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CENTRE FOR SMART ENERGY SYSTEMS

High-temperature Heat Pumps For Process Heat Decarbonisation: A Systems Integration Perspective

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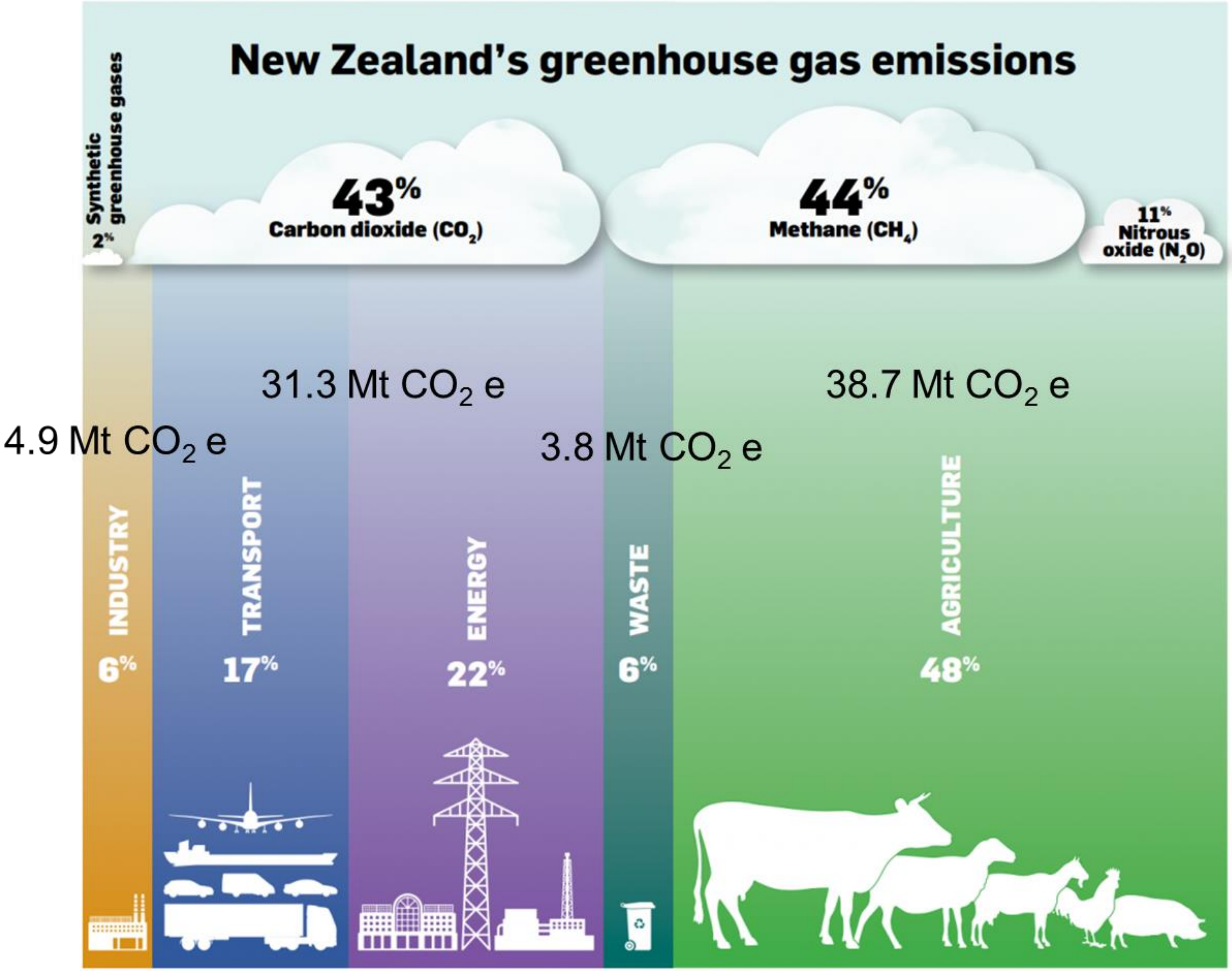
16th OERC Symposium, Dunedin, New Zealand

29 November 2022

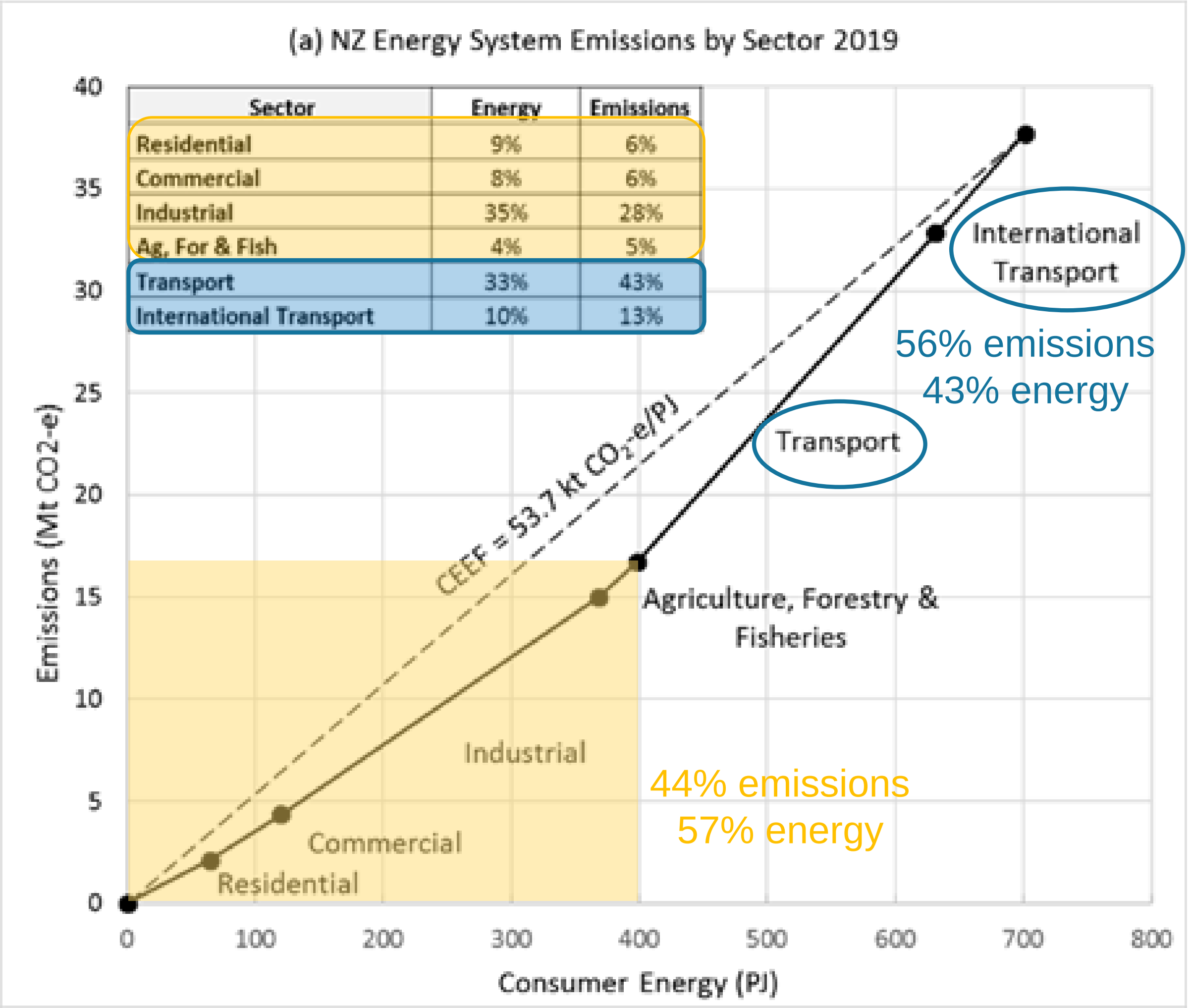
Outline

1) NZ's Decarbonisation Challenge
2) Project Ahuora and Our Approach
3) Digitalisation and Digital Twins
4) Demand-side Analysis by Sector
5) Heat Pump Technology Analysis
6) Conclusion

