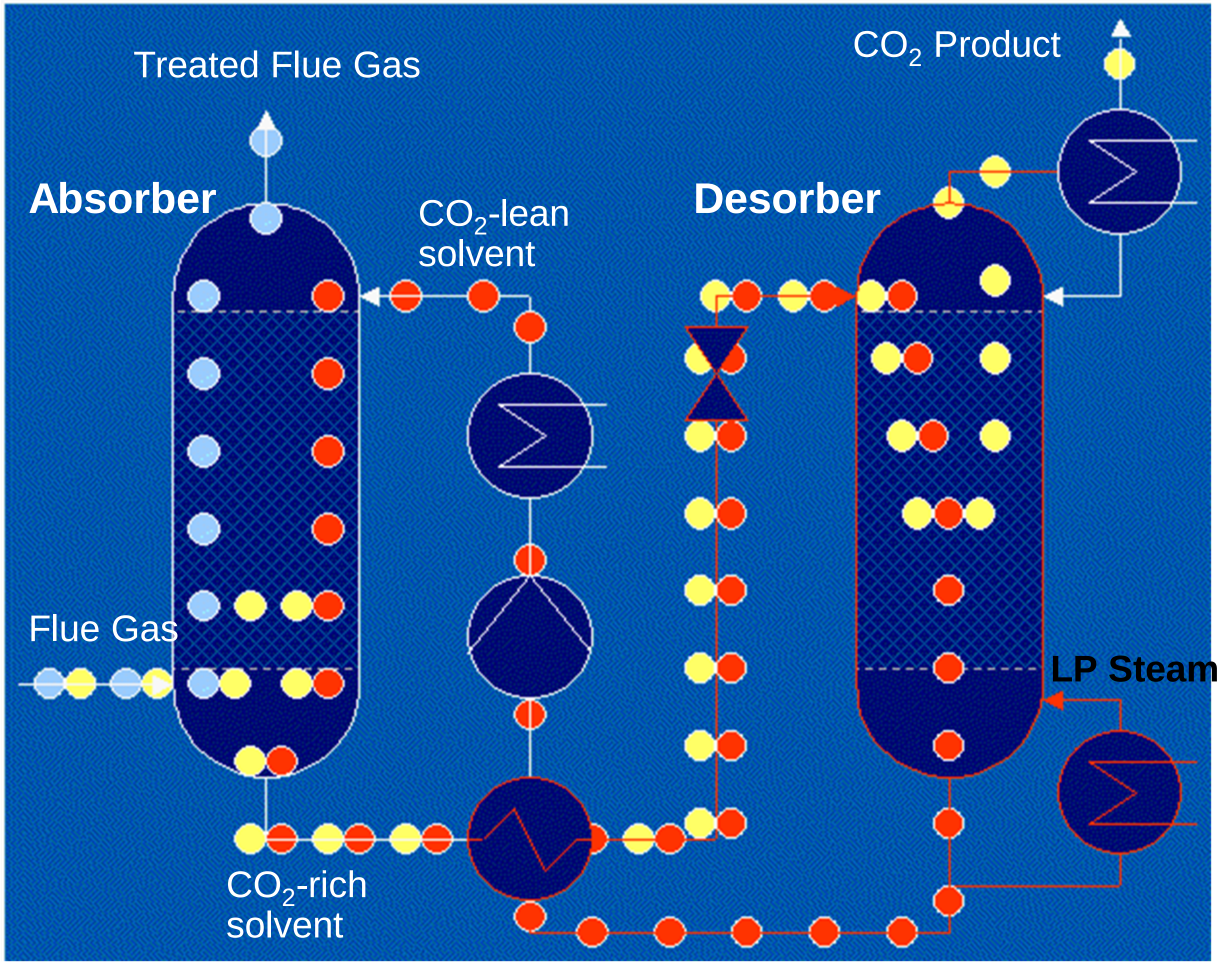
Energy penalty and impact on PCCC



The CO_2 Capture Process



CO_2 capture process – solvent



- Flue Gas
- CO_2
- **Solvent**

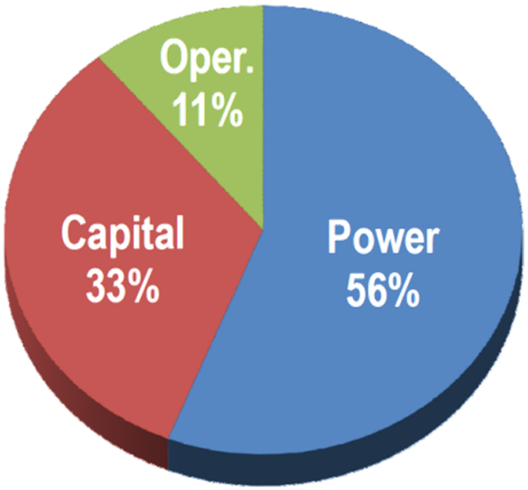
R&D Strategic Approach

Minimize reboiler heat duty

Breakdown of the Thermal Regeneration Energy Load

$$q_R = \left[\frac{C_P(T_R - T_F)}{\Delta\alpha} \cdot \frac{M_{sol}}{M_{CO_2}} \cdot \frac{1}{x_{sol}}\right] + \left[\Delta H_{V,H_2O} \cdot \frac{p_{H_2O}}{p_{CO_2}} \cdot \frac{1}{M_{CO_2}}\right] + \left[\frac{\Delta H_{abs,CO_2}}{M_{CO_2}}\right]$$

