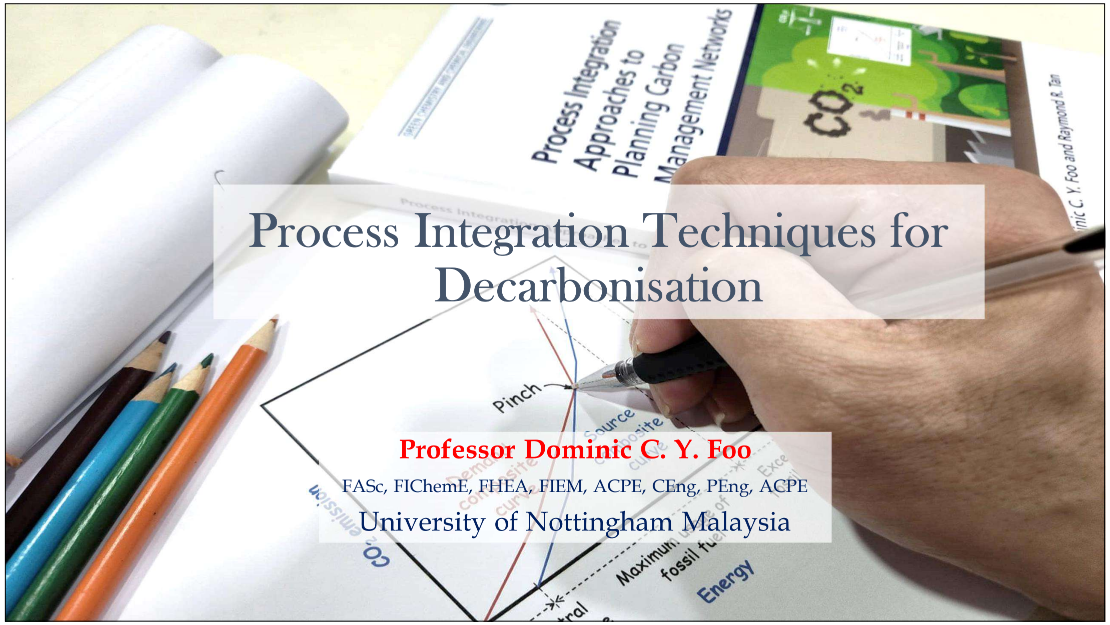


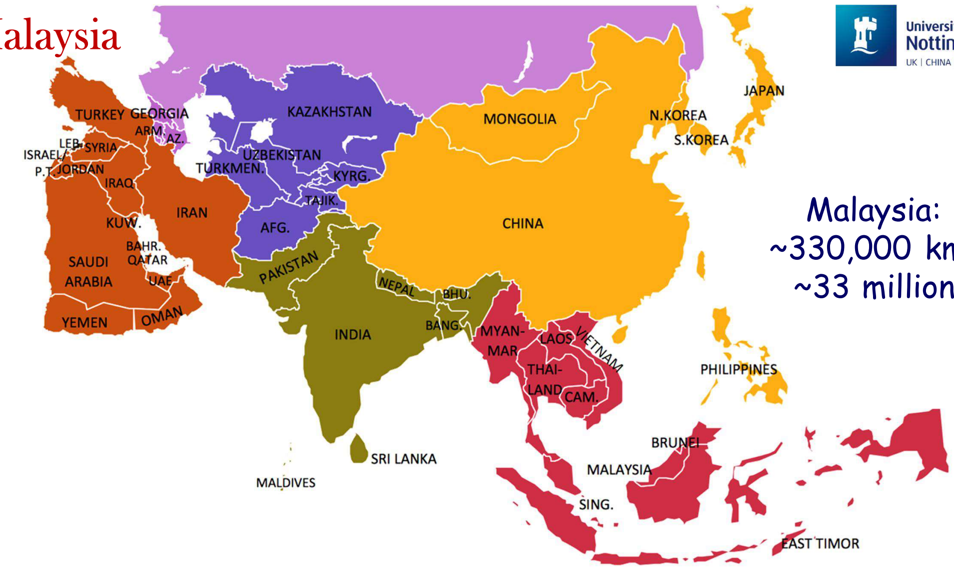
Process Integration Techniques for Decarbonisation

Professor Dominic C. Y. Foo
FASc, FIChemE, FHEA, FIEM, ACPE, CEng, PEng, ACPE
University of Nottingham Malaysia

Dominic Foo

- Qualifications:
  - BEng and MEng & PhD (Chem Eng, Univ Teknologi M'sia)
  - **200+** papers published in ISI-indexed journals
  - **≥300** publications and ***h*-index ≥ 49** in Scopus
  - **>40** keynote/plenary presentations
  - Author & editors of **10 books**
  - Editorial activities: Editor-in-Chief for ***Process Integration & Optimisation for Sustainability*** (Springer Nature); Subject Editor for ISI-indexed IChemE journal ***Process Safety and Environmental Protection*** (Elsevier); Editorial Board members: ***Water Conservation Science and Engineering*** (Springer Nature); PROCESSES (MDPI); South African Journal of Chemical Engineering (Elsevier)
- Professional involvements:
  - Fellow, Academy of Science Malaysia (ASM)
  - Fellow, Institution of Chemical Engineers (IChemE)
  - Fellow, Institution of Engineers Malaysia (IEM)
  - Fellow, The Higher Education Academy (HEA), UK
  - Past President, Asia Pacific Confederation of Chemical Engineering (APCChE)
  - Chartered Engineer (Engineering Council UK)
  - Professional Engineer (Board of Engineers M'sia)
  - Past chairman, ChE Tech Division, Institution of Engineers Malaysia
- Important awards/recognitions:
  - Innovator of the Year 2009, Institution of Chemical Engineers UK
  - Young Engineer Award 2010, Institution of Engineers Malaysia
  - Outstanding Young Malaysian 2012, Junior Chamber International
  - Outstanding Asian Researcher and Engineer 2013, Society of Chemical Engineers, Japan
  - Top Research Scientist Malaysia 2016 , Academy of Science Malaysia
  - World Top 2% Scientist in Stanford List (2019-2021)

Malaysia



Malaysia:
~330,000 km^2
~33 million

University of Nottingham

Talk outline

- ❑ Climate change is here!
- ❑ Carbon-constrained energy planning:
  - ✓ Renewables
  - ✓ Carbon capture and storage
  - ✓ Negative emission technologies
- ❑ Carbon footprint for manufacturing
- ❑ Concluding remarks

Kajang (8 May 2024)

Dubai (April 2024)

Scientists find the fingerprints of climate change on Dubai's deadly floods

By Angela Dewan, CNN
4 minute read · Published 11:04 AM EDT, Thu April 25, 2024

Abandoned vehicles on a flooded highway in the city of Dubai after record rain, on April 17, 2024.
Christopher Pike/Bloomberg/Getty Images

Dubai deluge likely made worse by warming world, scientists find

Powerful rainstorm in the desert linked to climate change, though connection isn't clear cut

Benjamin Shingler · CBC News · Posted: Apr 25, 2024 4:21 PM EDT | Last Updated: April 26

Vehicles drive through standing floodwater caused by heavy rain in Dubai, United Arab Emirates, Thursday, April 18, 2024. It was the heaviest rain the desert nation has ever recorded, a deluge that flooded out Dubai International Airport and disrupted flights and left four people dead in the UAE. (Christopher Pike/Associated Press)

Los Angeles California (2024-2025)

California wildfires: What we know about L.A.-area fires, what caused them, who is affected and more

Fueled by powerful winds and dry conditions, a series of ferocious wildfires erupted the second week of January and roared across the Los Angeles area.

Get more news LIVE on NBC NEWS NOW.

Jan. 18, 2025, 11:32 AM GMT+8 / Updated Jan. 31, 2025, 12:50 PM GMT+8
By Tim Stelloh, Marlene Lenthang, Rebecca Cohen and Phil Helsel

Sponsored Stories by Taboola

CNN Weather Video Climate

LA fire areas brace for 'life-threatening' debris flows from the worst storm in a year as heavy snow hits the Midwest

By Mary Gilbert and Lauren Mascarenhas, CNN
6 minute read · Updated 5:29 PM EST, Wed February 12, 2025

Pasadena residents load sandbags into their cars to prepare for the torrential rain in the forecast, which could trigger dangerous mudslides. Frederic J. Brown/AFP via Getty Images

(CNN) — Southern California's most significant storm in more than a year is incoming, stoking fears of life-threatening debris flows in the Los Angeles area torched by historic wildfires last month.

Australia (Feb 2025)

University of Nottingham
UK | CHINA | MALAYSIA

CNN World · Africa · Americas · Asia · Australia · China · Europe · India · More

Australia braces for more destruction as deadly floods devastate northeast

By Helen Regan and Robert Shackelford, CNN
6 minute read · Updated 7:04 AM EST, Mon February 3, 2025

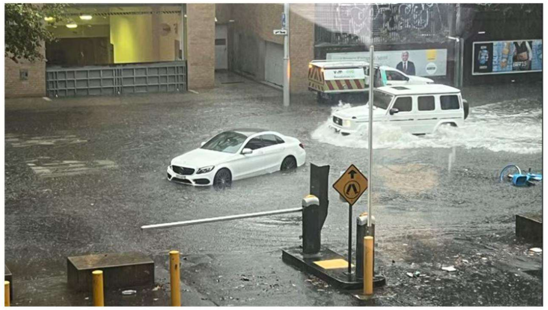
Northeast Queensland residents evacuate due to flooding in Townsville on February 3, 2025. Scott Radford-Chisholm/AAP Image/Reuters

Record warm seas supercharging Australia's weather from heatwaves to floods to cyclones

By ABC meteorologist Tom Saunders

Weather

4h ago



NSW has been hit with violent thunderstorms. (ABC News: Andrea Jonson)

Argentina (March 2025)

University of Nottingham
UK | CHINA | MALAYSIA

ALJAZEERA · News · Middle East · Explained · Opinion · Sport · Video
Trending · War on Gaza · Russia-Ukraine War · Donald Trump

News | Climate

Argentina mourns 16 killed in floods

Government pledges $9.2m in financial aid for Bahia Blanca, a port city of 300,000 people south of Buenos Aires.

The deadly floods struck on Friday when a year's worth of rain, estimated to be 260 millimeters (10 inches), fell in a matter of hours in and around Bahia Blanca [Pablo Presti/EPA]

Argentina flooding: 16 killed as two girls swept away by rising waters

Authorities warn more fatalities expected as a year's worth of rain falls on Bahía Blanca in eight hours

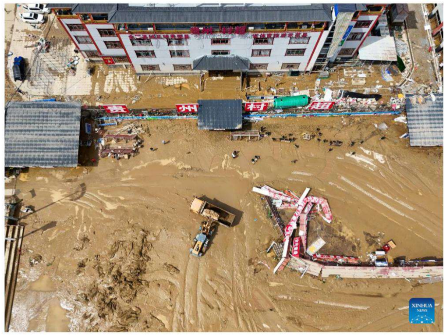
Firefighters and volunteers help people out of flooded areas in Bahía Blanca, Argentina, on 8 March 2025. Photograph: Pablo Presti/EPA

Guizhou, China (June 2025)

University of Nottingham
UK | CHINA | MALAYSIA

Rescue underway in flood-affected counties of Guizhou

Source: Xinhua Editor: huaxia 2025-06-26 07:33:22



An aerial drone photo shows people clearing silt at a football field of the Cun Chao stadium in Rongjiang County, southwest China's Guizhou Province, June 25, 2025. Continuous heavy rainfall and

Over 80,000 people flee severe flooding in southwest China

Story by AFP • 49m • 2 min read · Summarise

Not too long ago...

University of Nottingham
UK | CHINA | MALAYSIA

MENAFN · Thursday 3 July 2025
HOME · NEWS · PRESS DISTRIBUTION · MARKET DATA · RESEARCH · COUNTRIES · SECTIONS
US · Europe · Arab · Asia · Africa | Politics · Economy · Oil&Energy

Heavy Rains Batter Western Venezuela

3 dead as S. Korean region hit by most rain in 120 years

Story by AFP • 4h • 3 min read · Summarise

The western Seosan area was hit by rainfall peaking at 114.9mm per hour. (EPA Images pic)

SEOSAN CITY: At least three people were killed and more than 1,000 evacuated today after South Korea was hit by torrential rains, officials said, with one region pummelled by the

Ongoing now...