NZ GHG emissions by sector 2018



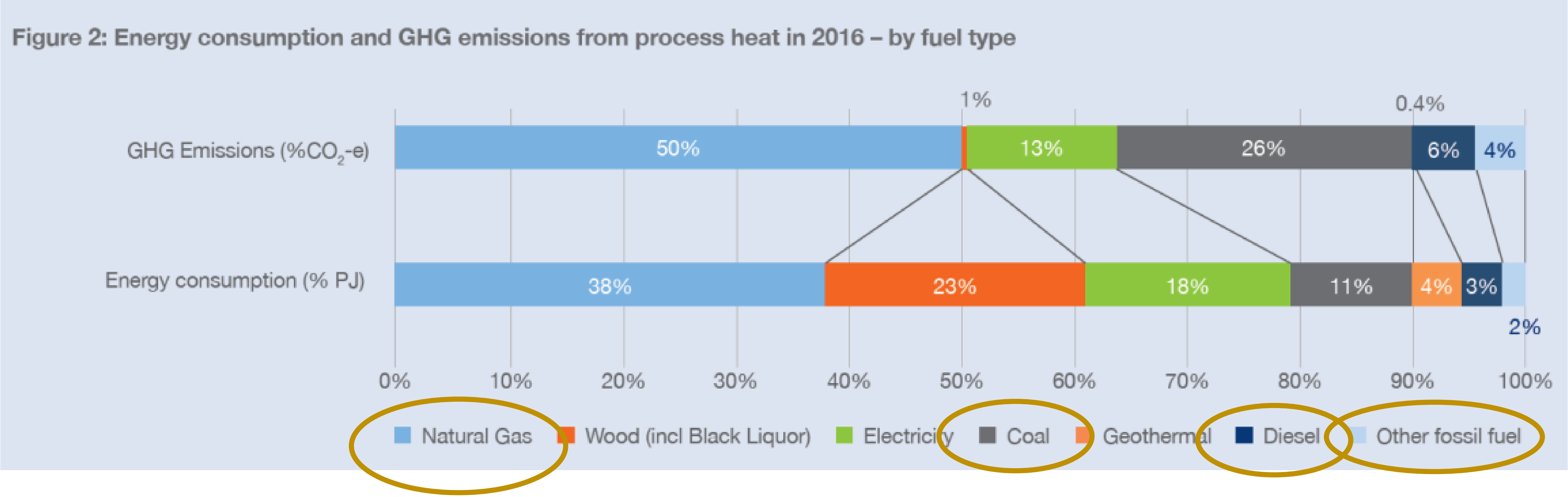
Industrial energy use



35% consumer energy for industry

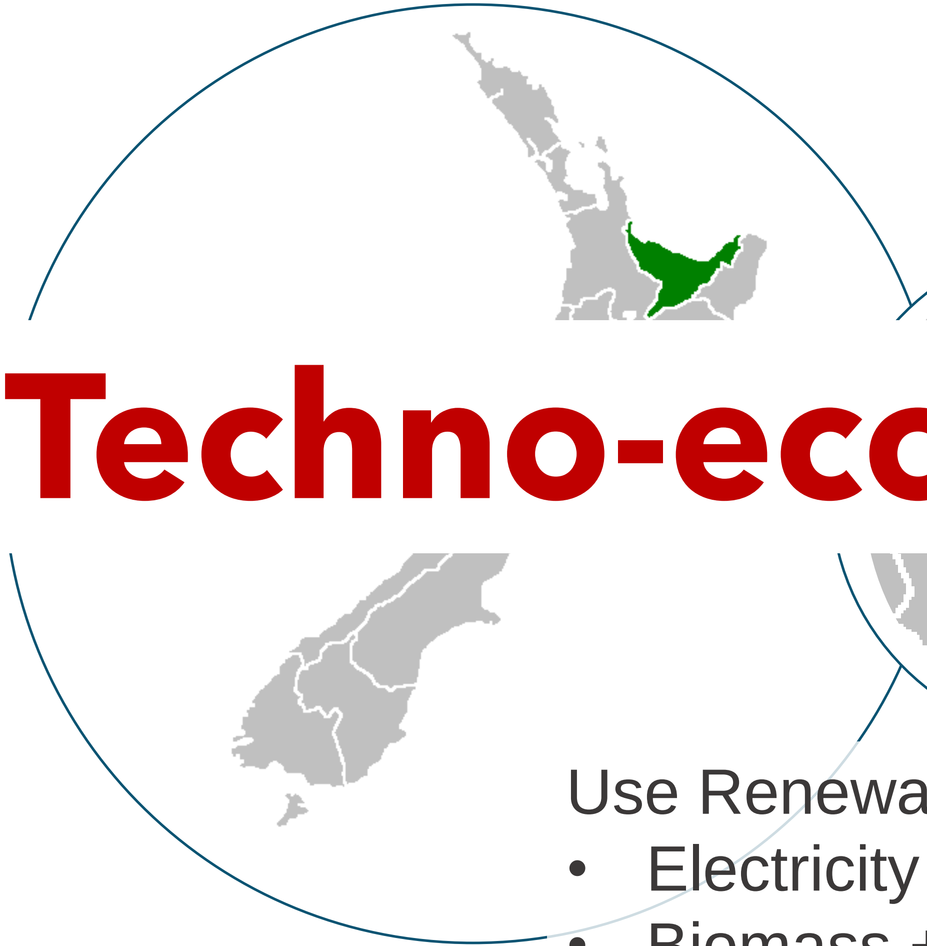
Process heat fuels

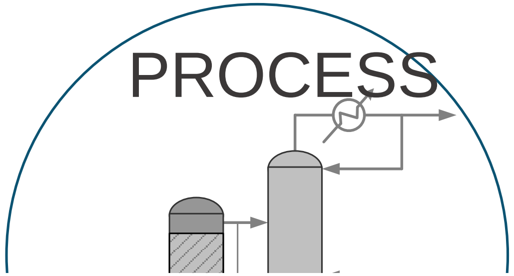
56% Fossil fuels



How to decarbonise industry?

Three options
(1) Reduce demand
(2) New technology
(3) Fuel switch





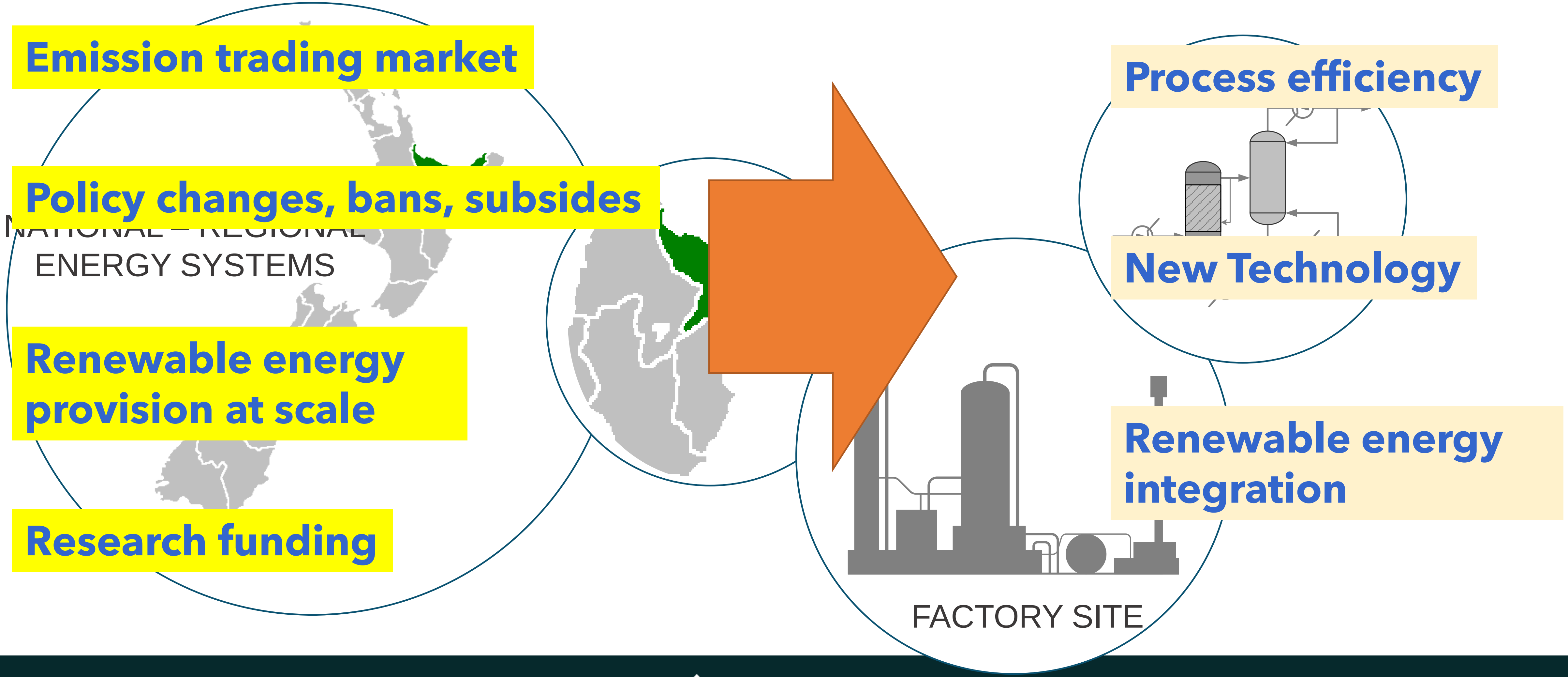
Techno-economic challenge

efficiency

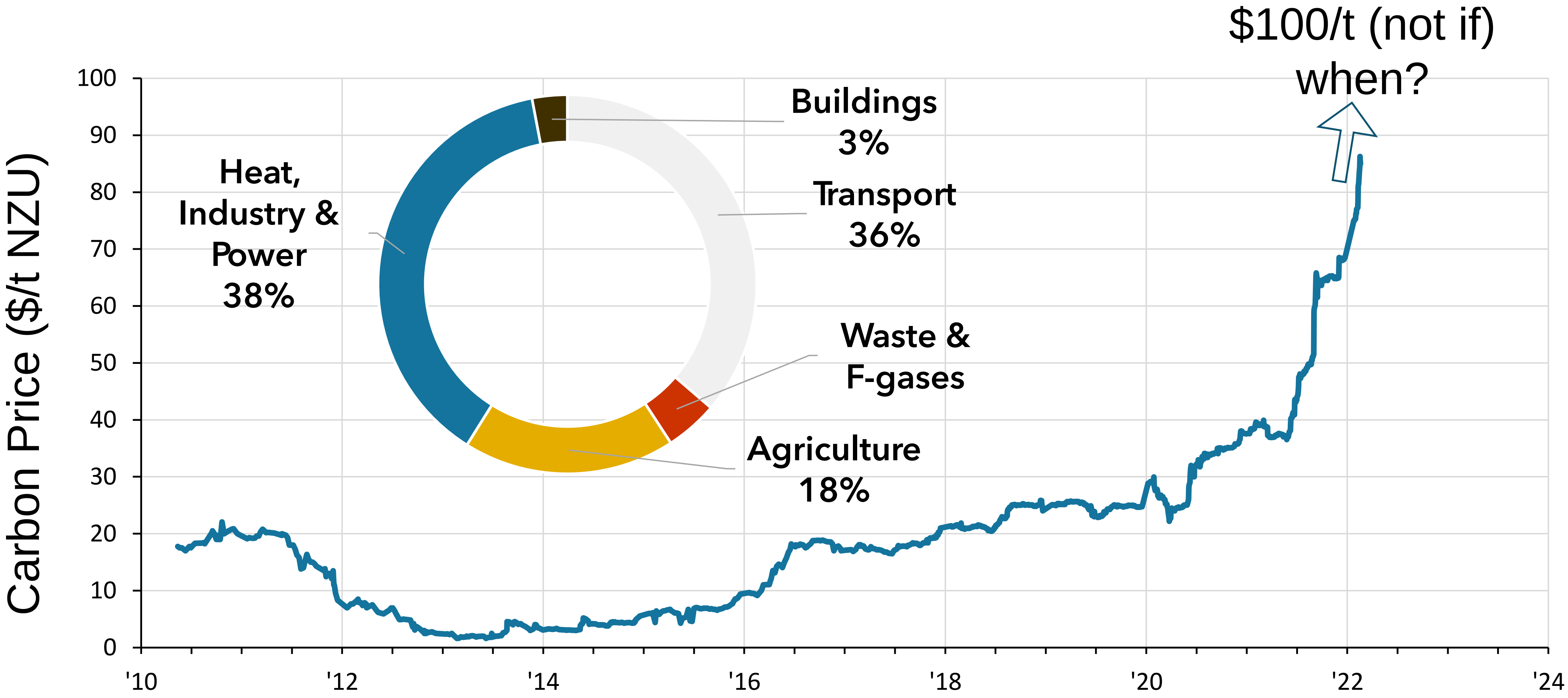
Use Renewable Energy
- Electricity
- Biomass + H2

Adopt low emissions technology

What are countries and companies doing to decarbonise HEAT?