Reboiler Heat Duty | Sensible Heat | Heat of Vaporization | Heat of Absorption

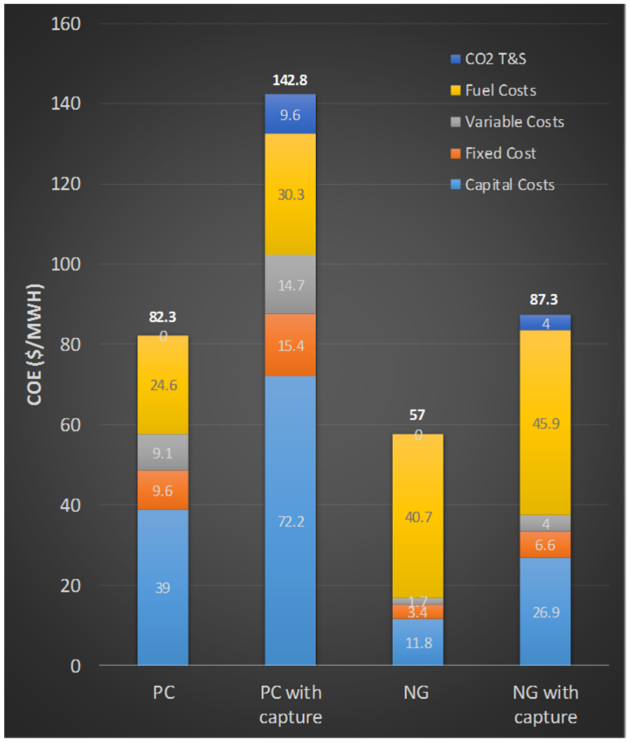


Solvent	C_p [J/g K]	Δh_{abs} [kJ/mol]	Δh_{vap} [kJ/mol]	X_{solv} [mol solv./ mol sol'n]	$\Delta\alpha$ [mol CO_2/ mol solv.]	Reboiler Duty [GJ/tonne CO_2]
MEA (30%)	3.8	85	40	0.11	0.34	3.22
Lower Energy Solvent System	↓	↓	↓	↑	↑	↓

[1] Rochelle, G. T. Amine Scrubbing for CO_2 Capture. *Science* **2009,** 325, 1652-1654.

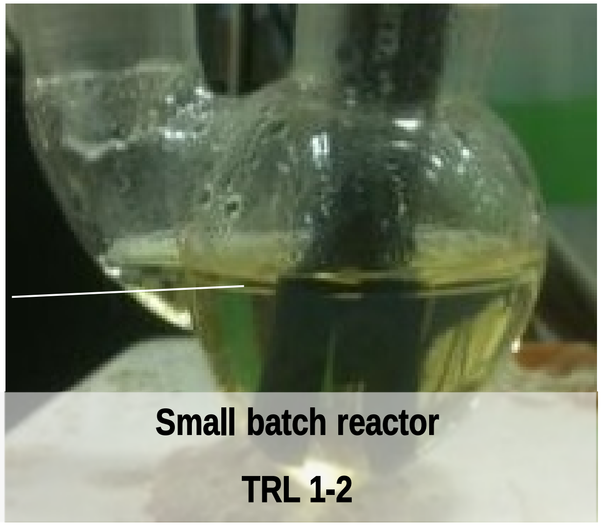
Cost Summary

http://www.nrg.com/generation/projects/petra-nova/



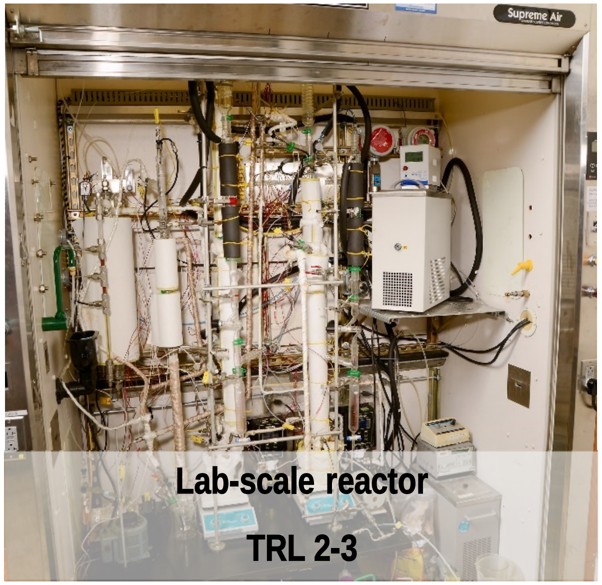
The Non-Aqueous Solvent

R&D through Technology Readiness Level (TRL)



Small batch reactor

TRL 1-2



Lab-scale reactor

TRL 2-3

Bench-scale reactor (1 kW)

TRL 3

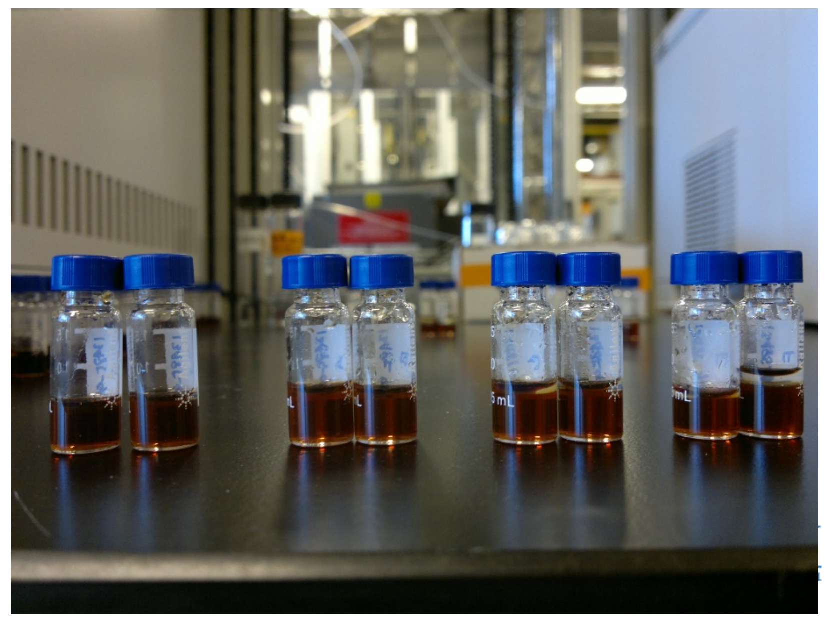
Pilot scale (50 kW)