WORLD NEWS

Torrential rains in southern Japan cause flooding, mudslides and travel disruptions

Extreme heatwave hits Europe with temperatures expected up to 44°C

Story by Euronews • 4d • 2 min read · Summarise

Europe is bracing for an exceptional heatwave expected on the weekend, with temperatures expected to be as high as 44 degrees Celsius in some countries.

According to France's official weather service, four southern departments including the Bouches-du-Rhône, Gard, Hérault and Pyrénées-Orientales are under heatwave alerts, while 14 departments are expected to be on Saturday.

Alerts of "severe" risks of wildfire, have also been issued.

One French meteorologist, Jérôme Cerisier, says they are expecting 10 to 15 degrees above the seasonal average.

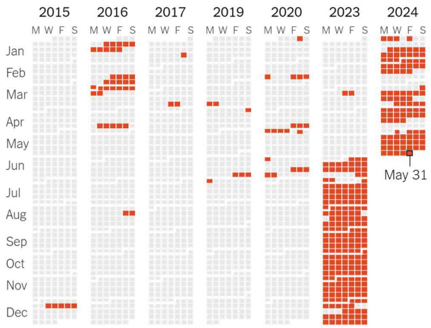
"A new anticyclone is settling over France, and we'll once again have what we call a 'heat dome', with temperatures rising by 1 to 2°C day after day. The warm air is self-sustaining, the skies are clear, so we'll once again see exceptional values, often 10 to 15°C above seasonal averages, and for the long term," said Cerisier.

Tourists with an umbrella walk in front of the Parthenon at the ancient Acropolis in central Athens, 12 June, 2024 AP Photo

Hottest? Or hotter?

2024 on Course to Outpace 2023 as the Hottest Year Ever

As of May 31, over 100 daily global surface temperature records have been set in 2024.



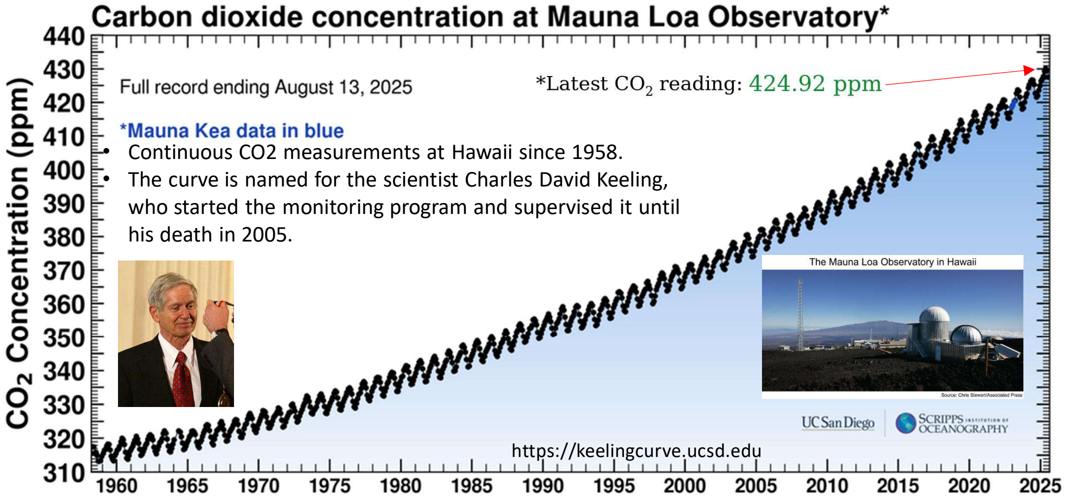
Note: Four days of the year have recorded the same highest temperature in two different years, and these are charted for both occurrences.
Source: Copernicus Climate Change Service (C3S) Climate Data Store (CDS), ERA5 | Graphic: Shad Frigui

Sustainable planetary boundaries

Earth-system Process	Parameters	Proposed Boundary	Current Status	Pre-industrial Value
Climate Change	Atmospheric CO_2 concentration (ppm by volume)	350	387	280
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415

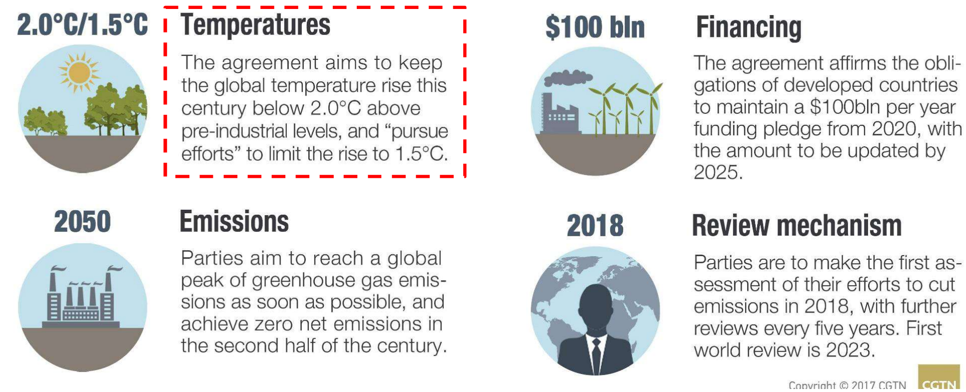
(Rockstrom *et al.*, 2009)

The Keeling curve



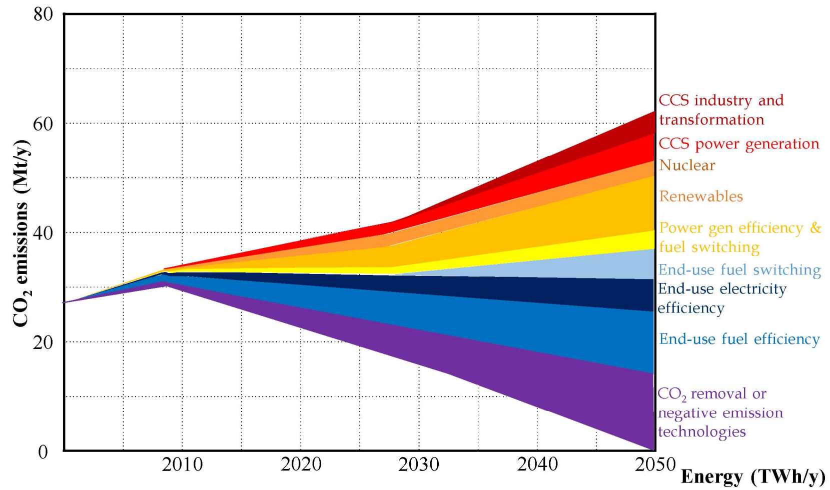
- Continuous CO2 measurements at Hawaii since 1958.
- The curve is named for the scientist Charles David Keeling, who started the monitoring program and supervised it until his death in 2005.

Paris agreement

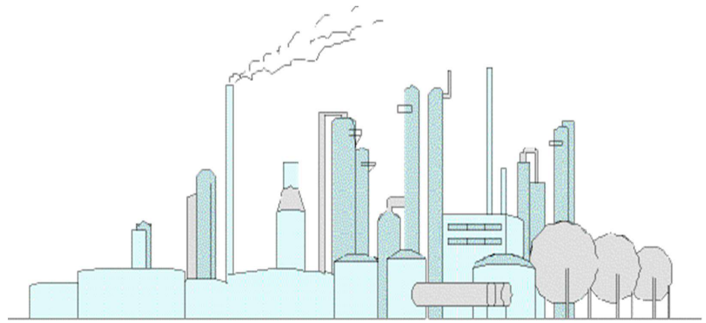


Other UN Climate Change Conferences

Decarbonisation wedges



Process Integration



Some milestones

1970s Heat exchanger network (HEN)

1989 Mass exchange network (MEN)

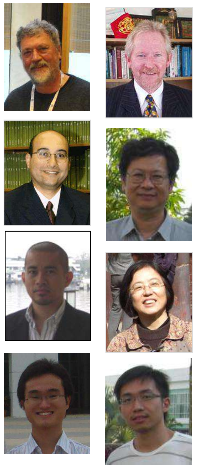
1994 Water minimisation (water pinch)

2002 Production supply chain

2002 Hydrogen network (H2 pinch)

2005 Property integration (property pinch)

2007 Energy planning (carbon pinch)



An established tool

Save water

Reduce utility

Reduce waste

Reduce cost

Reduce emission

Improve efficiency

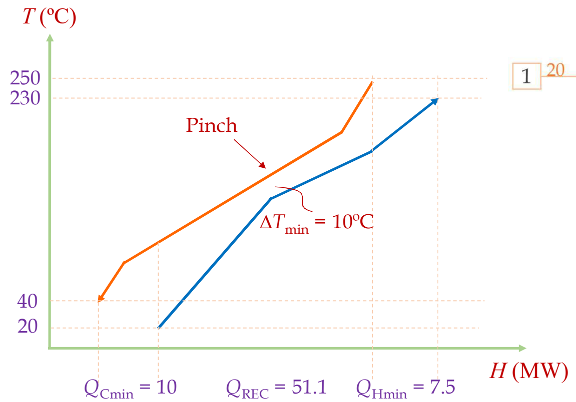
Reduce utility

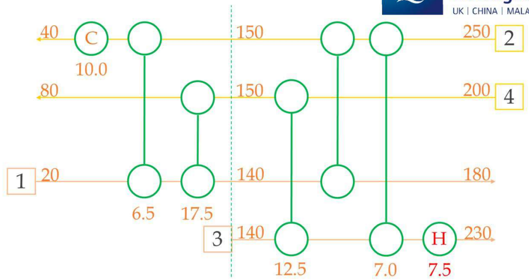
Increase throughput

The chemical industry

Chemical industry consumes **~28%** of the industrial energy, where most of it is obtained from fossil resources (IEA, 2017).