Carbon Price = Increasing Risk



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Government policy driving change

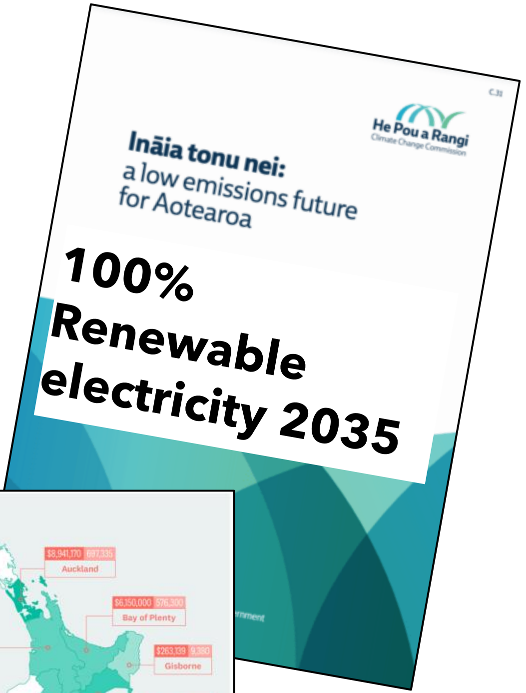
ZERO CARBON ACT NZ

EECA
TE TARI TIAKI PŪNGAO
ENERGY EFFICIENCY & CONSERVATION AUTHORITY

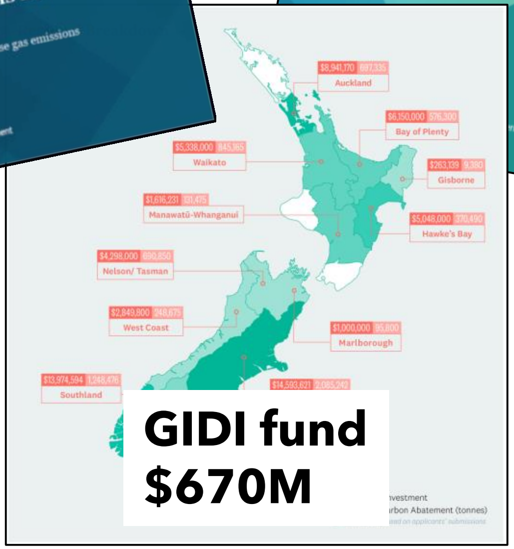
ETA programme

Off shore oil & gas ban

Coal boiler ban By 2037



100% Renewable electricity 2035



GIDI fund $670M

$50 million/ 7 years

Advanced Energy Technology Platform (AETP) research call – Nov 2019

FONTERRA IS "GETTING OUT OF COAL"

Robert Spurway, CEO
Fraser Whineray, COO

AETP research fund Nov 2019
What research is essential for decarbonisation?

- AETP = Technology at the **frontier of innovation**, with the potential to **advance and disrupt** global energy markets
- **Raise the research capacity** and capability of New Zealand in energy science (engineering) through **early stage research**
- Grow **international and national collaborations** among energy science (engineering) researchers and end users

Decarbonising industrial processing

Plant efficiency   Boilers & Heat pumps   Renewable energy

- Re-engineer the way we **use**, **convert**, and **provision** energy for process heat using a smart systems approach

- Produce open-access software tools for NZ industry

- Develop the next generation of **Energy Digital Twin** technology called **Adaptive Energy Digital Twin**

Smart design and operation

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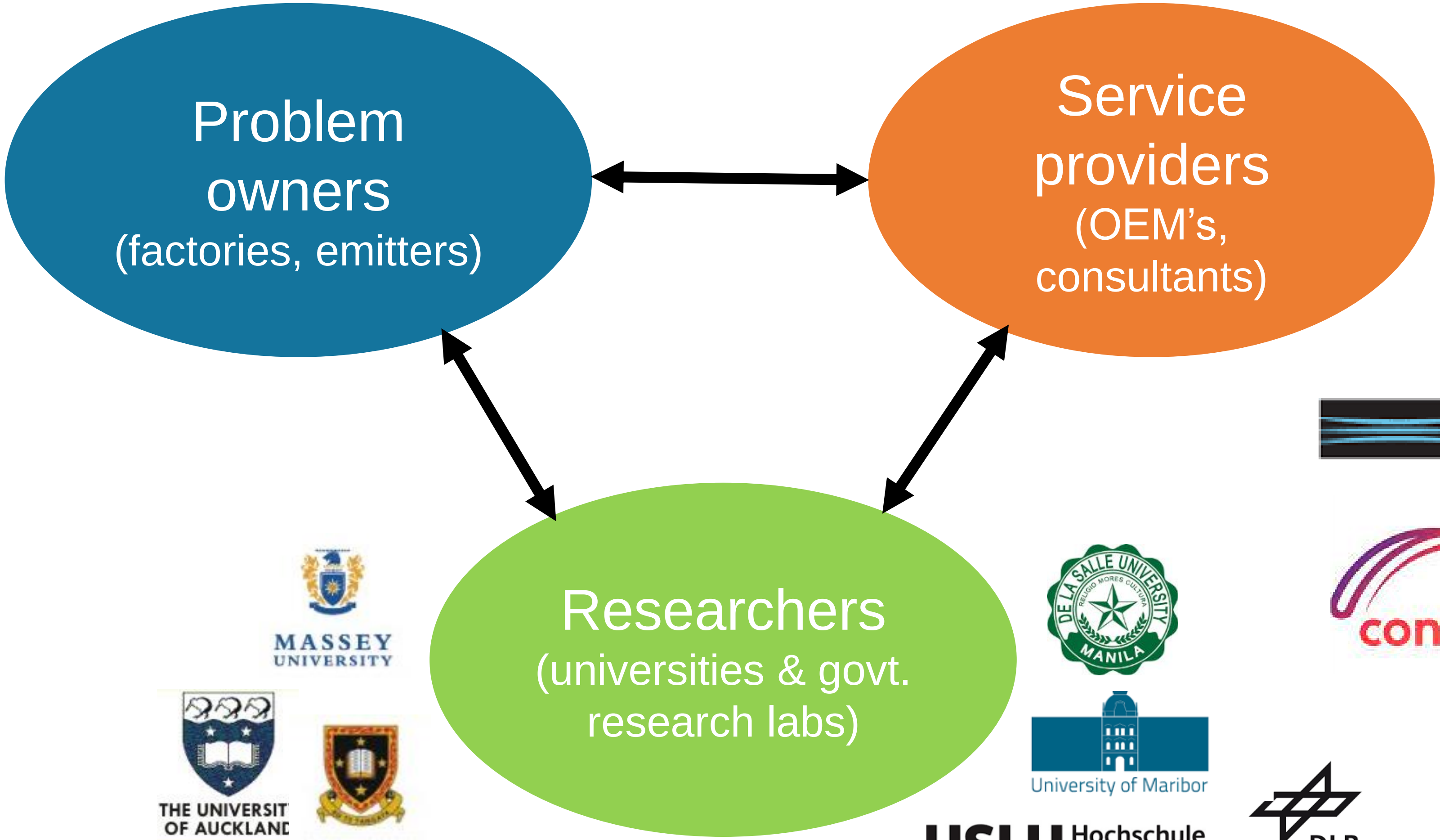
13 Academics (9 UoW)
2 Post Docs
18 PG & 5 UG students

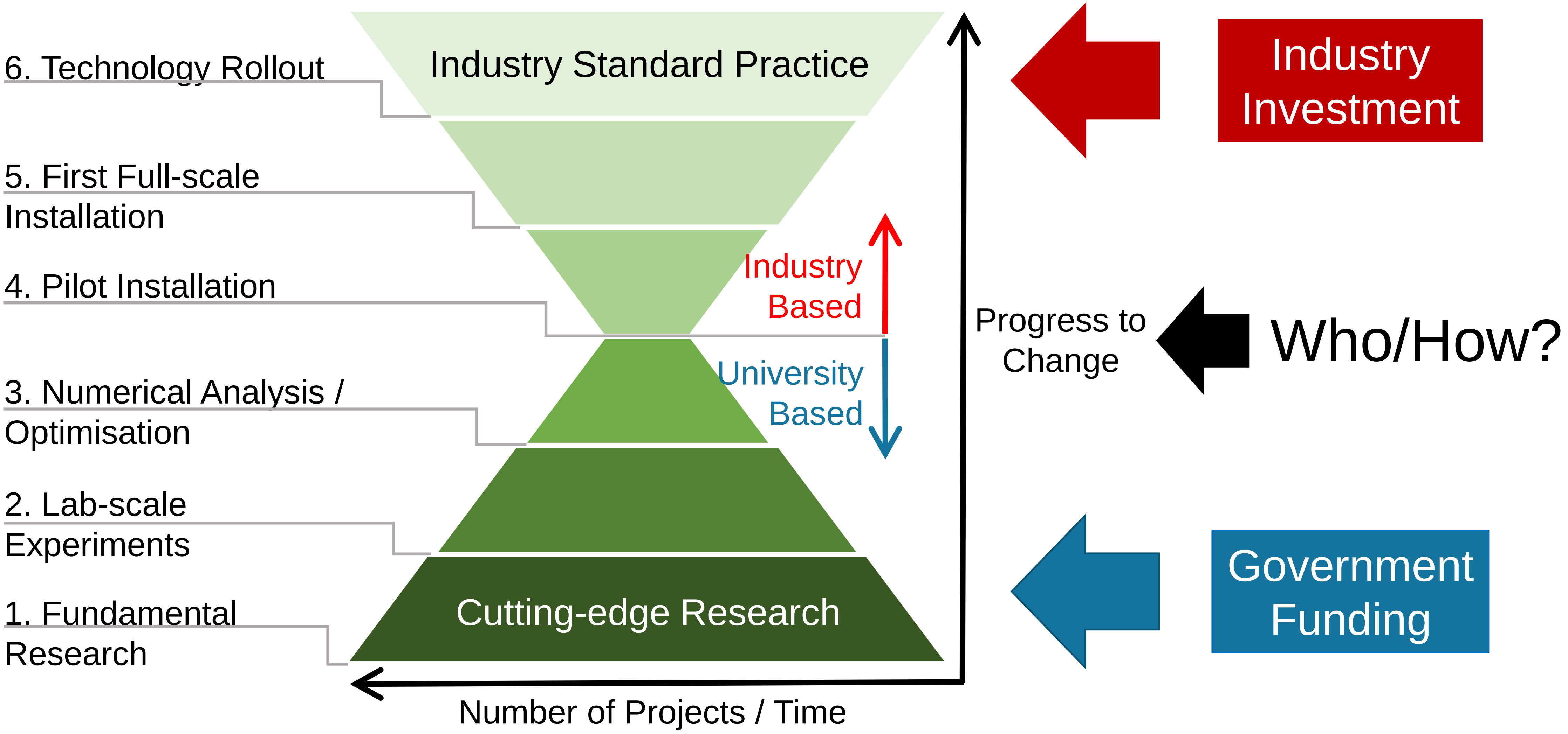
Helping create **sustainable, net-zero-carbon** New Zealand industries that sit in harmony with **taiao** and support **tāngata**.