TRL 4

RTI's Non-Aqueous solvent (NAS)

RTI evaluates wide range of low-cost, commercially-produced amines with the following characteristics:

- Low water solubility
- Low heat of absorption
- High working capacity
- Low regeneration temperature
- Low specific heat capacity
- Low heat of vaporization
- Low water solubility



Solvent Development – Current Optimization

$$q_R = \left[\frac{C_P(T_R - T_F)}{\Delta\alpha} \cdot \frac{M_{sol}}{M_{CO_2}} \cdot \frac{1}{x_{sol}}\right] + \left[\Delta H_{V,H_2O} \cdot \frac{p_{H_2O}}{p_{CO_2}} \cdot \frac{1}{M_{CO_2}}\right] + \left[\frac{\Delta H_{abs,CO_2}}{M_{CO_2}}\right]$$

Reboiler Heat | Sensible Heat | Heat of Vaporization | Heat of Reaction

Solvent	C_p [J/g K]	Δh_{abs} [kJ/mol]	Δh_{vap} [kJ/mol]	X_{solv} [mol solv./ mol sol'n]	$\Delta\alpha$ [mol CO_2/ mol solv.]	Reboiler Duty [GJ/tonne CO_2]
MEA (30%)	3.8	85	40	0.11	0.34	3.22
Lower Energy Solvent System	↓	↓	↓	↑	↑	↓
NAS	2.1-2.5	40-85	-	0.4	0.2-0.3	1.9-2.5

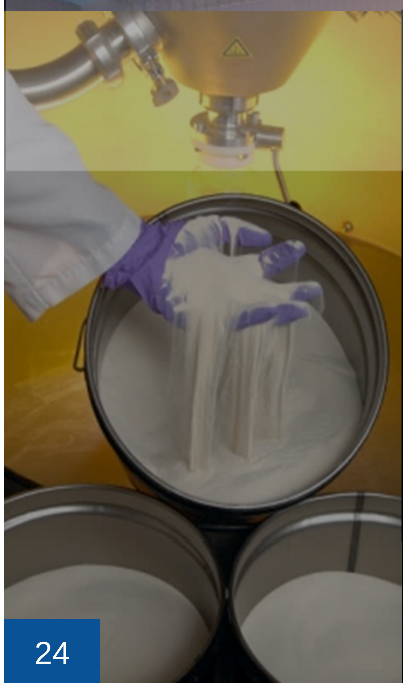
Other operating parameters:
- Low rate of degraded products formation
- Reduce solvent emission and enhance amine recovery by wash section
- Regeneration under moderate pressure
- Optimize column configurations for NAS with holistic evaluation of impact on ICOE