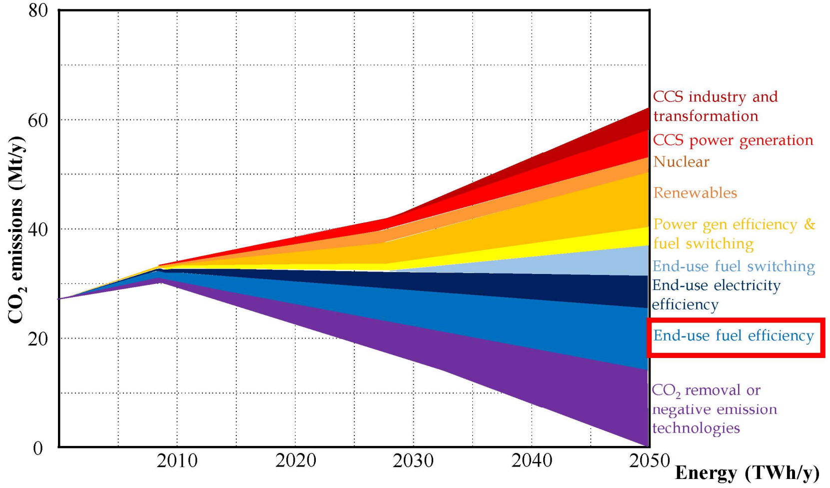
Graphical pinch diagram

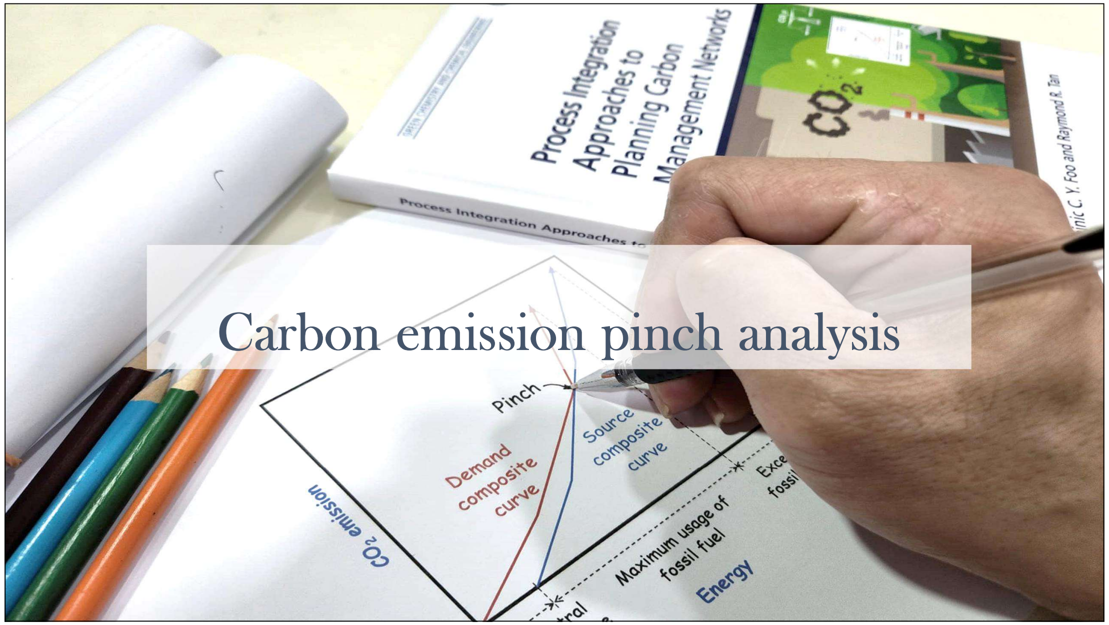




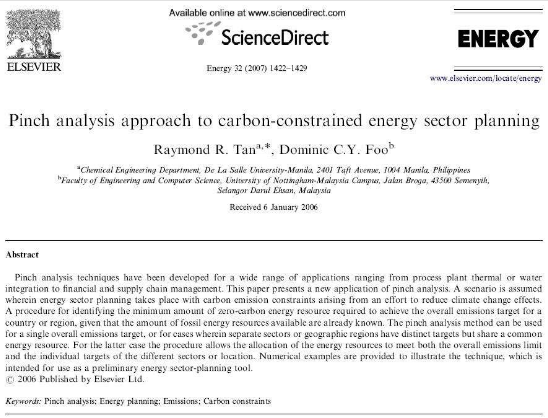
(Smith,2016)

Decarbonisation wedges





Seminal papers on CEPA



Available online at www.sciencedirect.com
ScienceDirect
ENERGY
ELSEVIER
Energy 32 (2007) 1422–1429
www.elsevier.com/locate/energy

Pinch analysis approach to carbon-constrained energy sector planning

Raymond R. Tan[a,*], Dominic C.Y. Foo[b]

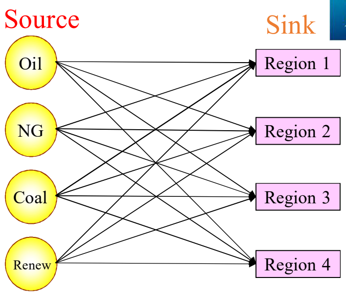
[a]Chemical Engineering Department, De La Salle University-Manila, 2401 Taft Avenue, 1004 Manila, Philippines
[b]Faculty of Engineering and Computer Science, University of Nottingham-Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia

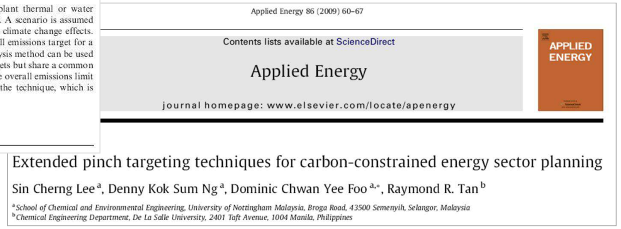
Received 6 January 2006

Abstract

Pinch analysis techniques have been developed for a wide range of applications ranging from process plant thermal or water integration to financial and supply chain management. This paper presents a new application of pinch analysis. A scenario is assumed wherein energy sector planning takes place with carbon emission constraints arising from an effort to reduce climate change effects. A procedure for identifying the minimum amount of zero-carbon energy resource required to achieve the overall emissions target for a country or region, given that the amount of fossil energy resources available are already known. The pinch analysis method can be used for a single overall emissions target, or for cases wherein separate sectors or geographic regions have distinct targets but share a common energy resource. For the latter case the procedure allows the allocation of the energy resources to meet both the overall emissions limit and the individual targets of the different sectors or location. Numerical examples are provided to illustrate the technique, which is intended for use as a preliminary energy sector-planning tool.
© 2006 Published by Elsevier Ltd.

Keywords: Pinch analysis; Energy planning; Emissions; Carbon constraints





Applied Energy 86 (2009) 60–67
Contents lists available at ScienceDirect
Applied Energy
journal homepage: www.elsevier.com/locate/apenergy
APPLIED ENERGY

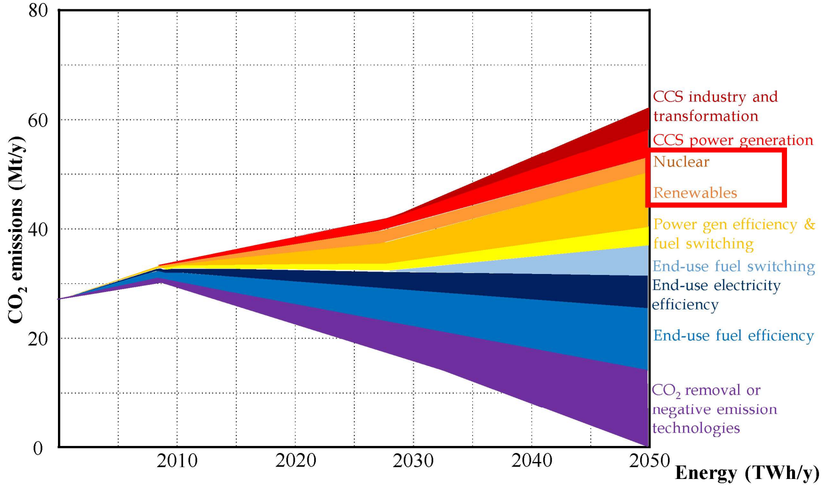
Extended pinch targeting techniques for carbon-constrained energy sector planning

Sin Cherng Lee[a], Denny Kok Sum Ng[a], Dominic Chwan Yee Foo[a,*], Raymond R. Tan[b]
[a]School of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
[b]Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines

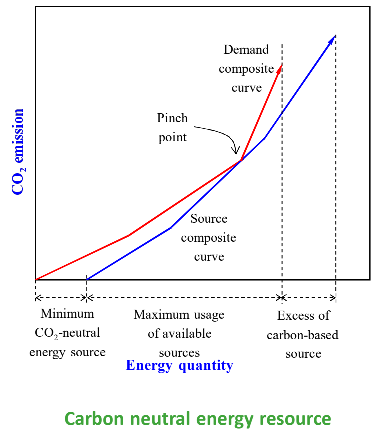
Problem statement

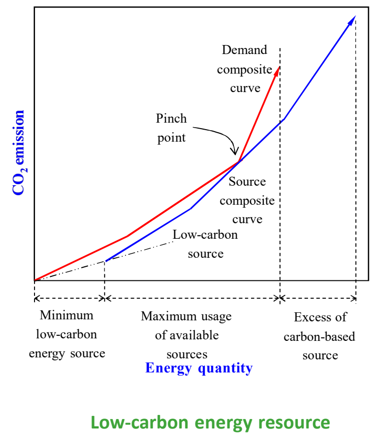
- Given a set of **energy demands** (e.g. geographical regions or economic sectors), designated as DEMANDS = {j | j = 1,2, …, M}.
  - Each demand requires energy consumption of D_j and at the same time, restricted to a maximum emission limit of $E_{D,\,j}$.
  - Dividing the emission limit by the energy consumption yield the emission factor for each demand, $C_{D,\,j}$.
- Given a set of **energy sources**, designated as SOURCES = {i | i = 1,2, …, N}, to be allocated to energy demands.
  - Each source (e.g. coal, oil, etc.) has an available energy of S_i and is characterized by a fixed emission factor, $C_{S,\,i}$.
  - Product of the available energy and the emission factor gives the total emission of the source $E_{S,\,i}$.
- The objective is to determine the **minimum CO_2-neutral and/or low-carbon energy sources** that fulfill the energy demand.

Decarbonisation wedges



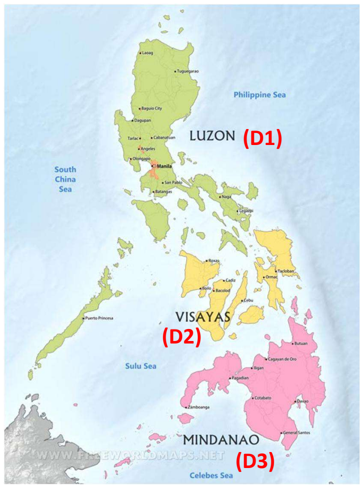
Energy planning pinch diagram (EPPD)





Case study – Philippines

- Three types of fossil fuels are to be supplied to three different regions.
- Renewables may be used to supplement the fossil fuels.
- Task – determine the minimum amount for the following renewables:
  - Carbon-neutral renewables (C_{RE} = 0 t/TJ)
  - Low-carbon renewables, with intensity C_{RE} = 16.5 t/TJ



Case study (Tan & Foo, 2007)

(a) Energy demands

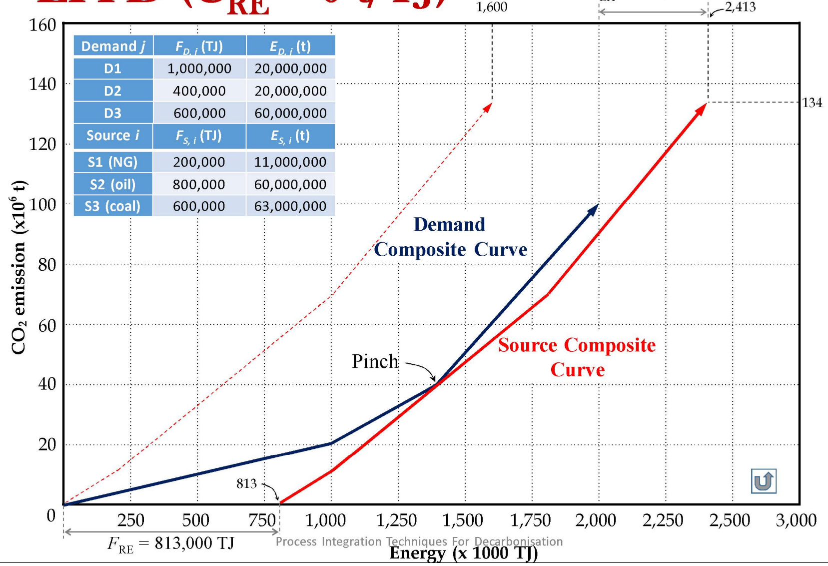
Demand j	Energy, $F_{D,j}$ (TJ)	Carbon intensity, $C_{D,j}$ (t/TJ)	CO_2 emission, $E_{D,j}$ (t)
D1	1,000,000	20	20,000,000
D2	400,000	50	20,000,000
D3	600,000	100	60,000,000

(b) Energy sources

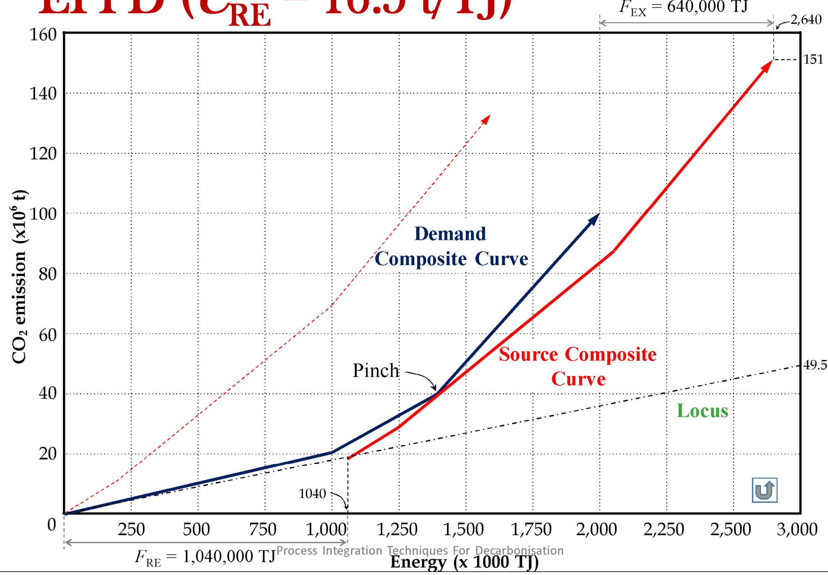
Source i	Energy, $F_{S,i}$ (TJ)	Carbon intensity, $C_{S,i}$ (t/TJ)	CO_2 emission, $E_{S,i}$ (t)
S1 (NG)	200,000	55	11,000,000
S2 (oil)	800,000	75	60,000,000
S3 (coal)	600,000	105	63,000,000