Collaboration model



Tetra Pak
GEA
Windsor Engineering
DETA Consulting
aurecon
Transpower
contact
genesis energy
Fonterra
ANZCO Foods
Ballance agri-nutrients
Golden Bay Cement
methanex the power of agility
Massey University
The University of Auckland
The University of Waikato
De La Salle University Manila
University of Maribor
HSLU Hochschule Luzern
DLR

Collaboration can lead to change



Understanding each other

Researchers	Industry
Love to be the first	Happy to follow, too risky being first
Love proposing new theories	Happy with the tried and true
Prefer simplified studies	Want real plant studies
Optimistic with costs	Pessimistic with costs
Hope for the best case	Expect the worst case
Bear no risk, no capital investment	Bear all risk, investment
Publishing is king	**Production is king**

Trust takes time, effort & collaboration; not a high h-index

Starting with small steps…

- Hosted a **'digital twin' training day** for 15 industry professionals from Fonterra, Aurecon, DETA, Worley (15 Nov. 2022)
- Covered the basics of **process simulation** – start with common ground!
- Built **connections** between the problem owner, service provides, and us

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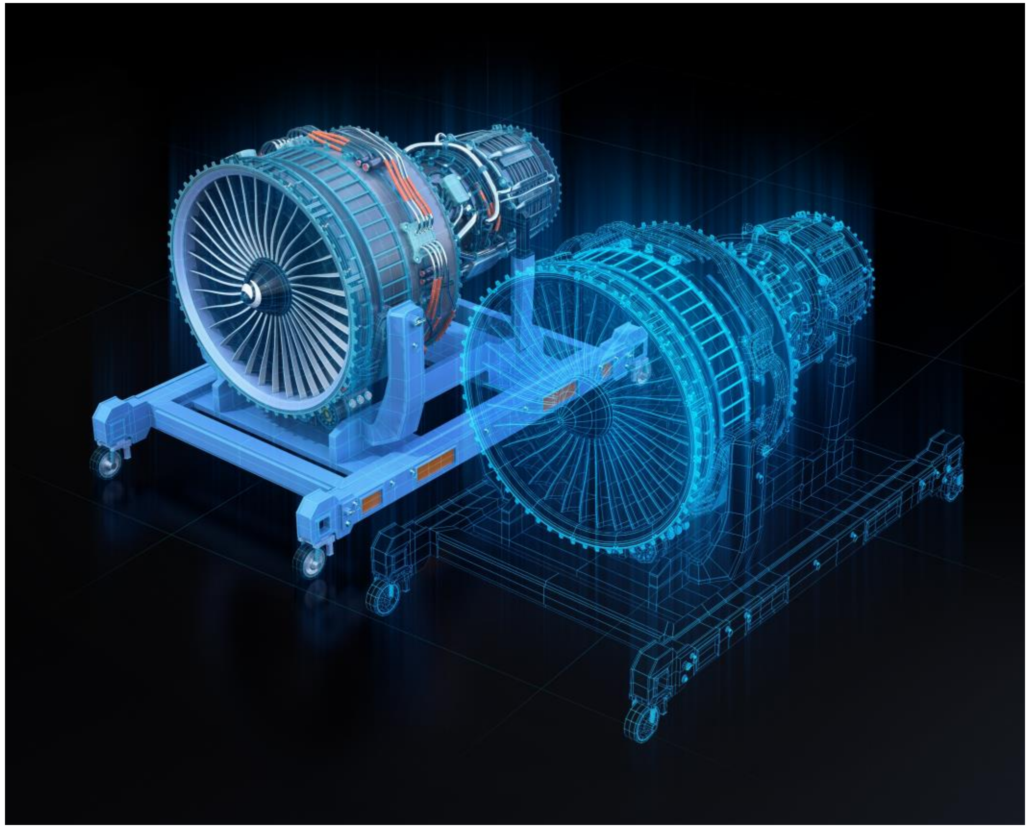
Digitalisation