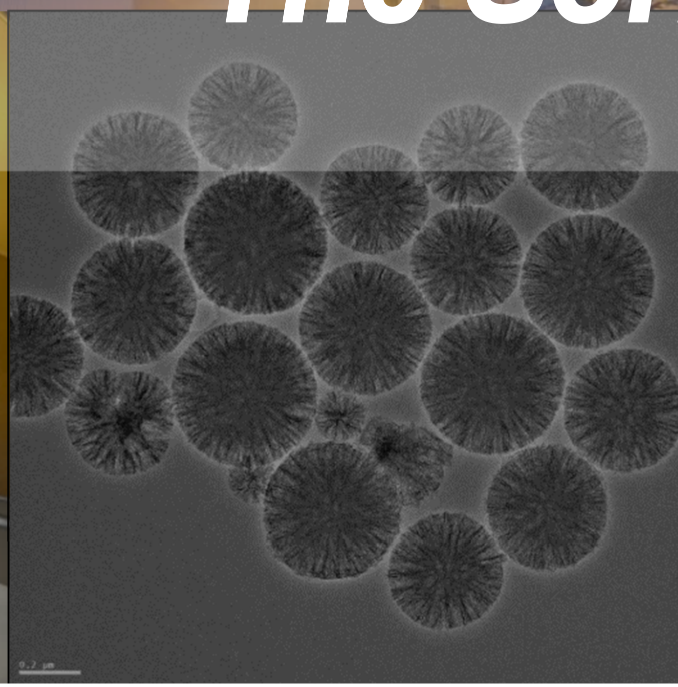
Economic evaluation: NAS vs. base cases

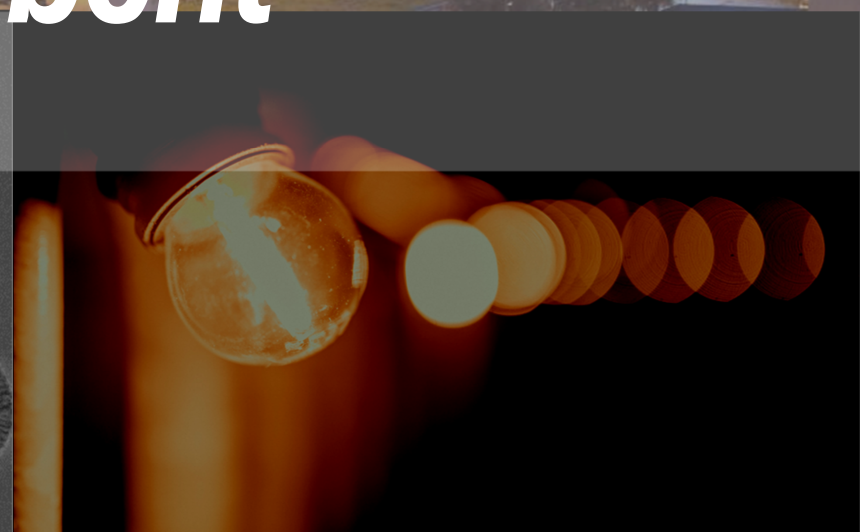
	Base Case 1	Base Case 2	Case 1	Case 2	Case 3
Description	No Capture (DOE Case 11)	CO_2 Capture (DOE Case 12) using 30Wt % MEA	RTI NAS @HP optimized	10% CAPEX increase due to EC	RTI NAS w/EC @HP optimized NOAK
Solvent		MEA	NAS	NAS	NAS
SRD (GJ/t-CO_2)		3.6	1.9	1.9	1.9
Regenerator pressure (bar)		1.6	4.4	4.4	4.4
Coal flow rate (lb/hr)	409,528	565,820	495,610	495,610	495,610
Gross power output (kWe)	580,400	662,800	637,350	637,350	637,350
Aux. power req. (kWe)	30,410	112,850	87,350	87,350	87,350
Net power output (kWe)	549,990	549,950	550,000	550,000	550,000
Net plant HHV efficiency (%)	39.28%	28.43%	32.46%	32.46%	32.46%
Power plant cost ($MM)	1,090	1,361	1,250	1,250	1,250
CO_2 capture cost ($MM)		506	243	267	267
CO_2 compression cost ($MM)		88	58	58	58
TPC ($MM)	1,090	1,955	1551	1575	1575
TOC ($MM)	1,349	2,409	1917	1946	1946
Total OPEX ($MM)	199.1	297.6	254.8	255.9	255.9
COE, excl CO_2 TS&M, mills/kWh	83.7	137.2	113.0	114.0	110.3
Cost of CO_2 Capture ($/t-$CO_2$)[a]		**56.45**	**36.72**	**37.83**	**33.59**

Note: @HP = High Pressure; COE = Cost of Electricity; EC = emissions control; HHV = High Heating Value; NOAK = n^{th}-of-the-kind;
TOC =Total Overnight Cost; TPC = Total Plant Cost; TS&M = Transport, Storage, and Monitoring.

The Sorbent





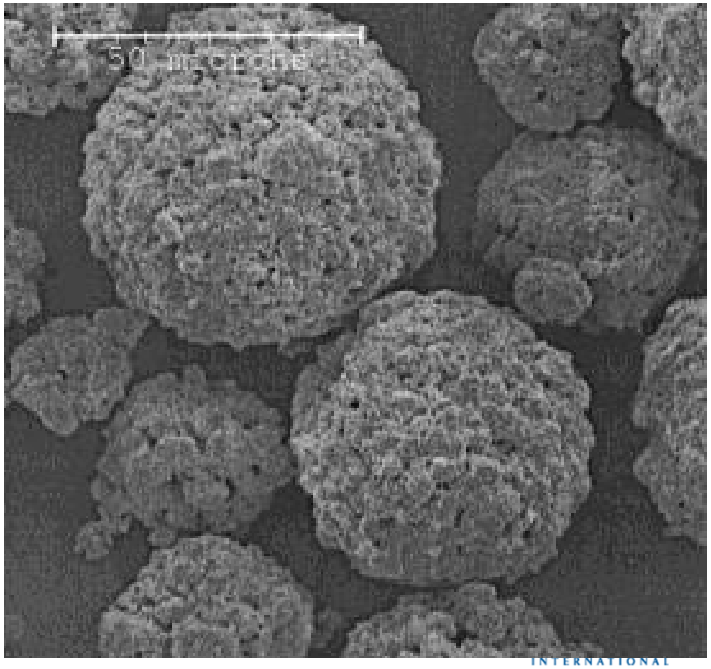


RTI's Solid Sorbent

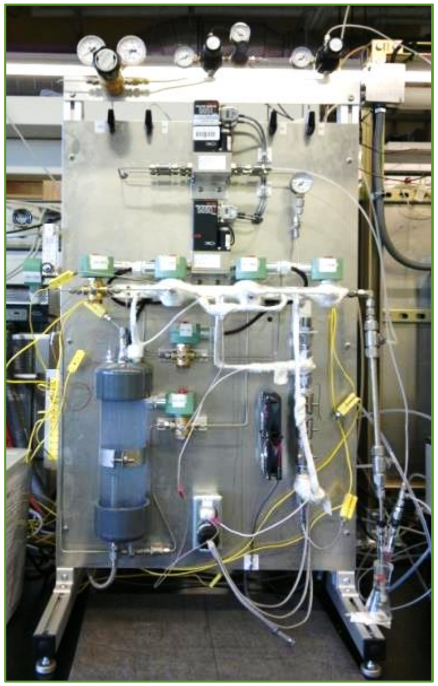
Objective: Address the technical hurdles to developing a solid sorbent-based CO_2 capture process by transitioning a promising sorbent chemistry to a low-cost sorbent suitable for use in a fluidized-bed process

RTI explores a non-conventional technology for the next generation CO_2 capture. The solid sorbent demonstrates several attractive features:

- High reaction surface area
- Low heat of absorption
- High working capacity
- Low specific heat capacity
- Low heat of vaporization