EPPD (C_{RE} = 0 t/TJ)

Demand j	$F_{D,j}$ (TJ)	$E_{D,j}$ (t)
D1	1,000,000	20,000,000
D2	400,000	20,000,000
D3	600,000	60,000,000
Source i	**$F_{S,i}$ (TJ)**	**$E_{S,i}$ (t)**
S1 (NG)	200,000	11,000,000
S2 (oil)	800,000	60,000,000
S3 (coal)	600,000	63,000,000



EPPD (C_{RE} = 16.5 t/TJ)



CEPA applications

University of Nottingham
UK | CHINA | MALAYSIA

Automated Targeting Model (ATM)

University of Nottingham
UK | CHINA | MALAYSIA

C_k	ΔC_k	$\Sigma_j F_{D,j}$	$\Sigma_i F_{S,i}$	$F_{Net,k}$	δ_k	ε_k
					$\delta_0 = F_{RE}$	
C_1		$\Sigma_j F_{D,j}$	$\Sigma_i F_{S,i}$	$F_{Net,1}$	$\Downarrow$	$\varepsilon_1 = 0$
	ΔC_1				δ_1	$\Downarrow$
C_2		$\Sigma_j F_{D,j}$	$\Sigma_i F_{S,i}$	$F_{Net,2}$	$\Downarrow$	ε_2
⋮	ΔC_2	⋮	⋮	⋮	δ_2	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
C_{n-1}	⋮	$\Sigma_j F_{D,j}$	$\Sigma_i F_{S,i}$	$F_{Net,2}$	⋮	ε_{n-1}
	ΔC_{n-1}				$\delta_{n-1} = F_{EX}$	$\Downarrow$
C_n						ε_n

Constraints of ATM

- Follow **Steps i - iii of the algebraic targeting** technique for the first 5 columns.
- Energy cascade across all carbon intensity levels:

$$\delta_k = \delta_{k-1} + F_{\mathrm{Net},k} \quad \forall k \qquad (3.7)$$

- **Residual emission load** (ε_k) in the emission load cascade:

$$\varepsilon_k = \begin{cases} 0 & k = 1 \\ \varepsilon_{k-1} + \delta_{k-1}\Delta C_{k-1} & k \geq 2 \end{cases} \qquad (3.8)$$

- Residual energy entering the first (δ_0) and leaving the last levels (δ_{n-1}) should take non-negative values:

$$\delta_{k-1} \geq 0 \quad k = 1, n \qquad (3.9)$$

- All residual loads must take non-negative values:

$$\varepsilon_k \geq 0 \quad k \geq 2 \qquad (3.10)$$

Objective of ATM

- To minimize **renewable energy** (F_{RE}):

$$minimise F_{RE} \qquad (3.11)$$

- To minimize **overall cost** for all renewable energy h:

$$minimise F_{RE,h} C_{RE,h} \qquad (3.12)$$

where $F_{\mathrm{RE}h}$ & $C_{\mathrm{RE}h}$ are amount & unit cost of renewable energy.

- Variables:
  - Amount of renewable energy (F_{RE} ; $F_{\mathrm{RE}h}$)
  - Residual energy at level k (δ_k)
  - Residual load at level k (ε_k)
- Parameters:
  - Intensity level (C_k),
  - Energy demands ($F_{\mathrm{D}j}$) and sources ($F_{\mathrm{S}i}$)
- ATM formulation is a *linear program* (LP) – ensure global solution.

Case study (Tan & Foo, 2007)

(a) Energy demands

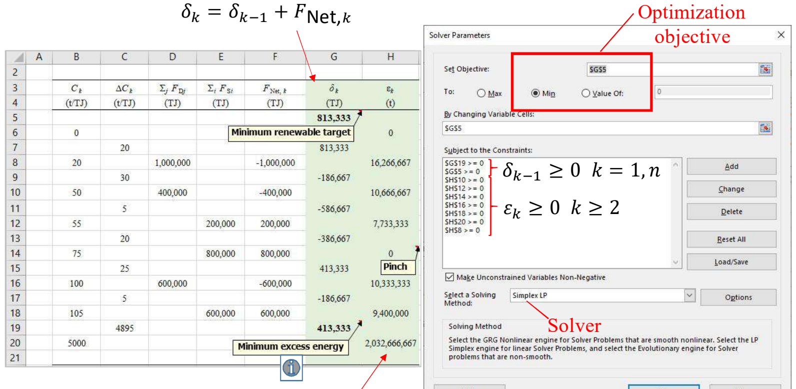
Demand j	Energy, $F_{D,j}$ (TJ)	Carbon intensity, $C_{D,j}$ (t/TJ)	CO_2 emission, $E_{D,j}$ (t)
D1	1,000,000	20	20,000,000
D2	400,000	50	20,000,000
D3	600,000	100	60,000,000

(b) Energy sources

Source i	Energy, $F_{S,i}$ (TJ)	Carbon intensity, $C_{S,i}$ (t/TJ)	CO_2 emission, $E_{S,i}$ (t)
S1 (NG)	200,000	55	11,000,000
S2 (oil)	800,000	75	60,000,000
S3 (coal)	600,000	105	63,000,000

ATM with spreadsheet

$$\delta_k = \delta_{k-1} + F_{\mathrm{Net},k}$$



$$\varepsilon_k = \begin{cases} 0 & k = 1 \\ \varepsilon_{k-1} + \delta_{k-1}\Delta C_{k-1} & k \geq 2 \end{cases}$$

Effect of biodiesel price

C_k (t/TJ)	ΔC_k (t/TJ)	$\Sigma_j F_{Dj}$ (TJ)	$\Sigma_i F_{Si}$ (TJ)	$F_{Net,k}$ (TJ)	δ_k (TJ)	ε_k (t)
					0	
0						
	16.5				0	
16.5			1042735	1,042,735		0
	3.5				1,042,735	
20		1,000,000		-1,000,000		3,649,573
	30				42,735	
50		400,000		-400,000		4,931,624
	5				-357,265	
55			200,000	200,000		3,145,299
	20				-157,265	
75			800,000	800,000		0
	25				642,735	
100		600,000		-600,000		16,068,376
	5				42,735	
105			600,000	600,000		16,282,051
	4895				**642,735**	
5000						##########

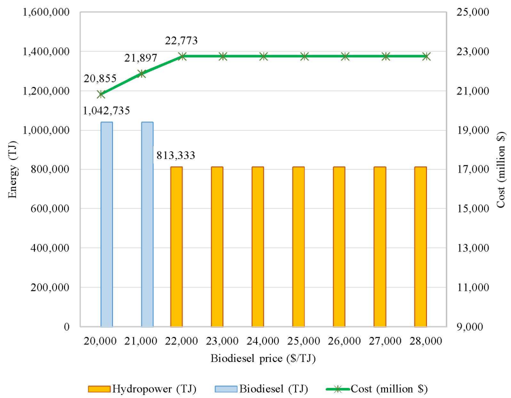
Minimum low-carbon energy

Minimum carbon-neutral energy

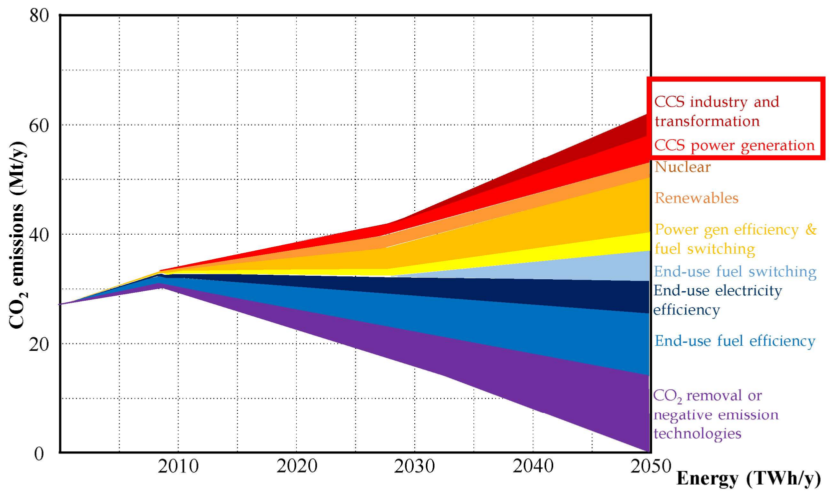
Pinch

Minimum excess energy

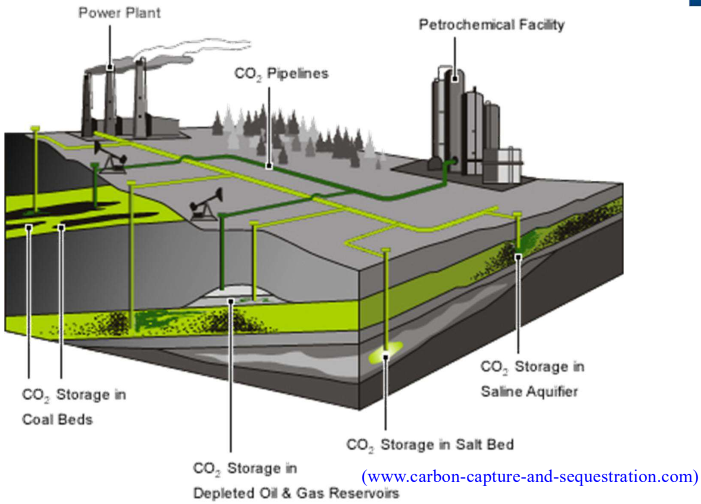
	Energy (TJ)	Unit cost ($/TJ)	Cost (million $)
Carbon-neutral energy (hydro):	0	28,000	0
Low-carbon energy (biodiesel):	1,042,735	20,000	20,855
		Total cost	**20,855**



Decarbonisation wedges

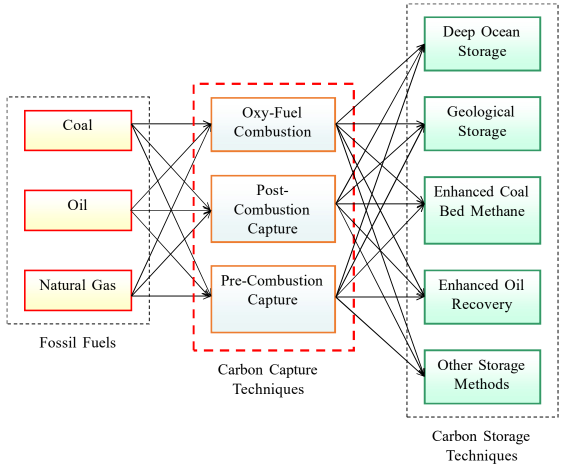


Carbon capture & storage (CCS)



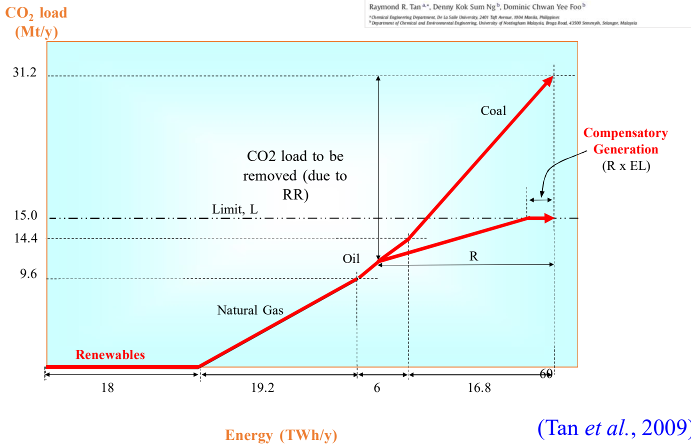
(www.carbon-capture-and-sequestration.com)