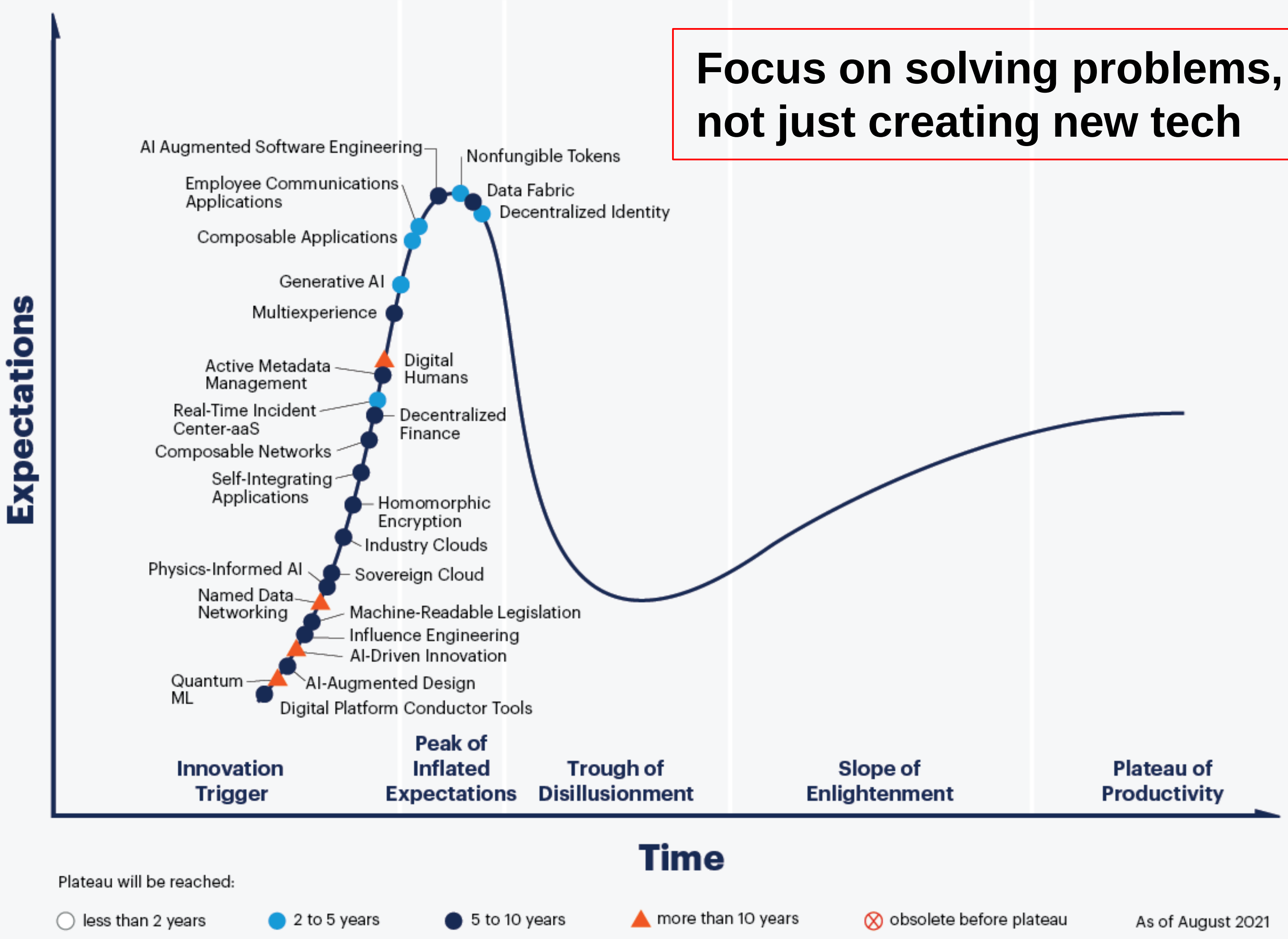
Leveraging digital technologies

→ I.e., Not digitisation
Converting information to a digital form



Hype Cycle for Emerging Technologies, 2021

Focus on solving problems, not just creating new tech

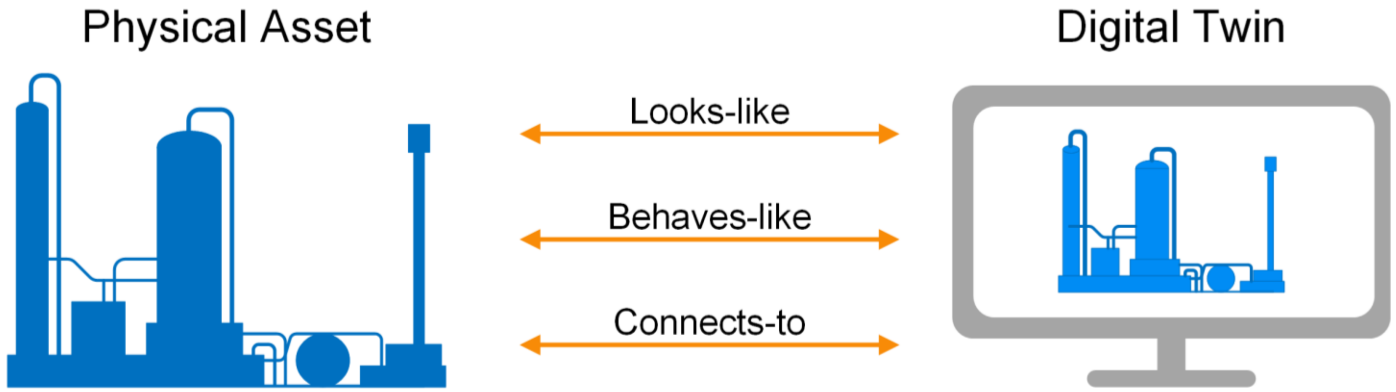


gartner.com

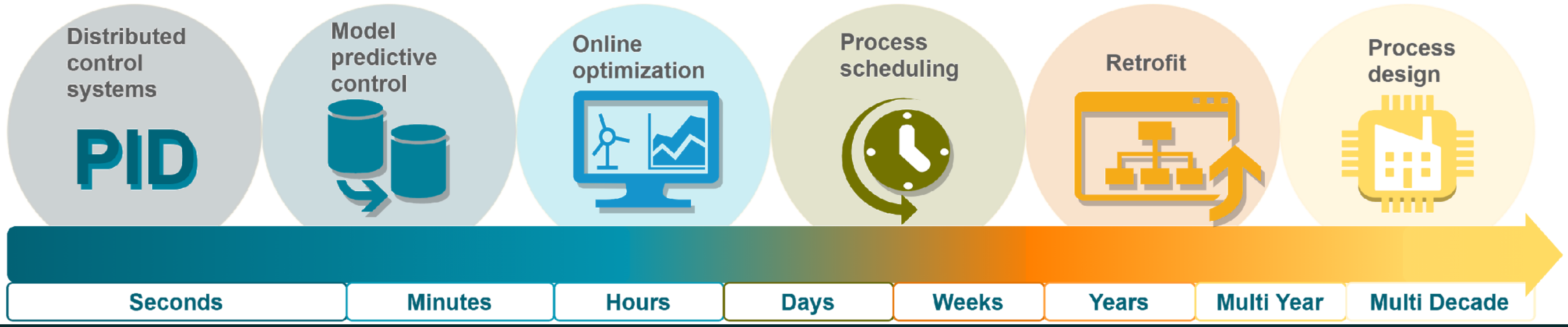
Source: Gartner

Gartner

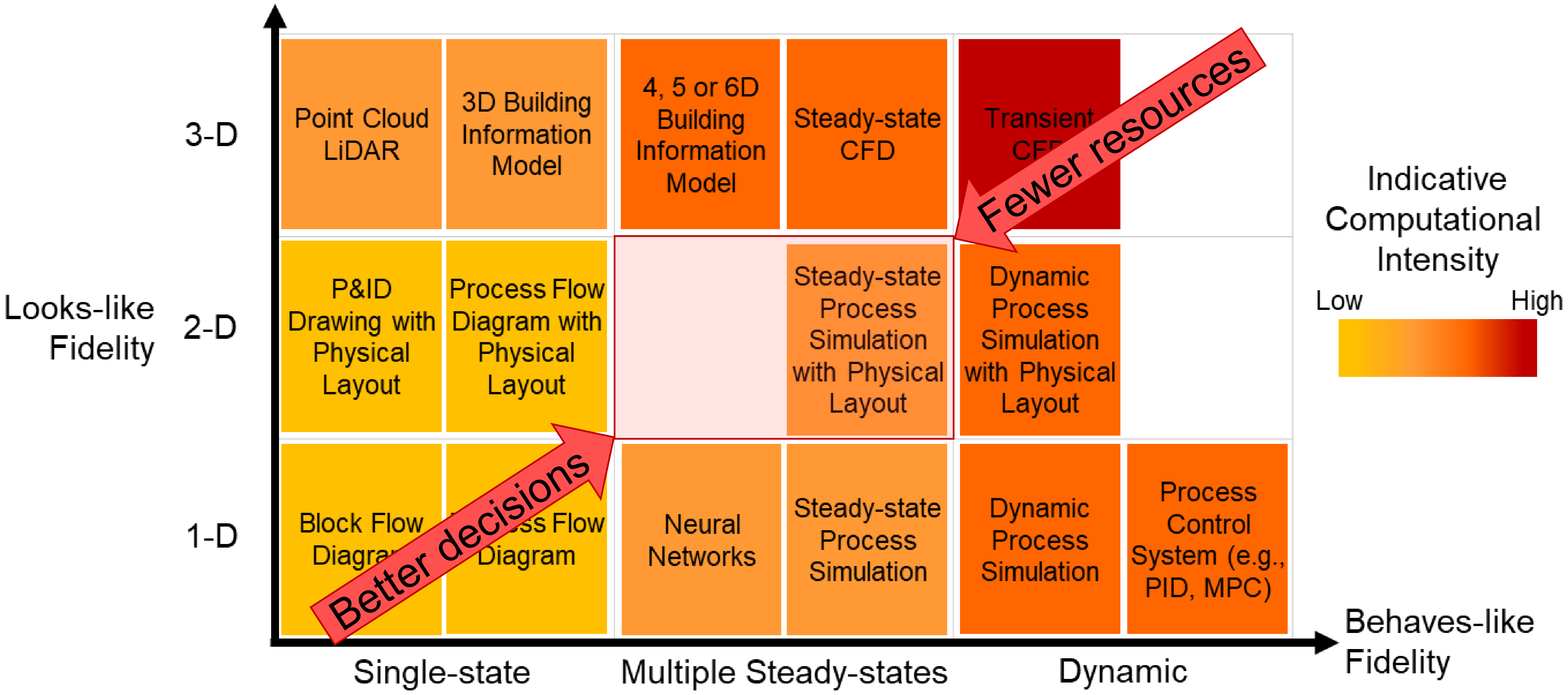
What is an Energy Digital Twin?



Digital twins aim to improve
decision-making across all time horizons



Digital Twin classification

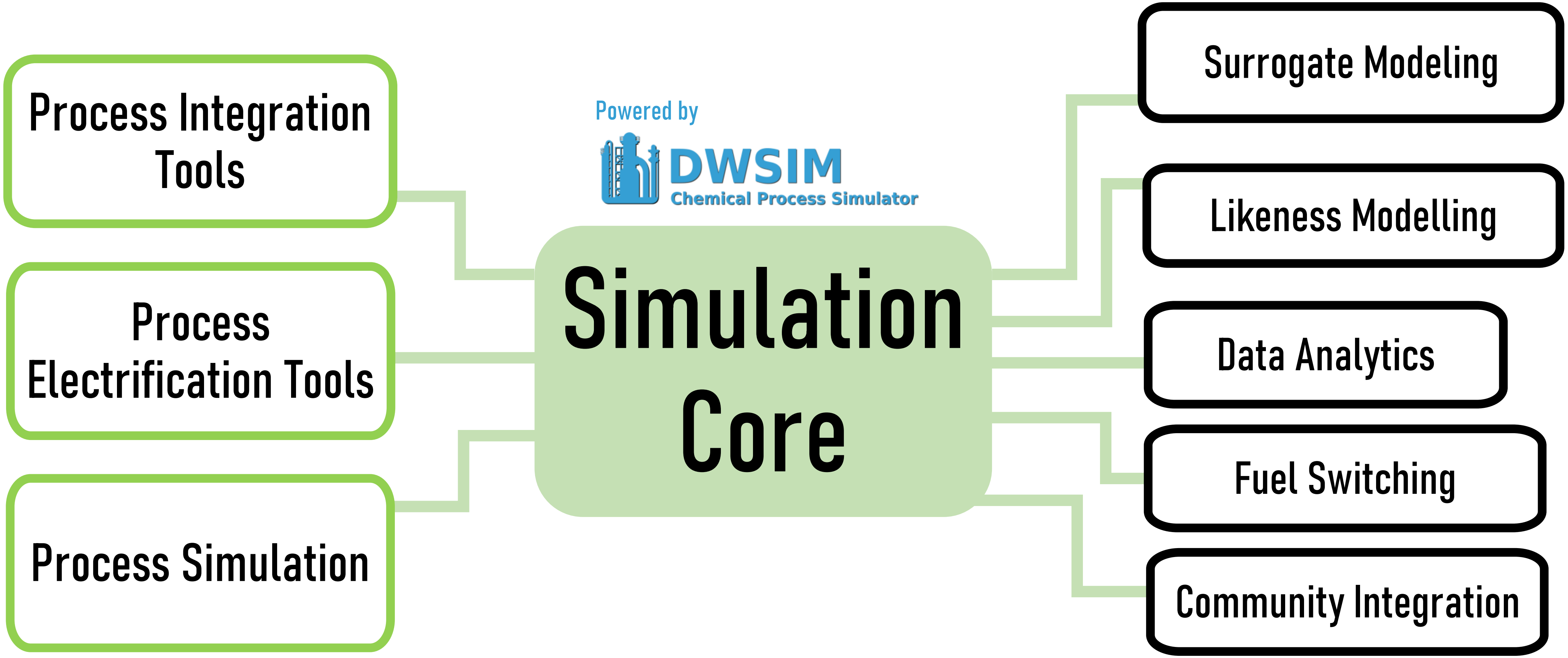


Digital Twin lifecycle applications

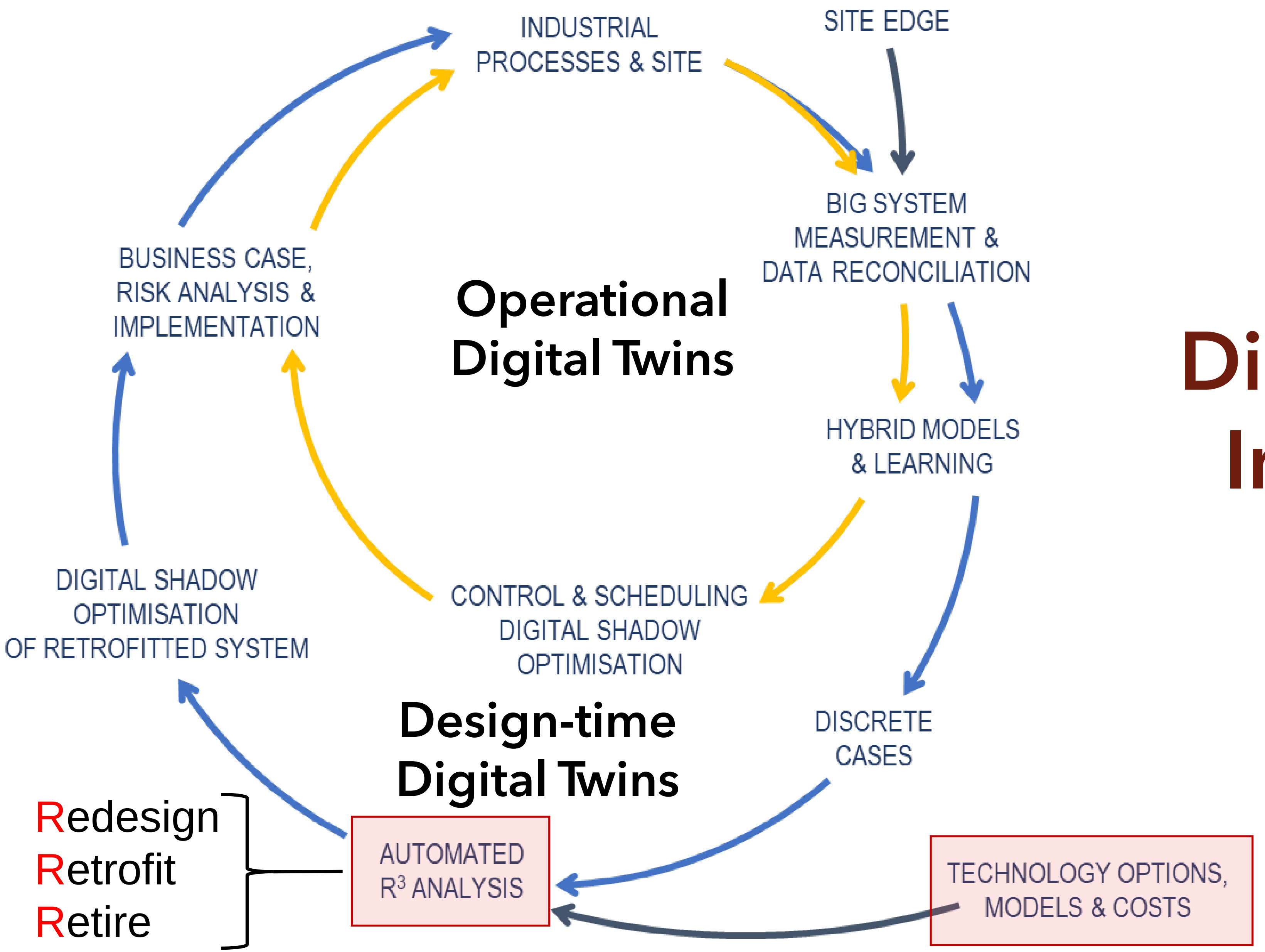
Goals:
Accurate
De-risked
Predictive
Optimal
Low-carbon

- **Design phase**
  - Optimisation
  - Data generation
  - Virtual evaluation, verification, and validation
  - Low-carbon design & process electrification
- **Operation phase**
  - Process monitoring
  - Production control
  - Process prediction
  - Process optimisation and production planning
  - Process training
- **Service phase**
  - Predictive maintenance
  - Fault detection and diagnosis
  - Virtual testing