RTI's Solid Sorbent for CO_2 capture



Small batch reactor

TRL 1-2

Lab-scale reactor

TRL 2-3

Bench-scale reactor

TRL 3

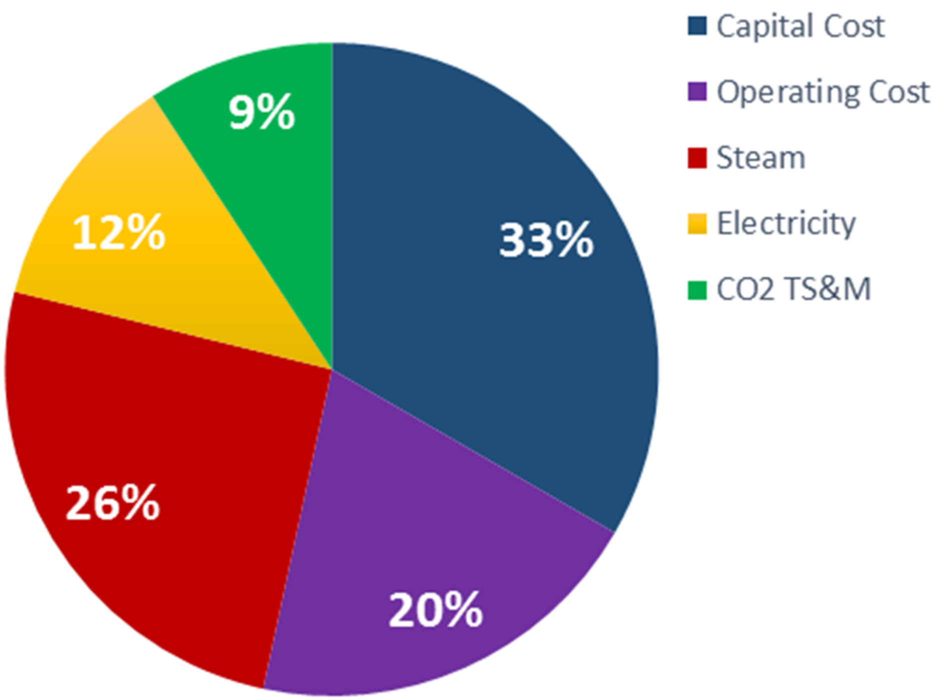
Pre-Pilot scale

TRL 4

Updated Economic Analysis

Summary

Breakdown of Main Contributors to Cost of CO_2 Captured



- ***Basis***: DOE/NETL's Cost and Performance Baseline for Fossil Energy Plants – **updated with lab and bench-scale test data**
- Total cost of CO_2 captured ~ **45.0 \$/T-CO_2**
- 43.3 \$/T-CO_2 achievable through use of unproven spent sorbent scrubbing strategy
- Represents **> 25% reduction** in cost of CO_2 capture, significant energy and capital savings compared to SOTA aqueous amine solvents

Main Factors impacting TEA

- Sorbent Cost
- CO_2 content in Regenerator
- Sorbent working capacity
- Regeneration temperature

Pathway to Cost Reductions

- Adsorber/Regenerator Design
- Heat recovery and integration
- Sorbent stability and cost

RTI INTERNATIONAL

Norcem-RTI Project Overview

Objective:

Demonstrate the technical and economic feasibility of RTI's advanced, solid sorbent CO_2 capture process in an operating cement plant

Period of Performance:

- 5/1/2013 to 12/31/2016

Location:

- Norcem's cement plant in Brevik, Norway

Project is structured in two phases:

Phase I

- Evaluate sorbent performance using simulated and actual cement plant flue gas (testing in Norway)
- Prove economic viability of RTI's technology through detailed economic analyses
- Develop commercial design for cement application

Phase II

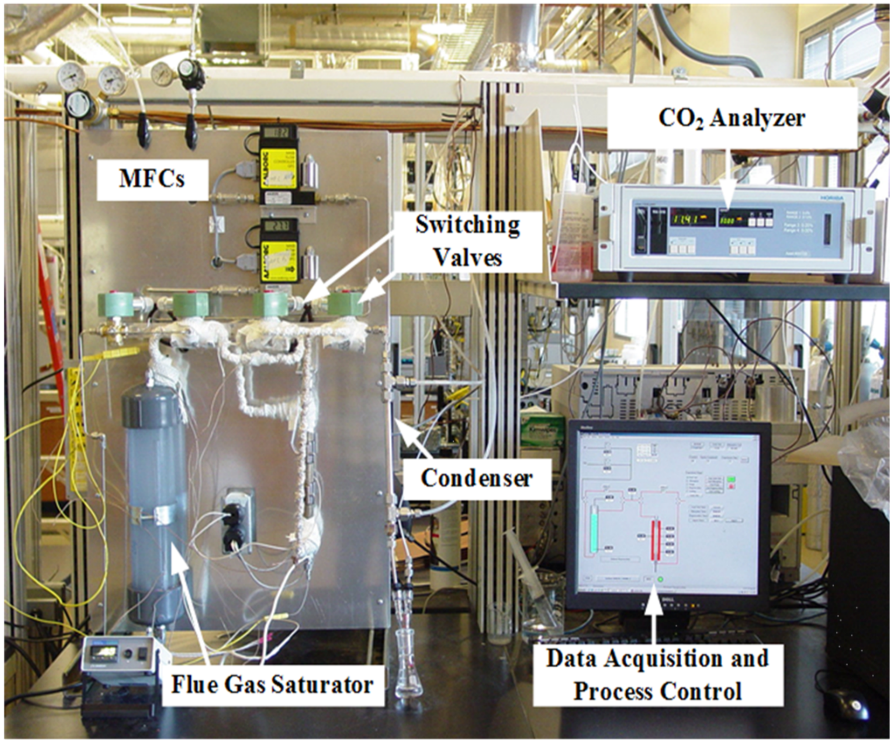
- Design, build, and test a pilot-scale system of RTI's technology at Norcem's Brevik cement plant
- Demonstrate long-term stability and effective CO_2 capture performance
- Update economic analyses with pilot test data