Options for CCS



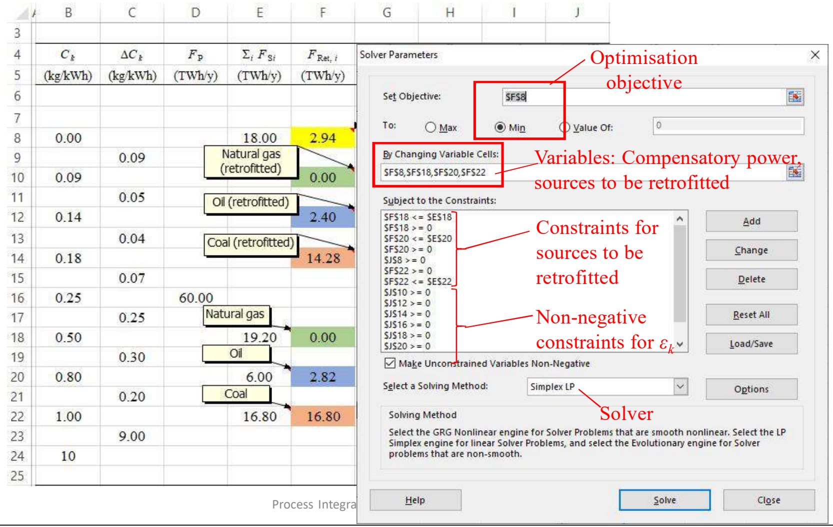
(Tan *et al.*, 2009)

Graphical tool for CCS



(Tan *et al.*, 2009)

ATM for CCS

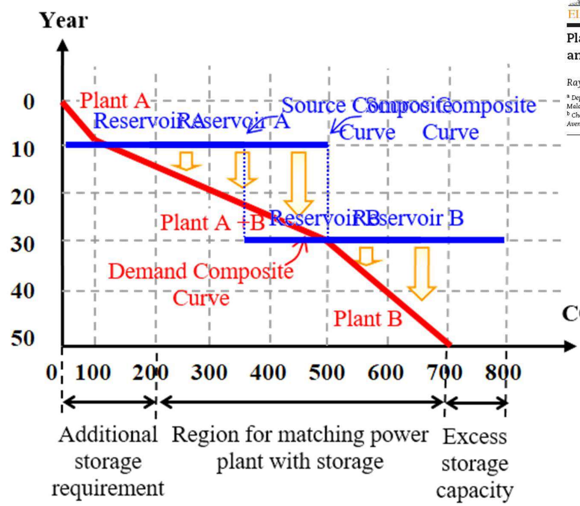


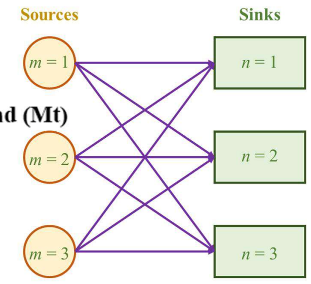
Superstructural model

Lingo 16.0 - [Lingo Model - CH 5 - Ex 5.3]

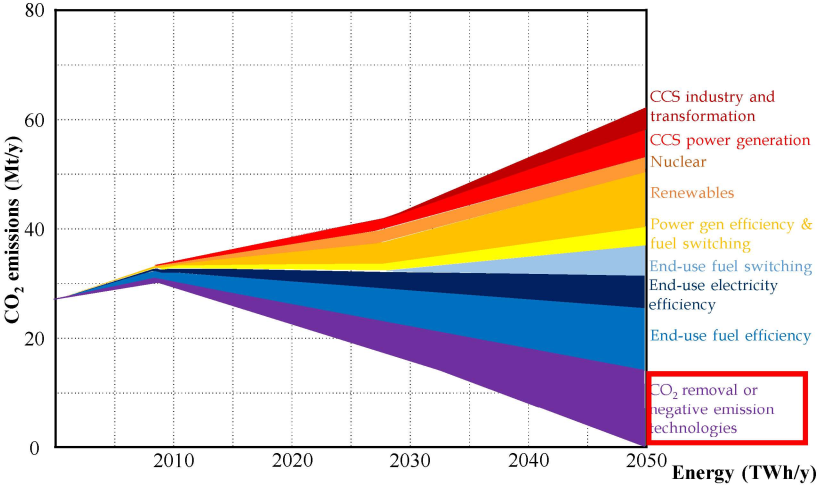
```
min = COMP;

PRICE <= 1.3*3100 ;
PRICE = 1.4*FRE + 1.0*FS + 1.6*FRET ;


!Energy balances for demands;

COMP + FS + FRET = 3100;

FS =
FS1 + FS2 + FS3 + FS4 + FS5 +
FS6 + FS7 + FS8 +
FS9 + FS10 ;

FRET =
FRET1 + FRET2 + FRET3 + FRET4 + FRET5 +
FRET6 + FRET7 + FRET8 +
FRET9 + FRET10;


!CO2 balances for demands;

COMP*0.1 + FSCO2 + RCO2 <= 3100*0.355;

FSCO2 =
(FS1 + FS2 + FS3 + FS4 + FS5)*1 +
(FS6 + FS7 + FS8)*0.5 +
(FS9 + FS10)*0.7 ;

RCO2 =
(FRET1 + FRET2 + FRET3 + FRET4 + FRET5)* CRETCOAL +
(FRET6 + FRET7 + FRET8)* CRETNG +
(FRET9 + FRET10)* CRETOIL ;

CRETCOAL = 1*(1-RR)/(1-X);
CRETNG = 0.5*(1-RR)/(1-X);
CRETOIL = 0.7*(1-RR)/(1-X);

X = 0.25 ;
RR = 0.9 ;

!Energy balances for sources;

FS1+ FS1RET = 200;
FS2+ FS2RET = 250;
FS3+ FS3RET = 150;
FS4+ FS4RET = 600;
FS5+ FS5RET = 500;
FS6+ FS6RET = 250;
FS7+ FS7RET = 300;
FS8+ FS8RET = 400;
FS9+ FS9RET = 200;
FS10+ FS10RET = 250;

!Plant(s) to be selected for retrofit;

200*(1 - X)* B1 = FRET1 ;
250*(1 - X)* B2 = FRET2 ;
150*(1 - X)* B3 = FRET3 ;
600*(1 - X)* B4 = FRET4 ;
500*(1 - X)* B5 = FRET5 ;
250*(1 - X)* B6 = FRET6 ;
300*(1 - X)* B7 = FRET7 ;
400*(1 - X)* B8 = FRET8 ;
200*(1 - X)* B9 = FRET9 ;
250*(1 - X)* B10 = FRET10 ;

FS1*(1-B1) + FS1RET*B1 = 200;
FS2*(1-B2) + FS2RET*B2 = 250;
FS3*(1-B3) + FS3RET*B3 = 150;
FS4*(1-B4) + FS4RET*B4 = 600;
FS5*(1-B5) + FS5RET*B5 = 500;
FS6*(1-B6) + FS6RET*B6 = 250;
FS7*(1-B7) + FS7RET*B7 = 300;
FS8*(1-B8) + FS8RET*B8 = 400;
FS9*(1-B9) + FS9RET*B9 = 200;
FS10*(1-B10) + FS10RET*B10 = 250;

!To define binary variables;

@bin(B1) ; @bin(B2) ; @bin(B3) ; @bin(B4) ; @bin(B5) ;
@bin(B6) ; @bin(B7) ; @bin(B8) ; @bin(B9) ; @bin(B10) ;
```


CO_2 storage





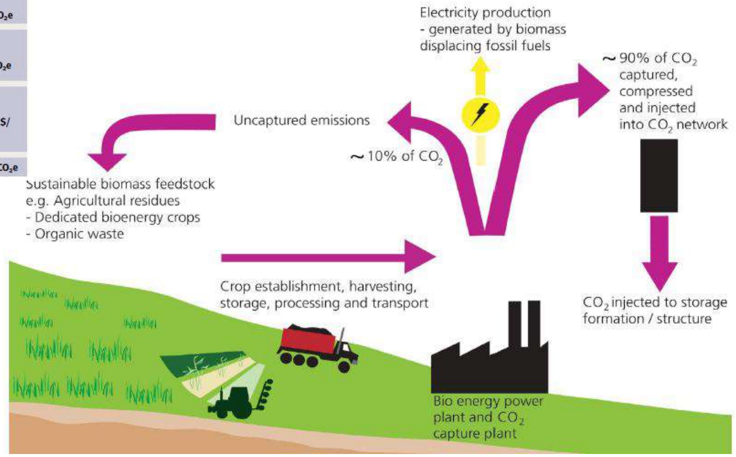
Decarbonisation wedges



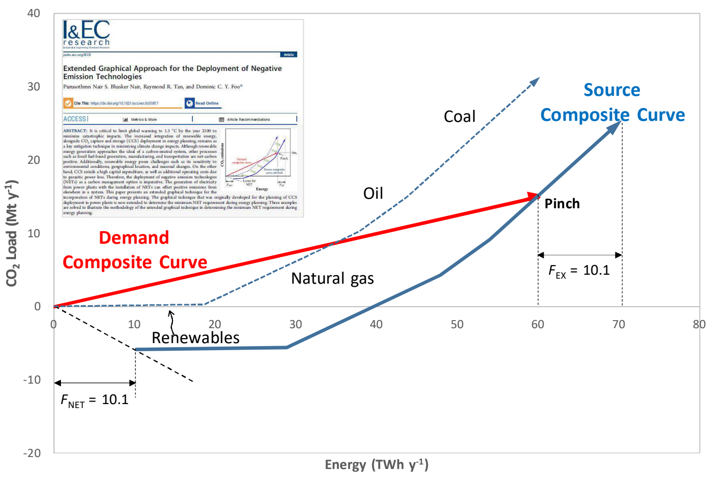
Bioenergy with CCS (BECCS)

Item	Amount/0.1 ppm CO_2	Cost
Energy		
Heat	102.2 GWe	(80.2) $/$tCO_2$e
Material		
Biomass incl. transport	0.64 Bt	86.9 $/$tCO_2$e
Equipment		
1 GW Dedicated biomass plant w CCS	~ 125 Units	52.1-104.2 $/$tCO_2$e
	Total	~59-111 $/$tCO_2$e

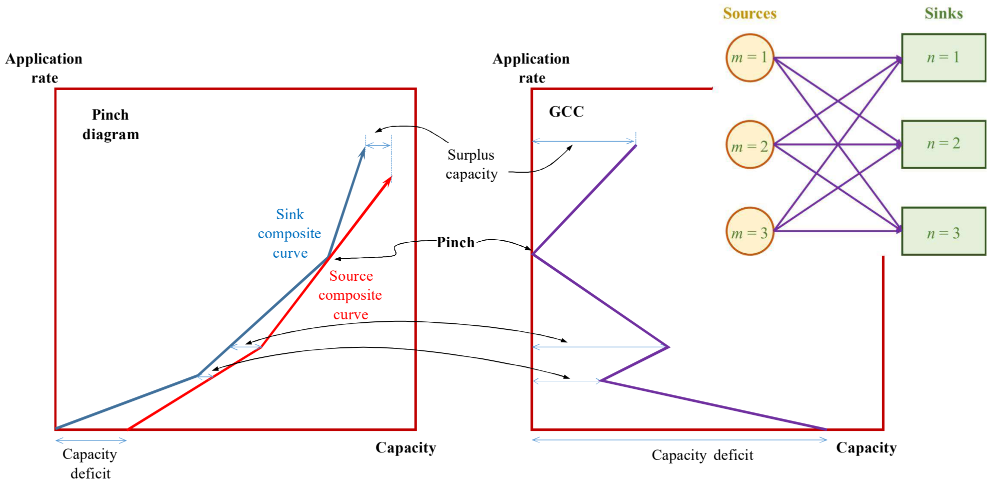
(McGlashan et al., 2012)