Towards a NZ-centric DT Platform

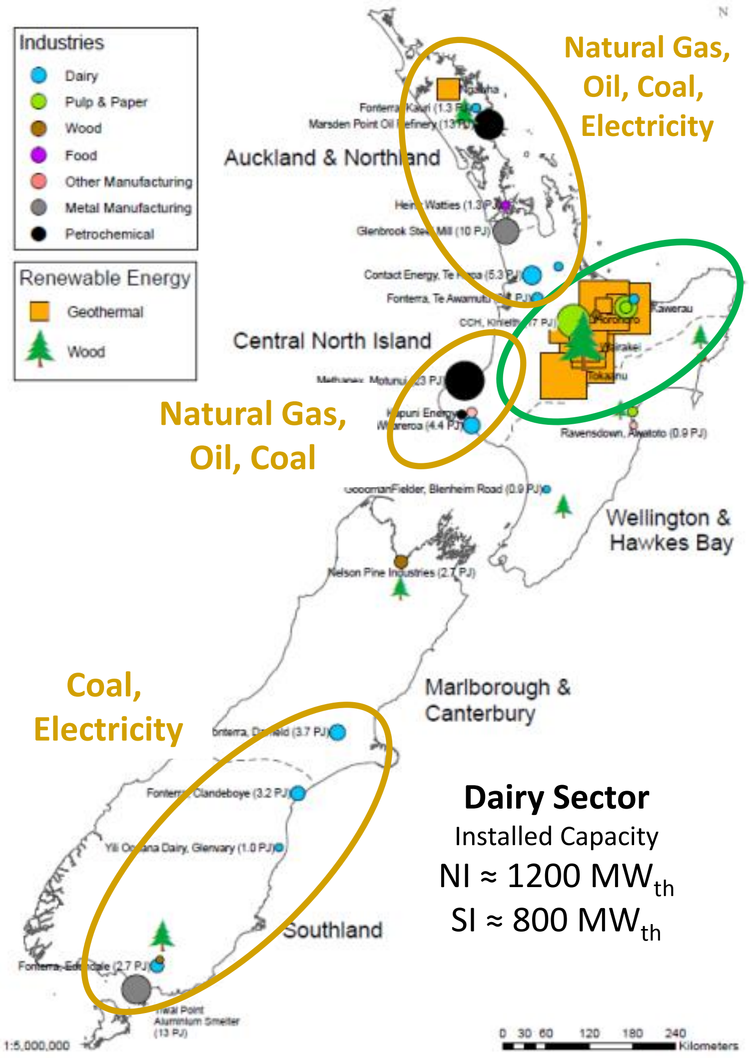


Energy Digital Twins & Improvement Cycles



Industrial-scale Heat Pumps

Why industrial heat pumps critical for NZ's decarbonisation



Dairy Sector

Installed Capacity

NI ≈ 1200 MW_{th}

SI ≈ 800 MW_{th}

Number of plants by sector

	Sector/process	Number of plants in New Zealand
Boiler plant	Dairy processing *milk powder / other*	≈80 *≈50/30*
	Meat processing	86
	Other food	44
	Wood processing	75
Tightly integrated	Methanol	2
	Urea	1
	Refining	1
	Steel	1
	Aluminium	1
	Cement	1
	Kraft pulp	2

54% emissions
~300 factories

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54% emissions
~300 factories

46% emissions
9 factories

What's their future??

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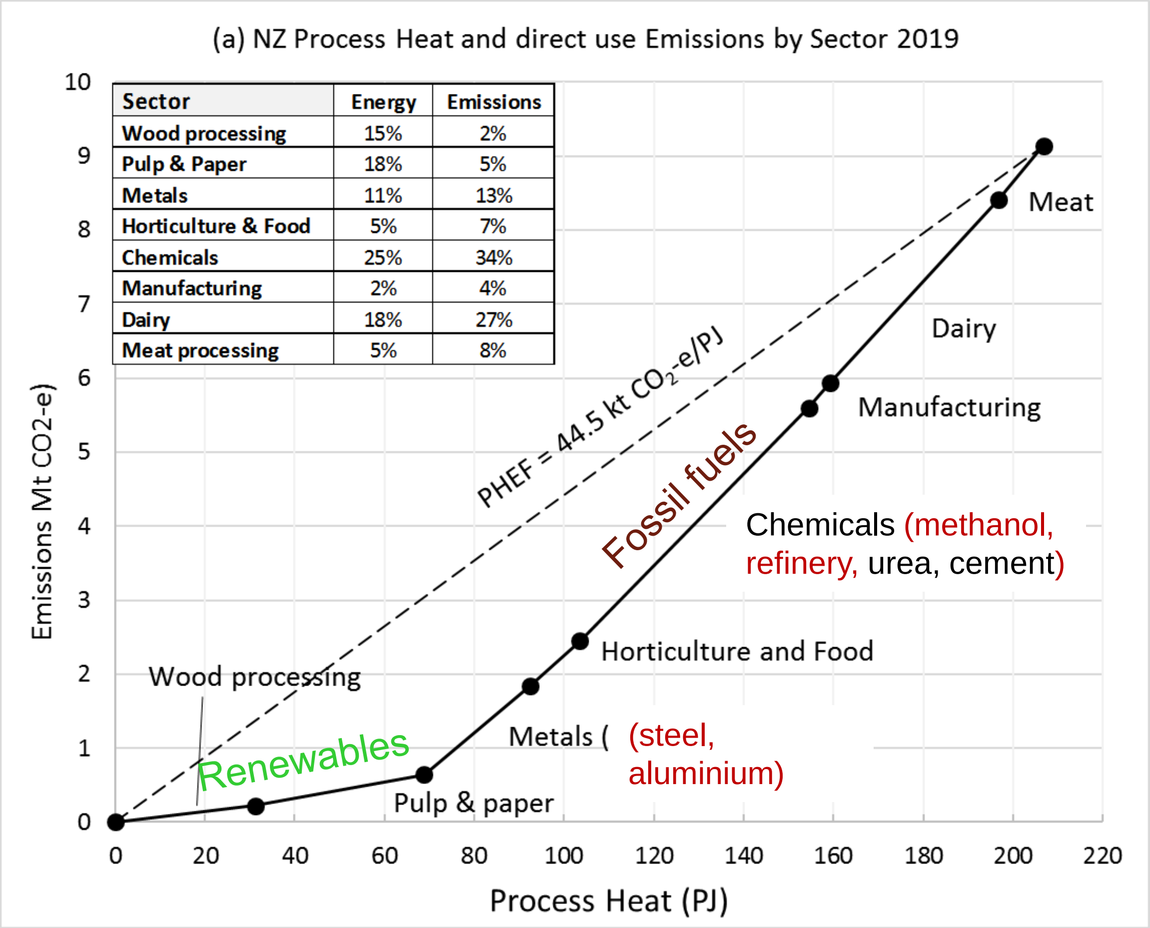
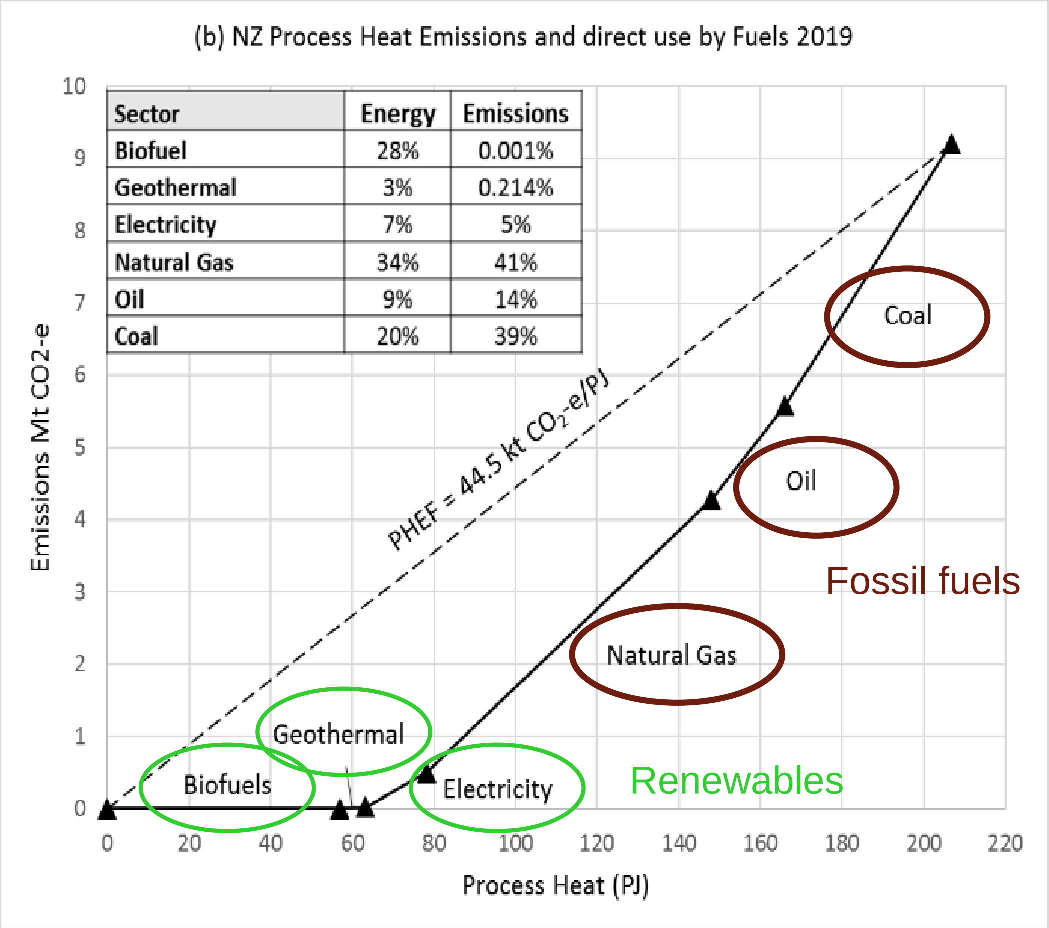
Sources of industrial emissions

>80% industrial energy is process heat



Sector	Energy	Emissions
Wood processing	15%	2%
Pulp & Paper	18%	5%
Metals	11%	13%
Horticulture & Food	5%	7%
Chemicals	25%	34%
Manufacturing	2%	4%
Dairy	18%	27%
Meat processing	5%	8%



Sector	Energy	Emissions
Biofuel	28%	0.001%
Geothermal	3%	0.214%
Electricity	7%	5%
Natural Gas	34%	41%
Oil	9%	14%
Coal	20%	39%