Norcem's Brevik Cement Plant

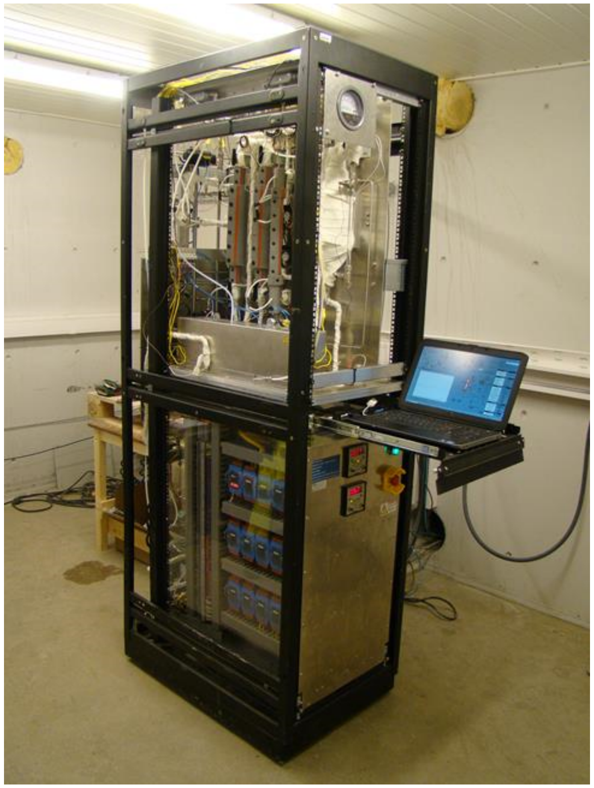
(Source: Norcem)

TRL 1-2 development and testing

RTI's Fully Automated, Packed-Bed Reactor System for multi-cycle CO_2 Capture-Regeneration Testing



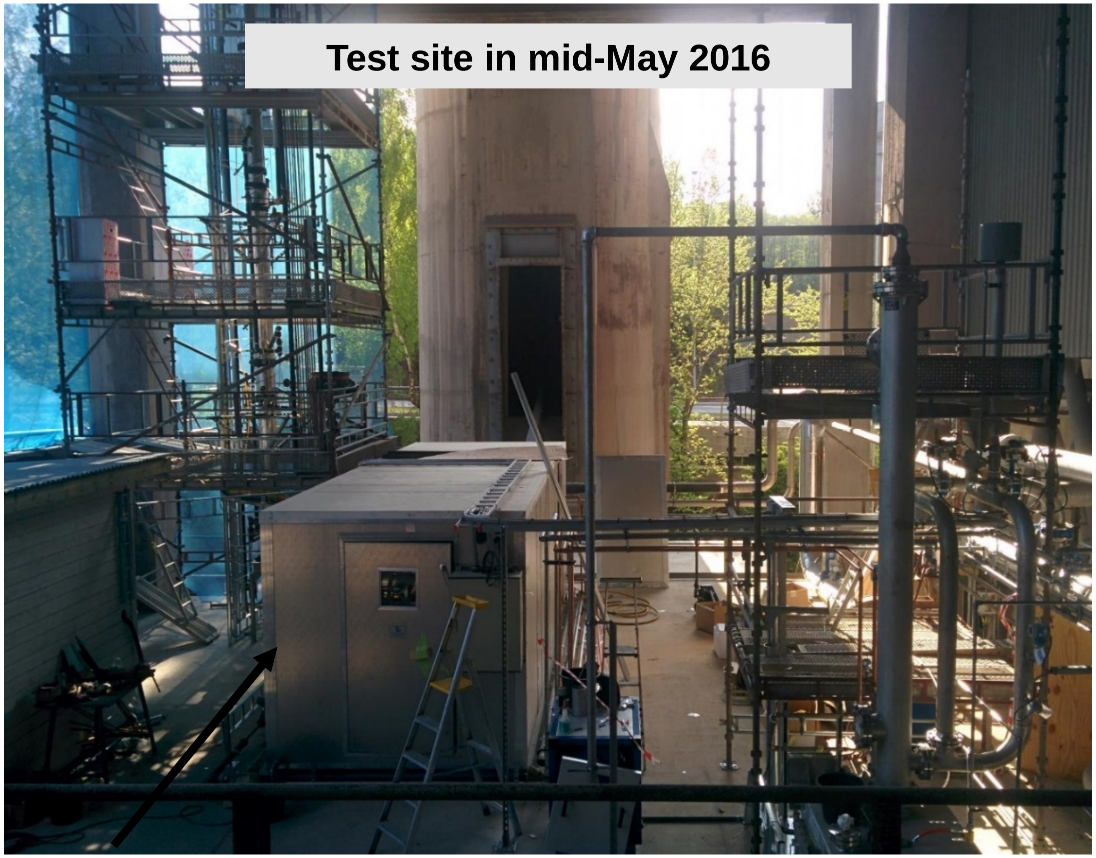
RTI's Automated Sorbent Test Rig (ASTR) installed at Norcem's cement production plant in Brevik, Norway



Measurables:
- Dynamic CO_2 loading capacity
- Rate of CO_2 loading on sorbent (wt%/min)
- Thermal waves due to absorption or desorption
- Pressure drop across packed bed

Capabilities:
- Fully-automated operation, data analysis
- Multi-cycle, absorption-regeneration experiments
- Comprehensive parametric evaluation and sorbent screening
- Long-term effect of contaminants

Pilot Installation and Commissioning



Pilot System specifications:

- Flue gas throughput: ~ 600 to 1,600 SLPM
- Sorbent inventory: ~ 80 kg
- Power: ~ 60 to 90 kWe
- Cooling water: 250 to 650 kg/h
- Additional utilities: steam; compressed air; waster disposal

Thailand 4.0

Current development direction for energy sector

- Focus on reduce energy consumption
  - National Energy Conservation Plan (NECP)
  - Alternative Energy Development Plan (AEDP)
- Replace coal and oil with biofuels/low carbon content fuels