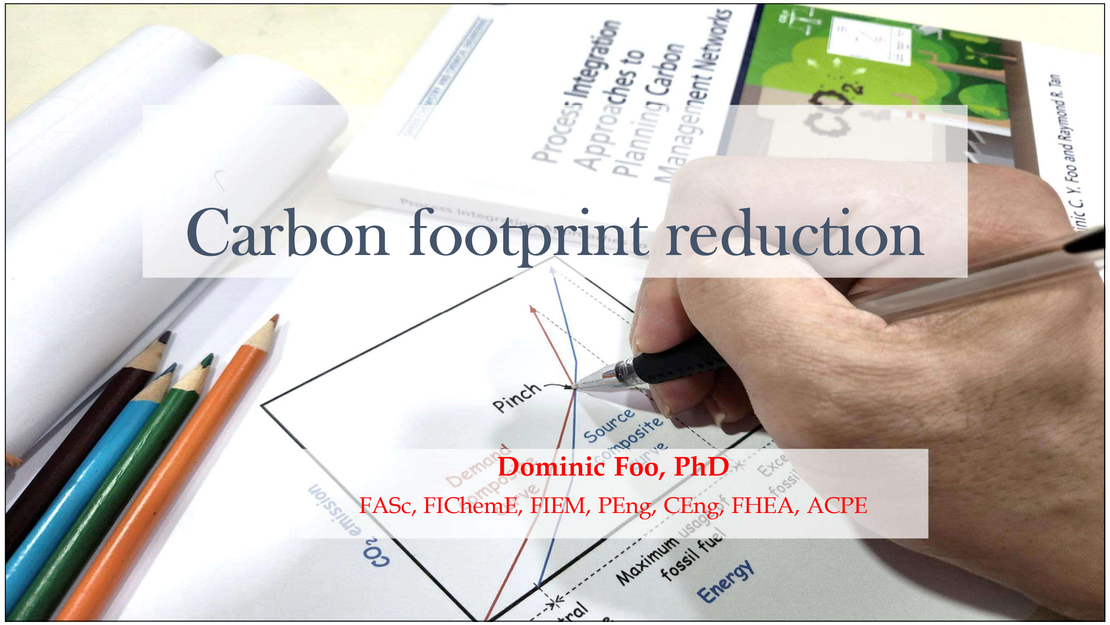


EPPD with NET



Enhanced weathering





Carbon footprint reduction

Dominic Foo, PhD

FASc, FIChemE, FIEM, PEng, CEng, FHEA, ACPE

Product carbon footprint reduction


Journal of Cleaner Production

A graphical representation of carbon footprint reduction for chemical processes

Wendy Tjan[a], Raymond R. Tan[b], Dominic C.Y. Foo[a,*]

Process Safety and Environmental Protection

A graphical method for carbon dioxide emissions reduction in multi-product plants

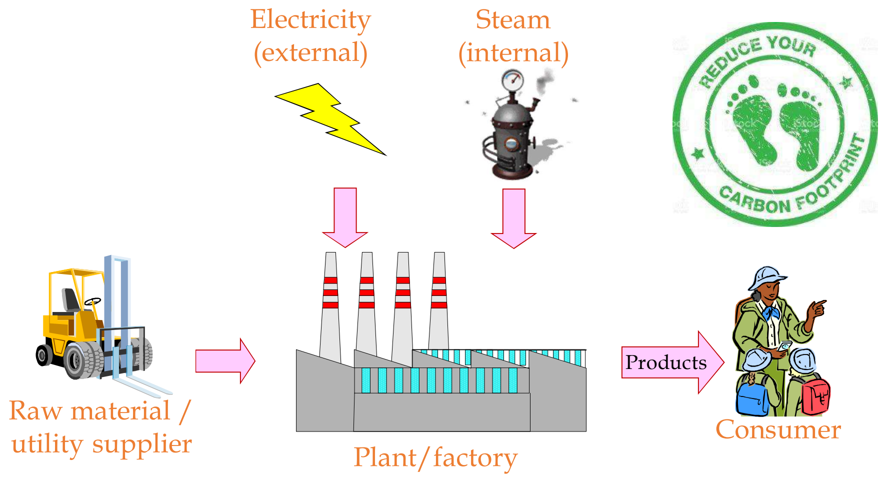
Jane Y. Yap[a], Jully Tan[b,*], Dominic C.Y. Foo[c], Raymond R. Tan[d], Stavros Papadokonstantakis[e], Sara Badr[e,1]

Chemical Engineering Research and Design

Integrated enterprise input-output and carbon emission pinch analysis for carbon intensity reduction in edible oil refinery

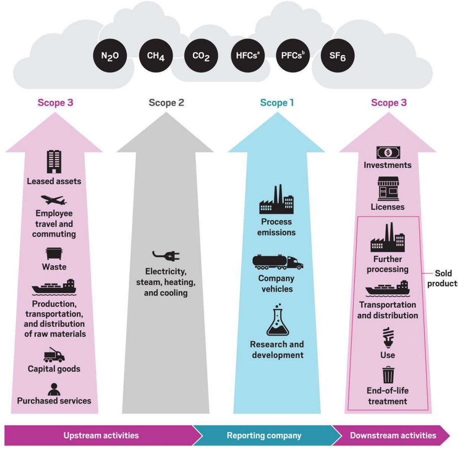
Tamelarasan Ramanath[a,*], Dominic C.Y. Foo[a], Raymond R. Tan[b], Jully Tan[c]

Product supply chain

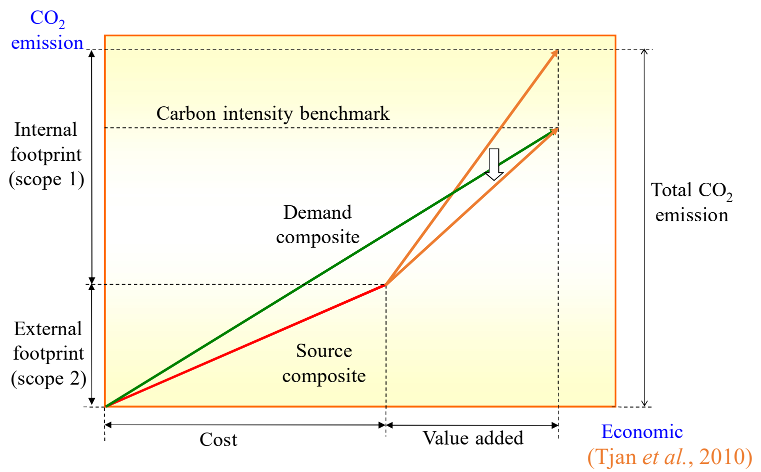


Scope of GHG

- Scope 1 emissions – those from a **company's production** & other internal operations.
- Scope 2 adds most forms of **power**.
- Scope 3 captures the **rest of the value chain** and is more complex; it has more overlap between companies and their customers.

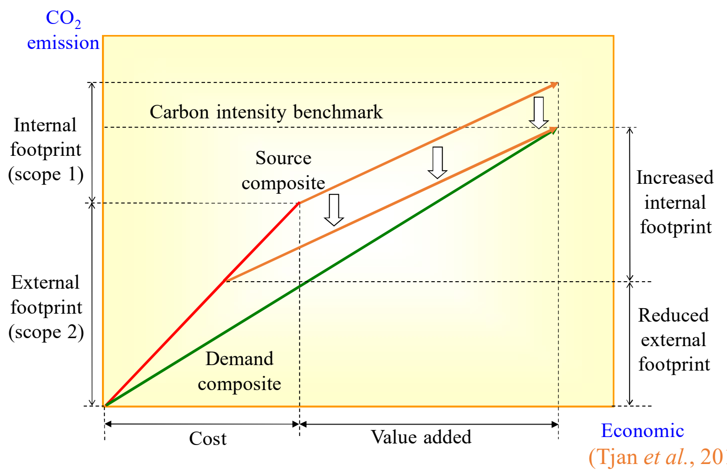


Case 1 – external < internal CF intensity



(Tjan *et al.*, 2010)

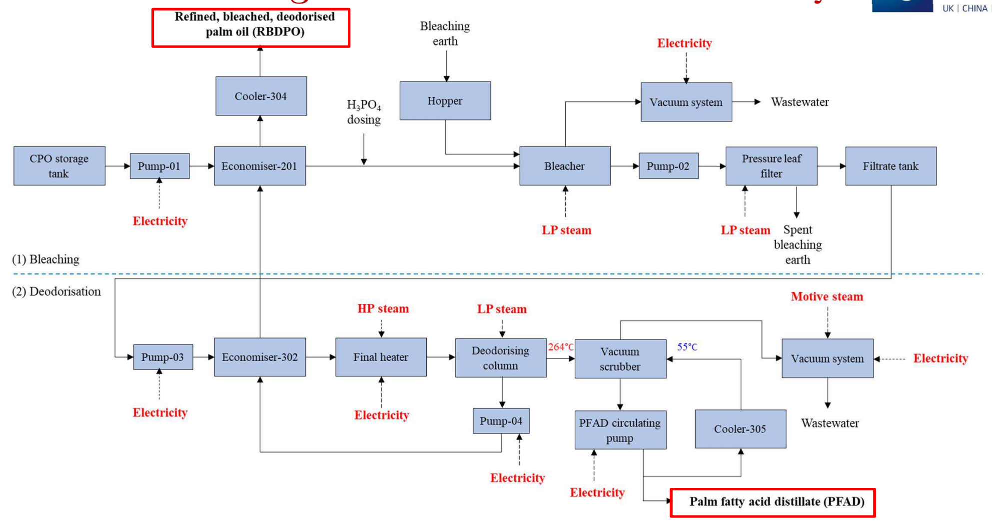
Case 2 – external > internal CF intensity



(Tjan *et al.*, 2010)

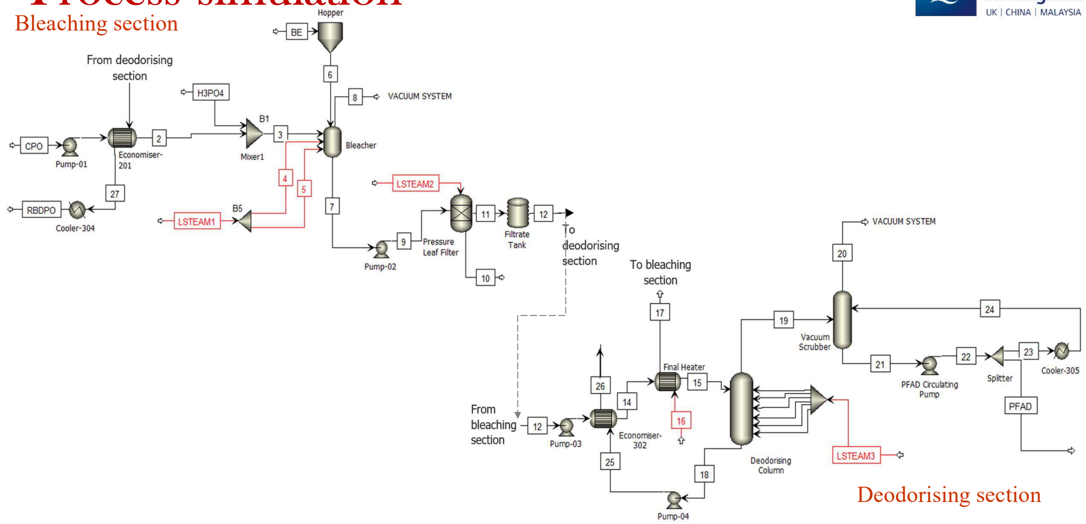
Case Study: Edible oil refinery

Process flow diagram for an edible oil refinery



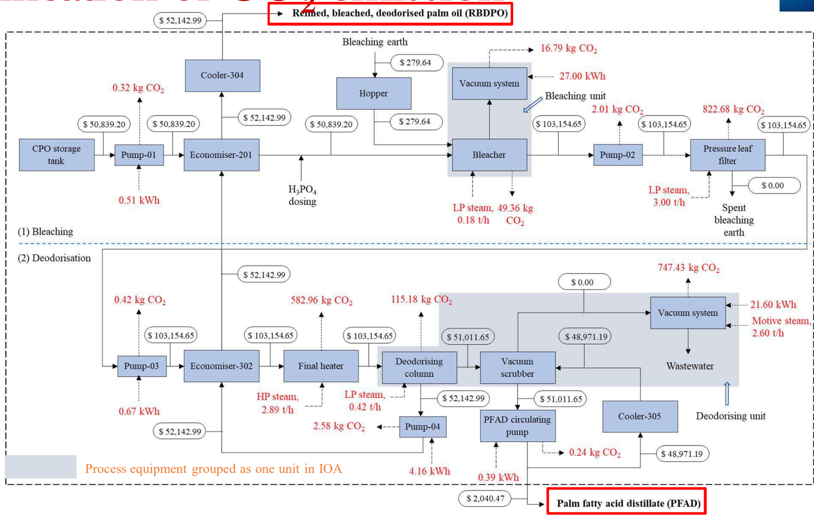
Process simulation

Bleaching section



Deodorising section

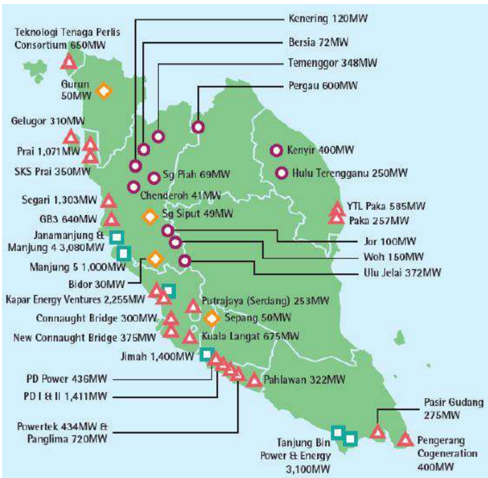
Identification of CO_2 emission



CO_2 emission from electricity

Energy source	Mix contribution (%)	Carbon intensity (kg CO_2/kWh)	Overall carbon intensity (kg CO_2/kWh)
Coal	42.8	1.001	0.428
Natural gas	40.2	0.469	0.189
Hydropower	14.8	0.004	0.001
Bioenergy	1.7	0.018	0.000
Diesel	0.5	0.84	0.004
Overall mix	100	-	0.622