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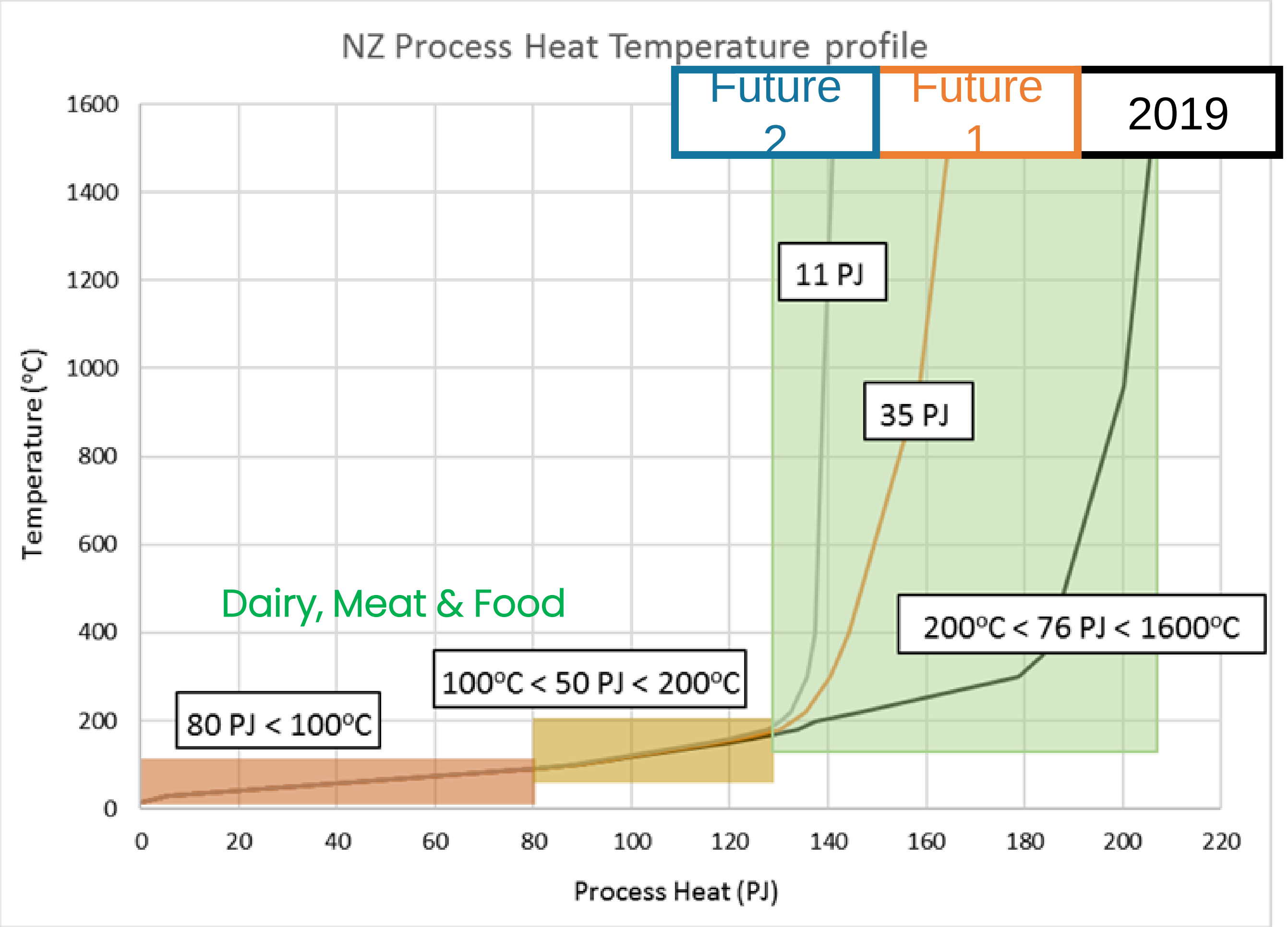
Industrial sector temperature-load profile

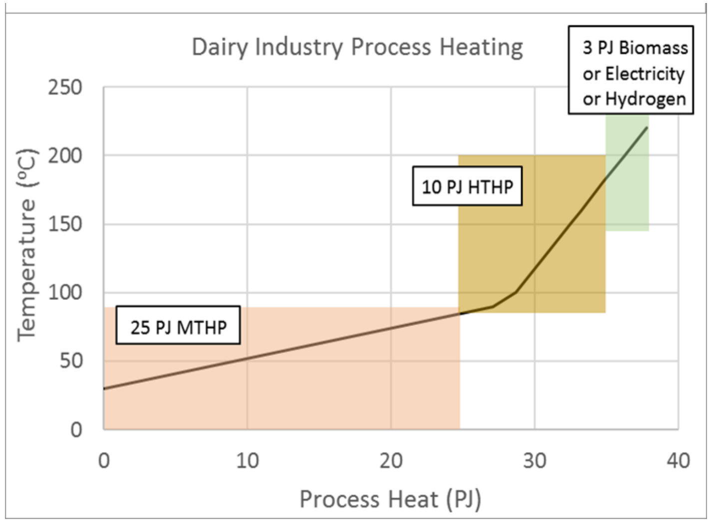


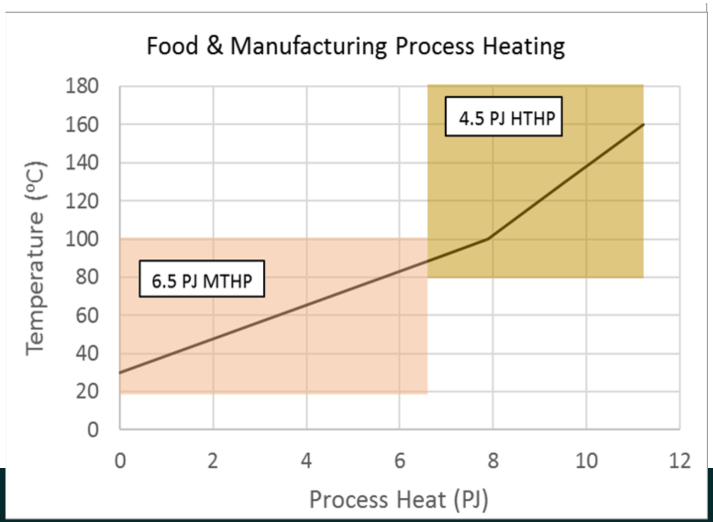
Future 1:
Refinery closed
Methanex closed

Future 2:
Refinery closed
Methanex closed
NZ Steel closed
Aluminium smelter closed

Key research focus: Dairy, Meat & Food processing factories

Food and fibre sector focus





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Food & Manufacture	6.5 PJ	4.5 PJ	
Wood + P&P			62 PJ
Horticulture	4 PJ		
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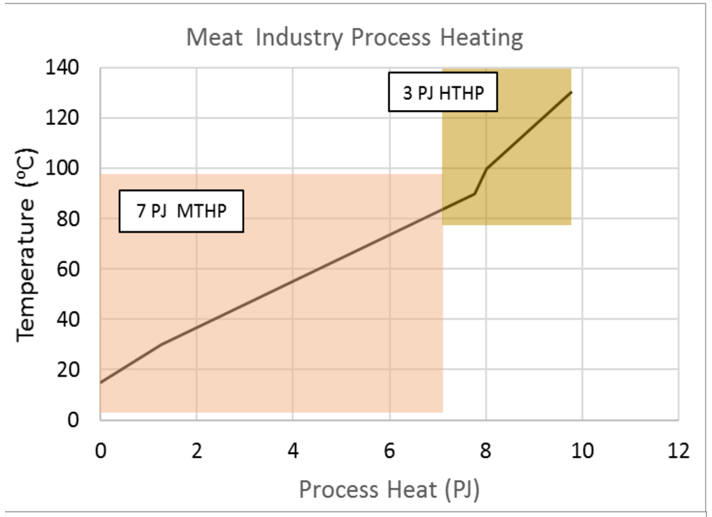

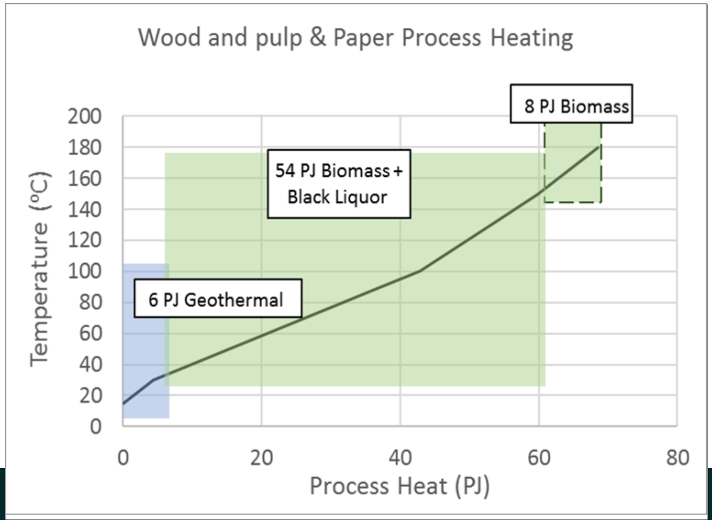

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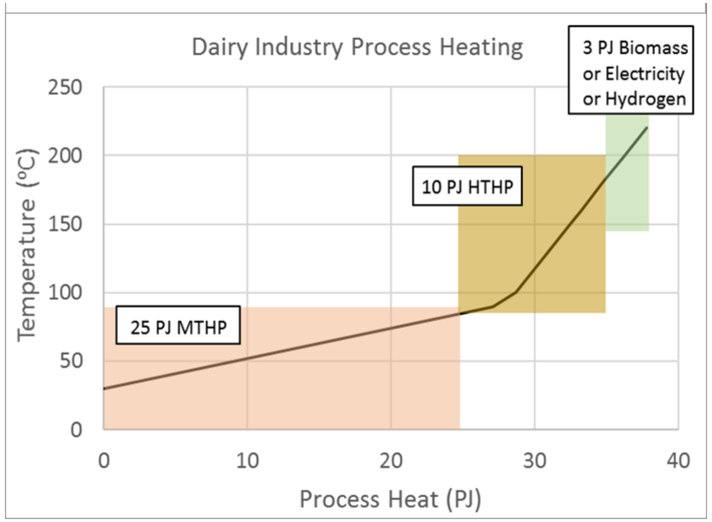

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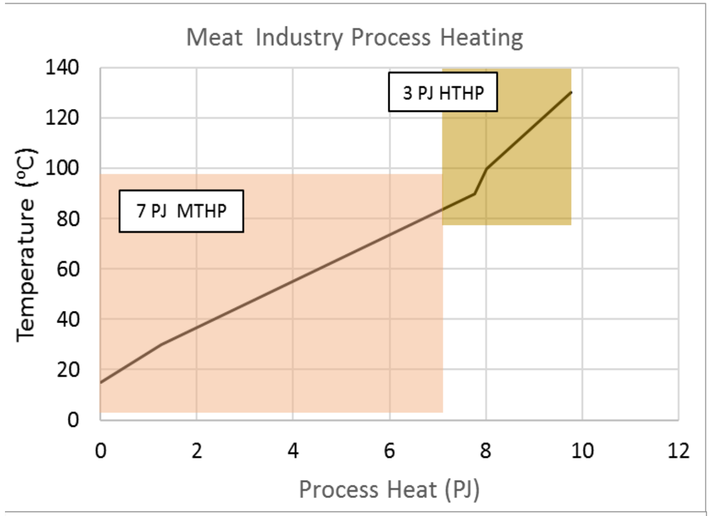