ปรับปรุงข้อมูลล่าสุด วันที่ 31 พฤษภาคม 2560

NO	Type of CDM Project	Approved LoA		Registered		Issued CERs	
		NO (Project)	Expected CERs (tCO_2eq/y)	NO (Project)	Expected CERs (tCO_2eq/y)	NO (Project)	CERs (tCO_2eq)
โครงการประเภททั่วไปและควบรวม (Single and Bundling Project)							
1	ผลิตพลังงานไฟฟ้าจากก๊าซชีวภาพ	63	3,214,248	49	2,167,277	28	6,284,448
2	ผลิตพลังงานไฟฟ้าจากชีวมวล	39	2,130,414	26	1,158,150	6	692,860
3	ผลิตพลังงานไฟฟ้าจากลมร้อนทิ้ง	9	532,009	4	253,020	0	0
4	ผลิตพลังงานไฟฟ้าจากพลังงานแสงอาทิตย์	26	603,529	26	571,368	8	516,158
5	ผลิตพลังงานไฟฟ้าจากพลังงานน้ำ	6	192,234	6	198,918	2	37,527
6	ผลิตพลังงานไฟฟ้าจากพลังงานลม	4	409,968	3	326,010	0	0
7	ผลิตพลังงานไฟฟ้าจากเชื้อเพลิง RDF	1	31,116	0	0	0	0
8	ผลิตพลังงานความร้อนจากก๊าซชีวภาพ	19	1,006,015	10	500,046	4	349,289
9	ผลิตพลังงานความร้อนจากชีวมวล	3	210,829	0	0	0	0
10	ผลิตพลังงานไฟฟ้าและพลังงานความร้อนจากก๊าซชีวภาพ	29	2,200,478	17	1,154,748	9	2,956,876
11	ผลิตพลังงานไฟฟ้าและพลังงานความร้อนจากชีวมวล	1	18,150	0	0	0	0
12	ผลิตพลังงานไฟฟ้าและพลังงานความร้อนจากก๊าซธรรมชาติ	2	452,872	0	0	0	0
13	เพิ่มประสิทธิภาพพลังงาน	2	29,875	1	394,874	1	1,121,677
14	ผลิตปุ๋ยชีวภาพ	1	397,500	0	0	0	0
15	ลดการปล่อยก๊าซไนตรัสออกไซด์	1	168,887	1	142,402	1	300,151
16	ลดการปล่อยก๊าซจากการขุดเจาะเชื้อเพลิง	2	45,093	1	26,163	1	10,581
17	ลดการปล่อยก๊าซจากภาคขนส่ง	1	34,711	0	0	0	0
18	ลดการปล่อยก๊าซมีเทนจากการย่อยสลายสารอินทรีย์ในน้ำเสีย	3	281,894	3	273,982	1	115,136
รวม		212	11,959,822	147	7,166,958	61	12,384,703

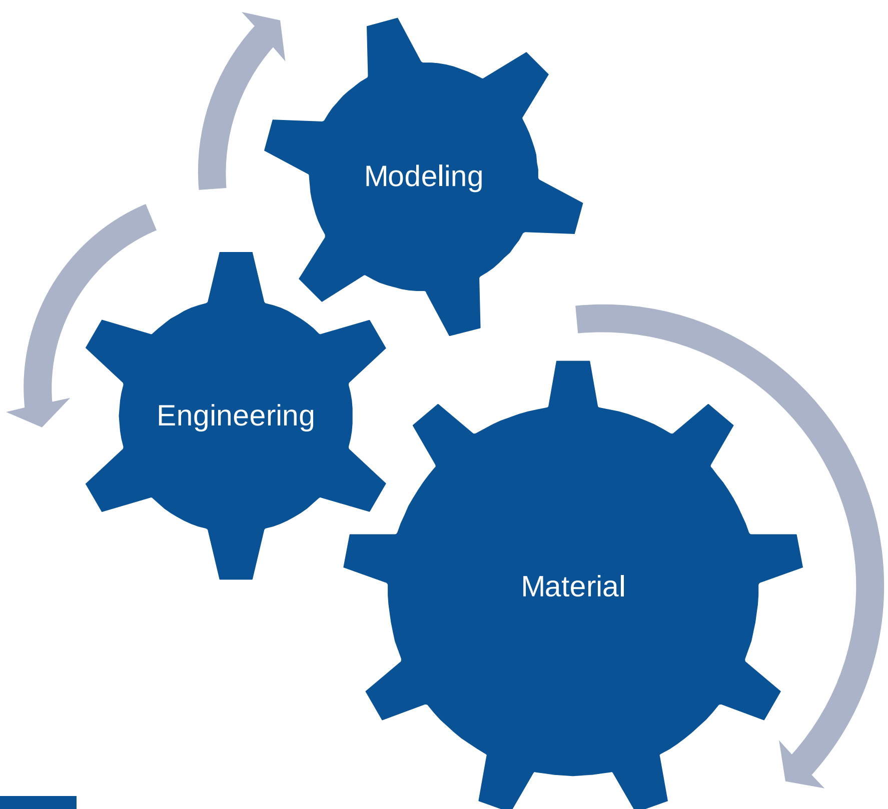
http://conference.tgo.or.th/download/tgo_or_th/Statistic/2017/May/CDM/sumIII_31_May_th.pdf

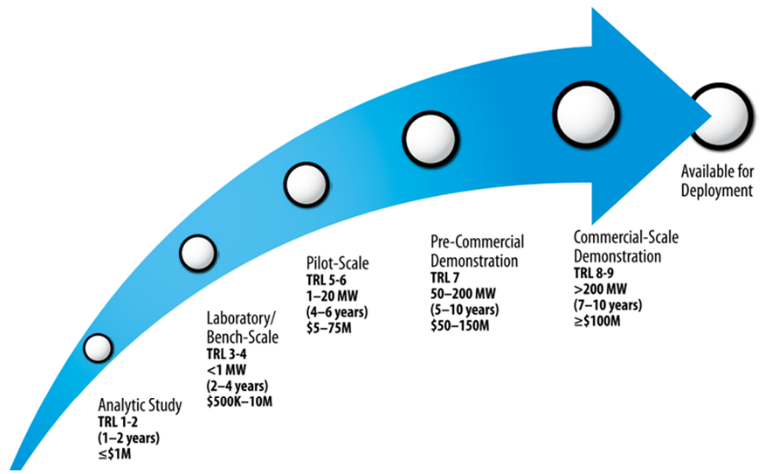
Recommendations:
- Incentivize static point source capture
- Initiate CO_2 capture from biofuels
- Promote federal subsidize to produce high value chemicals from CO_2
- Adopt deep sea saline storage