Unit	Power required (kWh)	CO_2 emission (kg CO_2/h)
Pump-01	0.507	0.315
Pump-02	3.236	2.013
Bleaching vacuum system	27.000	16.794
Pump-03	0.670	0.417
Pump-04	4.155	2.585
Deodorisation pump-around & vacuum system	21.600	13.435
PFAD circulating pump	0.390	0.242
Total	57.56	35.801



CO_2 emissions from steam

Unit	Steam type	Amount of steam (t/h)	CO_2 emission (kg CO_2/h)
Bleacher	LP steam	180.00	49.361
Pressure leaf filter	LP steam	3000.00	822.680
Final heater	HP steam	2892.00	582.955
Deodorising column	LP steam	420.00	115.175
Deodorisation pumparound and vacuum system	Motive steam	2604.00	733.993
Total		9096.00	2304.163

- Steam carbon intensity (kg CO_2/ kg steam)
  - LP steam: 0.274
  - HP steam: 0.202
  - Motive steam: 0.282

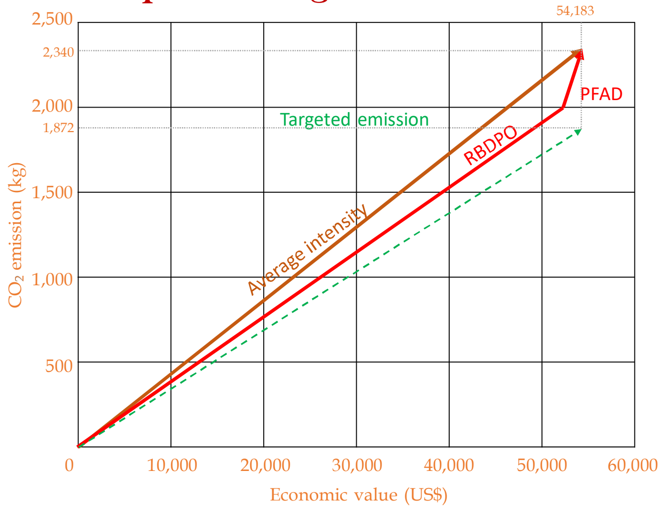
Economic values for products

Stream	Market value ($/t)	Mass flow (t/h)	Economic Value ($/h)	CO_2 emission (kg)
CPO	847.32	60.0	50,839	
RBDPO product	916.90	56.9	52,143	1,992
PFAD output		73.1	51,012	
PFAD recycle	697.770	70.2	48,971	
PFAD product		2.92	2,040	348

Main products

Economic values of RBDPO and PFAD products = 52,143 + 2,040 = $ 54,183 /h

CFP pinch diagram

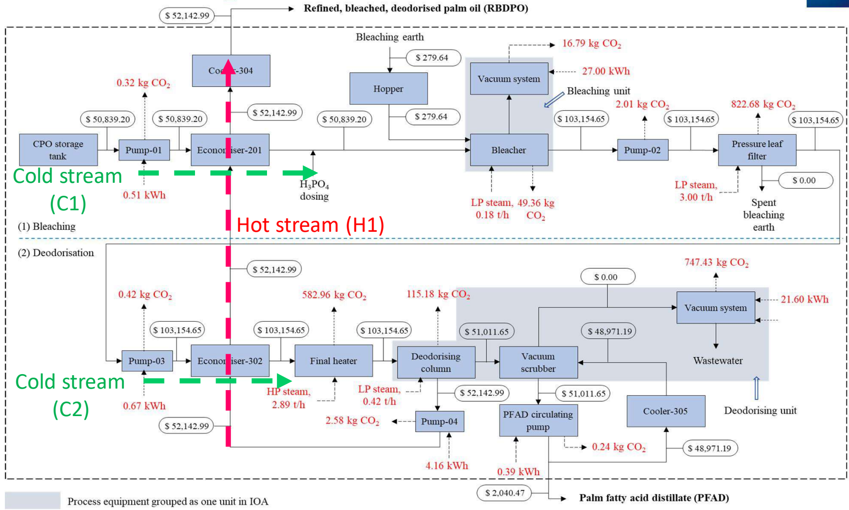


- Economic values of products: $ 54,183/h.
- Total CFP: 2340 kg CO_2
- Average carbon intensity: 0.0432 kg CO_2/$
- Reduction target: 20% of **current carbon intensity**: 0.0432 x 0.8 = 0.0345 kg CO_2/$
- Targeted CO_2 emission: 0.0345 x 54183 = 1872 kg/h.
- Targeted CO_2 reduction: 2340 – 1872 = 468 kg/h.

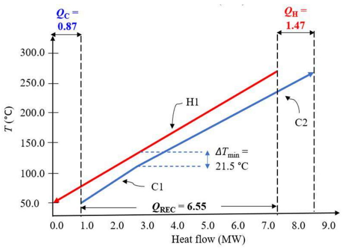
Scenarios for CFP reduction

- Scenario 1 – Improved **energy recovery**
- Scenario 2 – **Heat recovery** from hot vapour of deodorising column
  - Option 1 – preheat CPO
  - Option 2 – LP steam generation
- Scenario 3 – Implementation of **biomass boilers**
- Scenario 4 – **Co-firing of biomass** with LNG

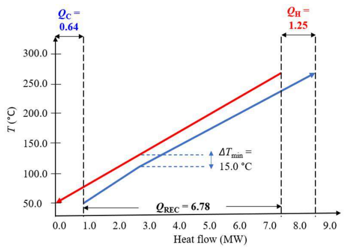
Scenario 1 – Improved energy recovery



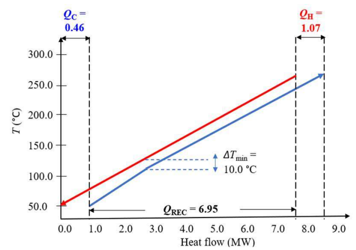
Scenario 1 – Improved energy recovery



ΔT_{min} = 21.5 ºC



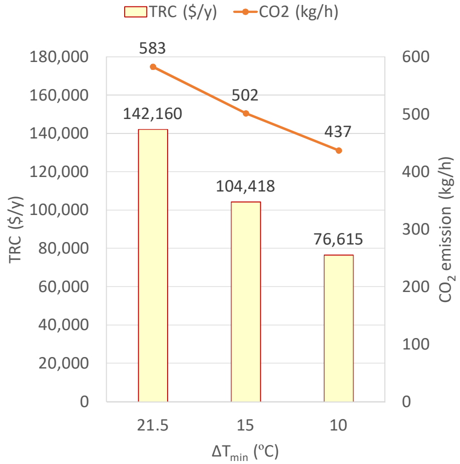
ΔT_{min} = 15 ºC



ΔT_{min} = 10 ºC

(Note: see appendix for details)

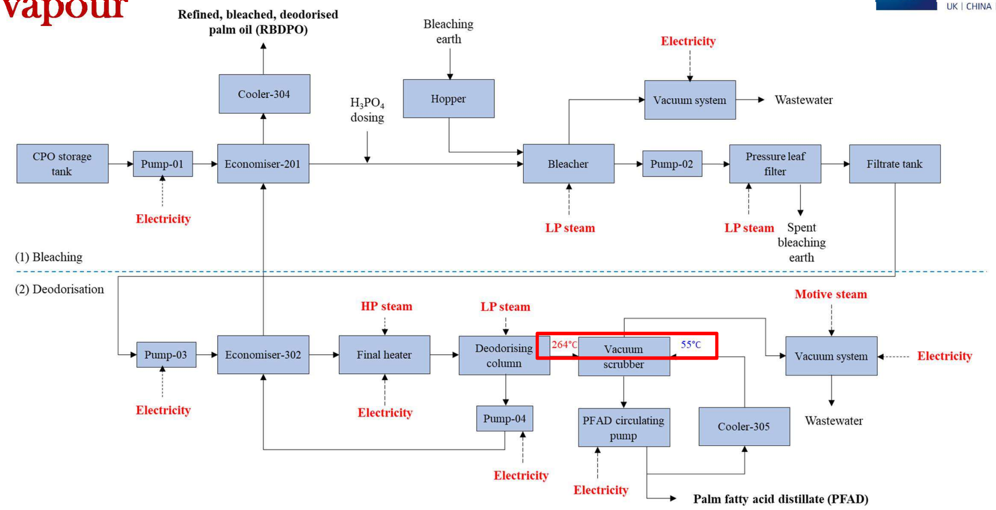
Scenario 1 – Improved energy recovery



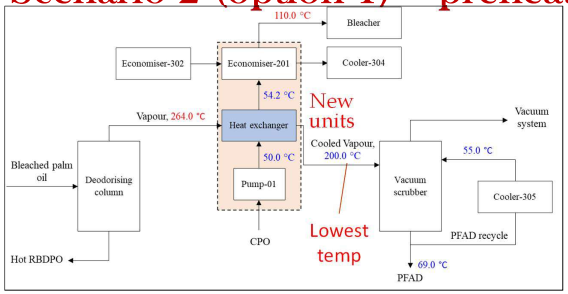
ΔT_{min} (°C)	C2 outlet temp (°C)	Area of heat exchanger (m²)			Boiler duty (MW)
		Economiser-302	Final heater	Economiser-201	
21.5	230.0	175.63	79.27	80.54	2.52
15.0	235.5	230.07	68.63	106.25	2.17
10.0	239.7	294.86	63.18	141.34	1.89

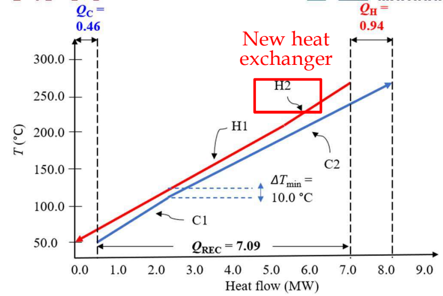
- For ΔT_{min} = **15 °C**:
- CAPEX: $544,331
  - Final heater: $19,985
  - Economiser-302: $57,868
  - Economiser-201: $29,030
  - Boiler: $437,448
- AF: 0.2374 (6% interest for 5 years)
- OPEX saving: 24,804 $/y
- TRC = 544,331*0.2374 – 24,804 = 104,420 $/y