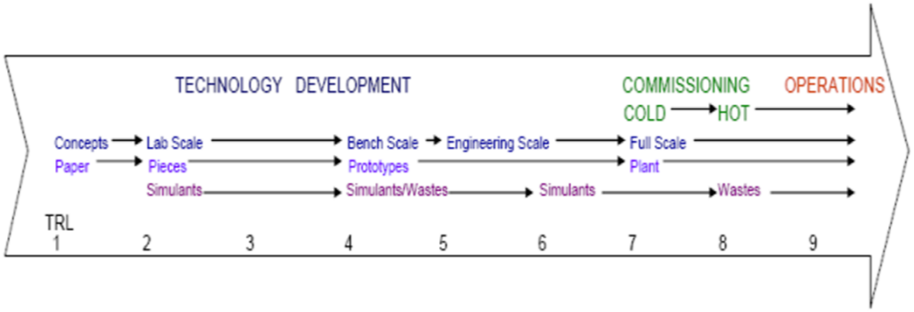
https://unfccc.int/files/national_reports/non-annex_i_natcom/submitted_natcom/application/pdf/snc_thailand.pdf

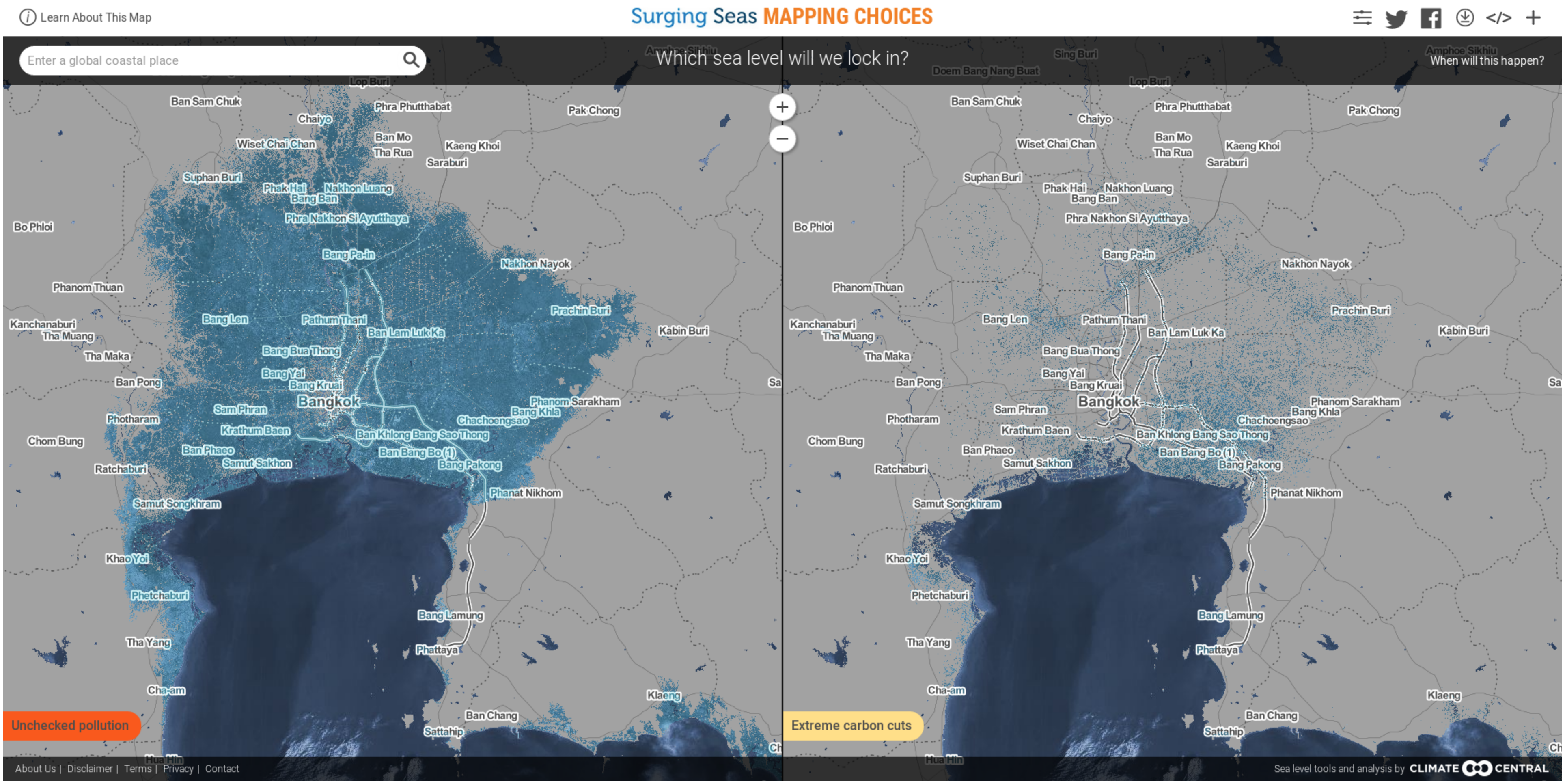
Gap analysis for Thailand 4.0

- Novel technology scale-up is difficult
    - Lack of expertise in transitioning between TRL
- Fully-Integrated development mechanism is not realized: Modelling, Material, and Process









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THANK YOU

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