Scenario 2 – Heat recovery from deodorizing vapour



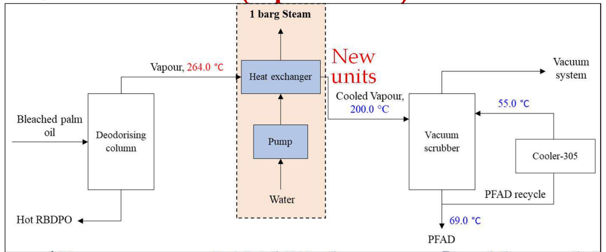
Scenario 2 (option 1) – preheat CPO





- ❑ Hot utility: 0.94 MW (36.2% lower than base case)
- ❑ Steam requirement reduces to 1.92 t/h ➔ CO_2 reduction: 387.02 kg/h
- ❑ CAPEX: $ 2,684 (HEX) + $ 45,240 (Economizer 201)
- ❑ OPEX saving: 57,853 $/y
- ❑ AF: 0.2374 (6% interest for 5 years)
- ❑ TRC = (2,684 + 45,240)*0.2374 – 57,853 = -46,476 $/y (cost saving)

Scenario 2 (option 2) – LP steam generation



- 3.6 t/h of LP steam are needed for bleacher, deodorising column, & pressure leaf filter.
- Simulation results:
  - 1,281 kg/h of 1 barg steam can be generated.
  - Emission factors: 0.274 kg CO_2/kg steam

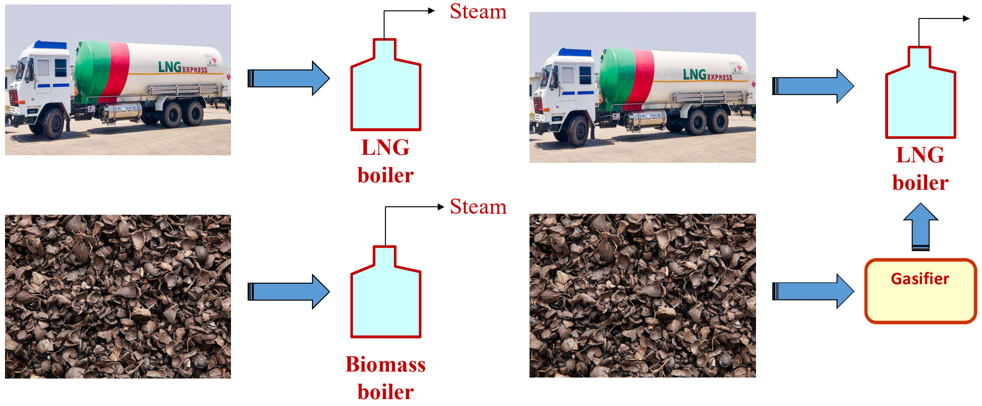
✓ Pump incurs 0.131 kW electricity ➔ additional CO_2 emission = 0.131 kW × 0.622 kg CO_2/kWh = 0.08 kg/h CO_2.

✓ Net total CO_2 emissions reduction = avoidance from steam generation – CO_2 from pump usage = 1281 x 0.274 – 0.08 = 350.9 kg/h .

- ❑ CAPEX: $ 14,928
- ❑ OPEX saving: 502,945 $/y
- ❑ AF: 0.2374 (6% interest for 5 years)
- ❑ TRC = 14,928*0.2374 – 502,945 = -499,401 $/y (cost saving)

Scenarios 3 & 4 – options with biomass

Scenario 3 **Scenario 4**



Scenario 3 – Implementation of biomass boilers

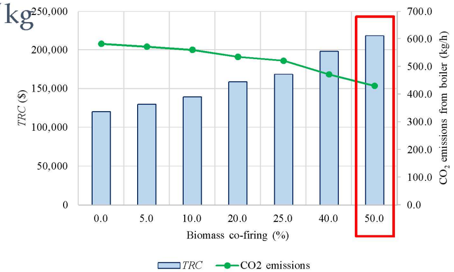
- Emissions from combustion of biomass is offset by CO_2 intake during photosynthesis ➔ **carbon-neutrality**.
- Example: LNG boiler can be replaced with palm biomass (e.g. empty fruit bunches, palm kernel shells) complete removal of CO_2 emissions of 582.96 kg/h (24.9 % reduction).
- Issue with direct biomass-powered boiler:
  - **High CAPEX** (~$ 1.26 M, i.e. 3x of liquified NG boiler
  - Ash adhesion on boiler surface
  - Large space requirement for biomass storage
  - Entangling issue of fibres in the boiler
- Possible solution: convert biomass into syngas via gasification as fuel source for the boiler.


palm kernel shells

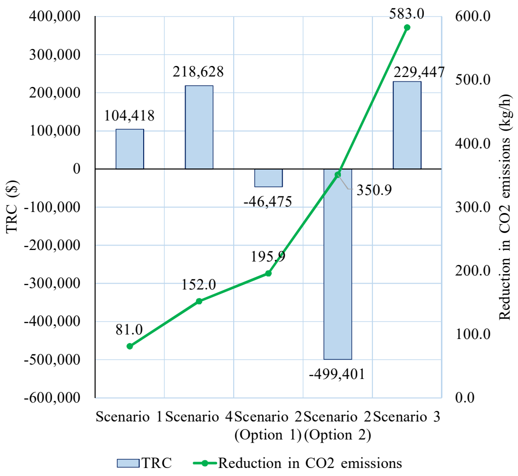

Palm fiber

Scenario 4 – Co-firing of biomass with LNG

- Advantage: reduce the CAPEX
- To calculate LHV of mixture: $LHV_{mix} = f\,LHV_{biomass} + (1-f)LHV_{LNG}$
- Example: co-combustion of **50% palm kernel shell** (PKS) with LNG:
  - LHV: 15,594 kJ/kg (PKS); 44,200 kJ/kg (LNG)
  - LHV_{mix} = 0.5(15,594)+0.5(44,200) =29,900 kJ/kg
- CAPEX calculation:
  - Biomass boiler: 997,451 $
  - Gasifier: 493,229 $
  - AF: 0.237 (6% interest for 5 years)
  - Annualised CAPEX: 236,791 $/y
- Cost saving: 18,160 $/y
- Total retrofit cost (TRC) = 23,6791 – 18,160 = 218,631 $/y

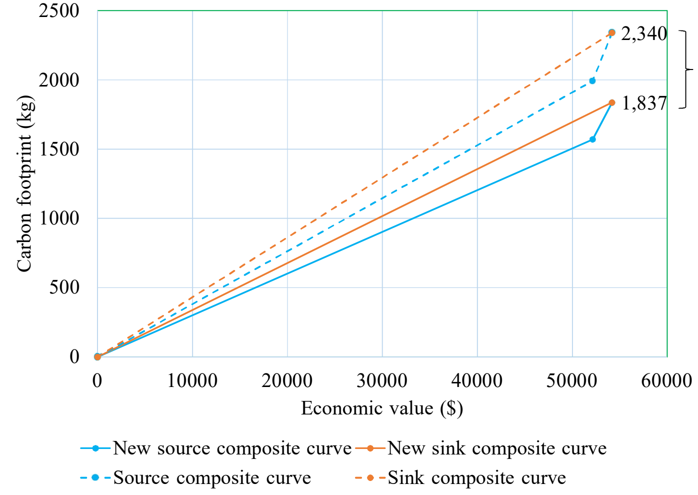


Scenarios comparison



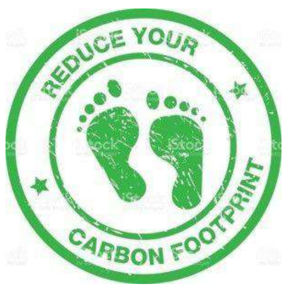
- Targeted CFP reduction: **468 kg/h CO_2**
- **Scenario 3** achieves target (538 kg CO_2 reduction), however too costly.
- Proposal 1: combine **Scenarios 4 & 2 (option 2)**:
  - TRC: 218,628 – 499,401 = 280,773 (saving)
  - CO_2 reduction: 152 + 350.9 = 502.9 kg
- Proposal 2: combine **Scenarios 3 & 2 (option 2)**:
  - TRC: 229,447 – 499,401 = 269,954 (saving)
  - CO_2 reduction: 583 + 350.9 = 933.9 kg

Initial and revised CECC (Scenarios 4 & 2 (option 2))



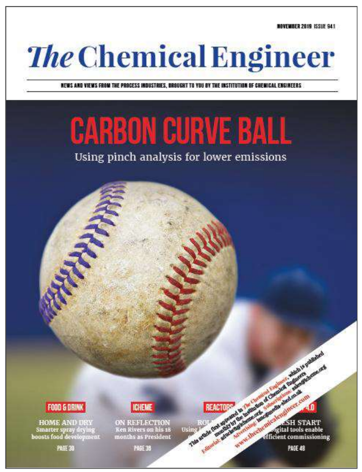
Concluding Remarks

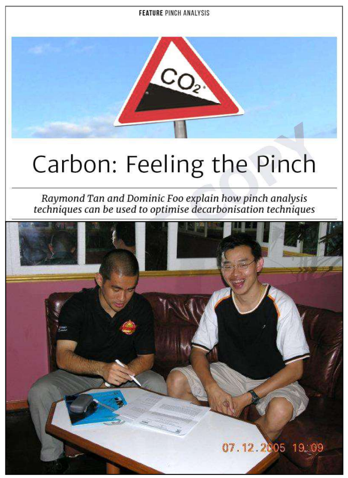
- There is a broad global consensus that climate change is a grave environmental issue
- Decision support tools based on PSE can help professionals to effectively plan various decarbonisation options.

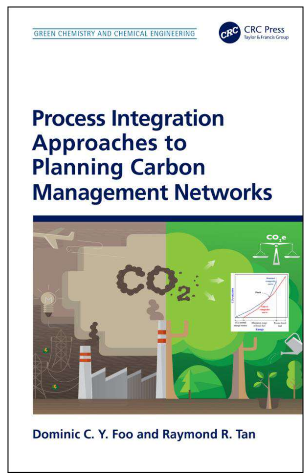


Carbon Management Networks

(Tan & Foo, 2007. Energy 32: 1422)

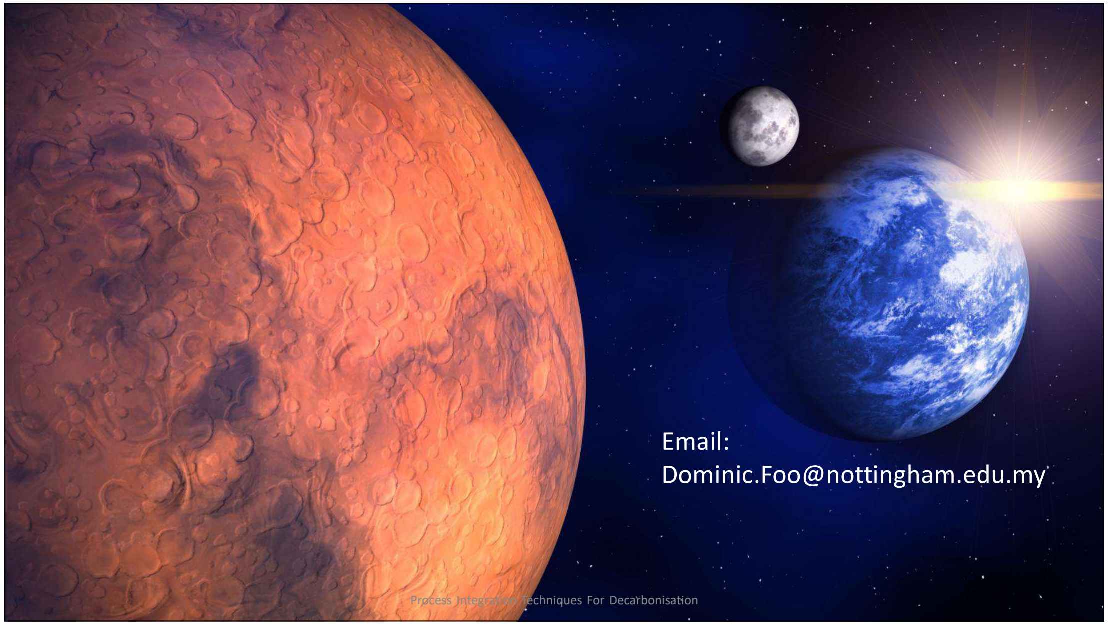






Acknowledgement

University of Nottingham
UK | CHINA | MALAYSIA



Process Integration Techniques For Decarbonisation