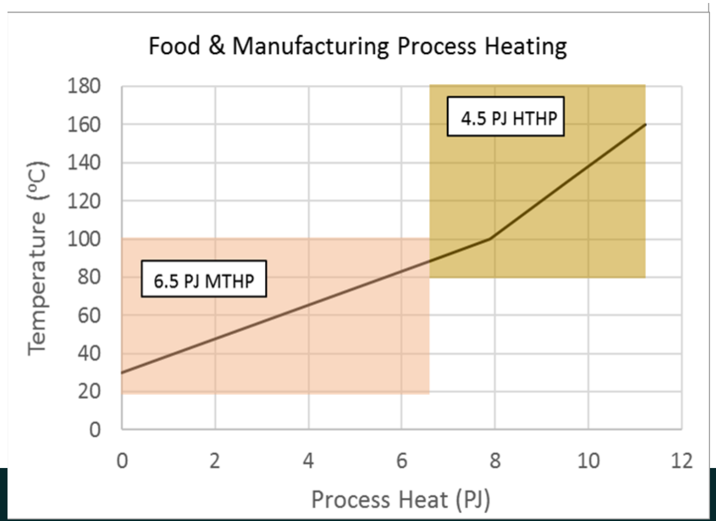

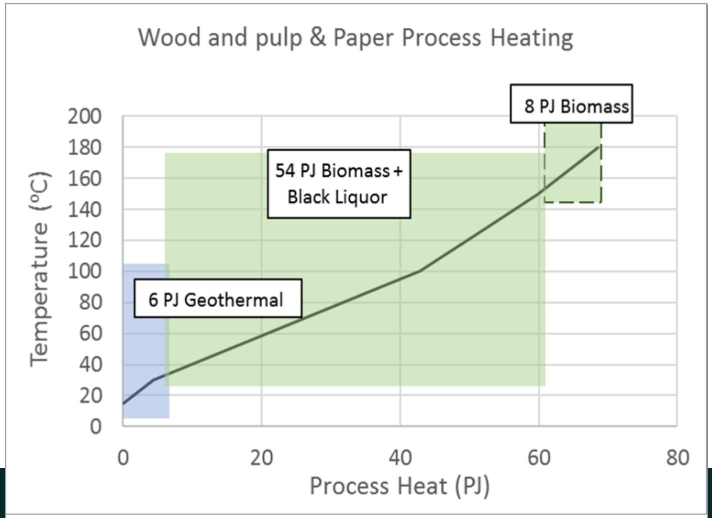

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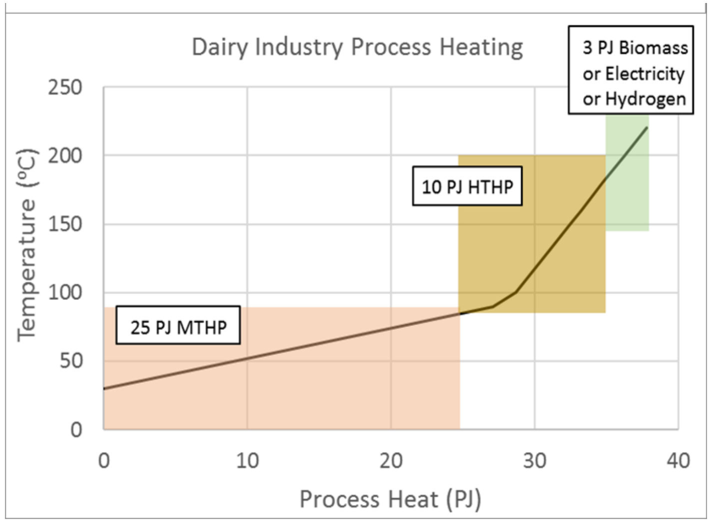

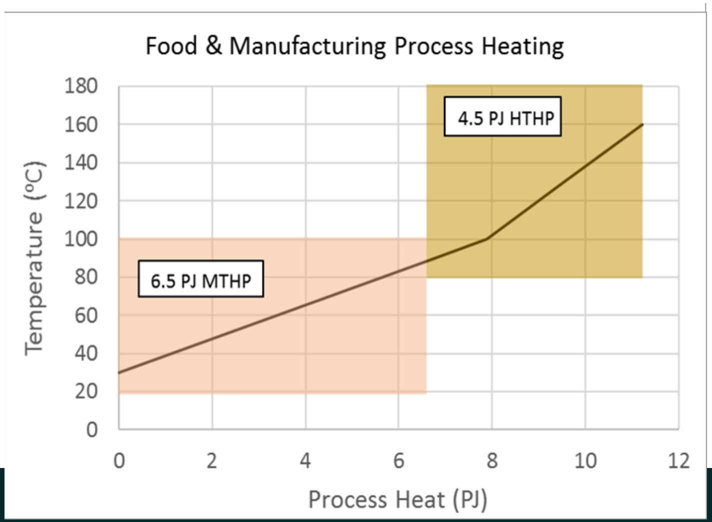

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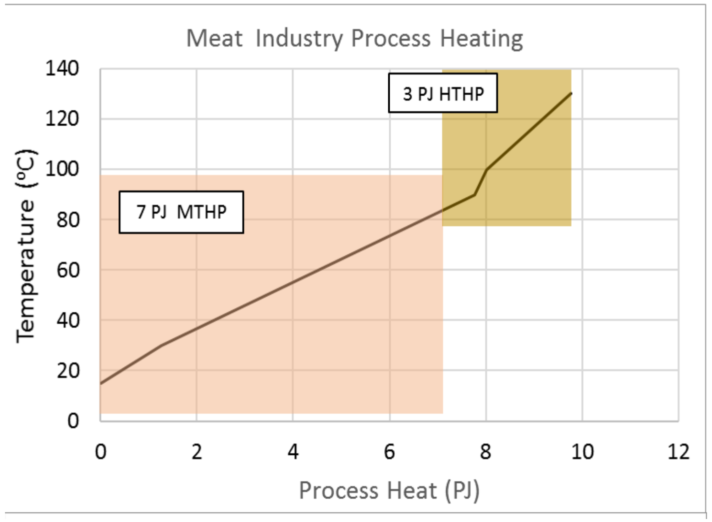
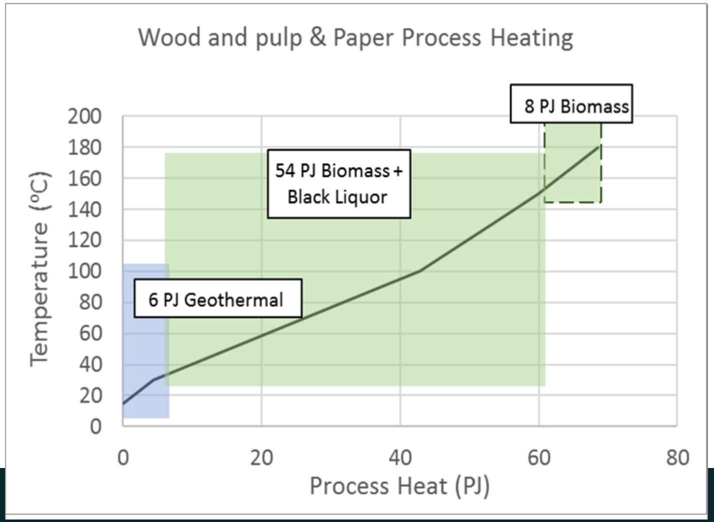
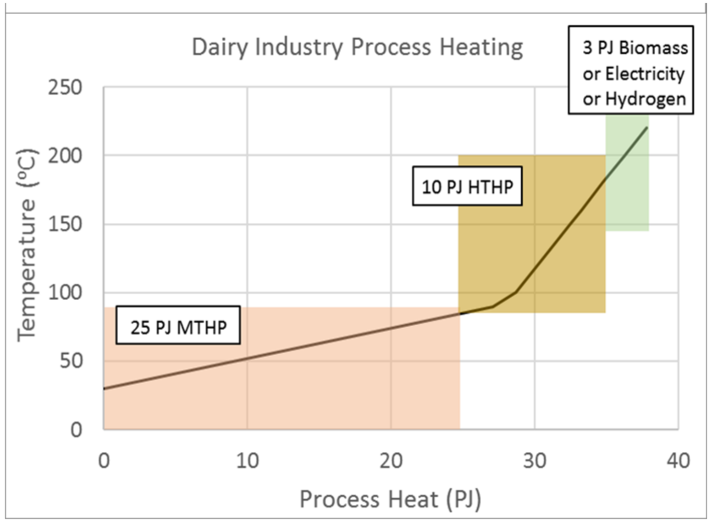
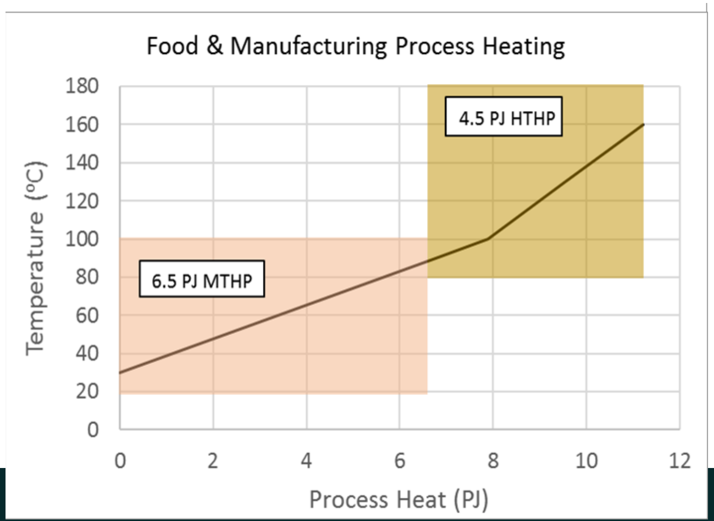




Food and fibre sector focus





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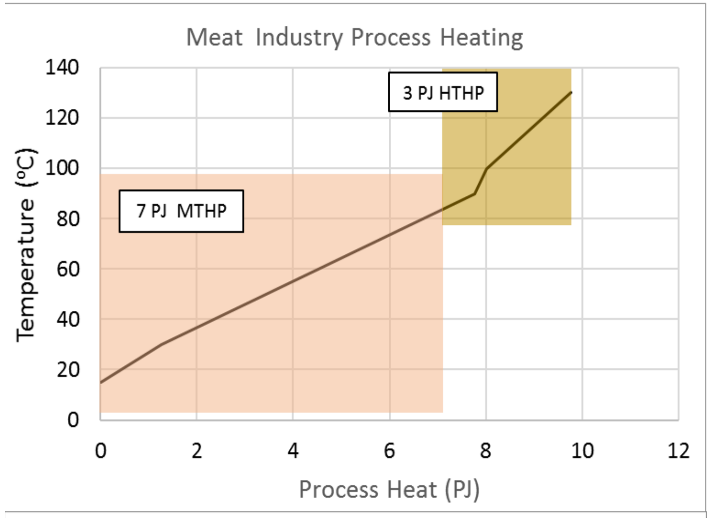

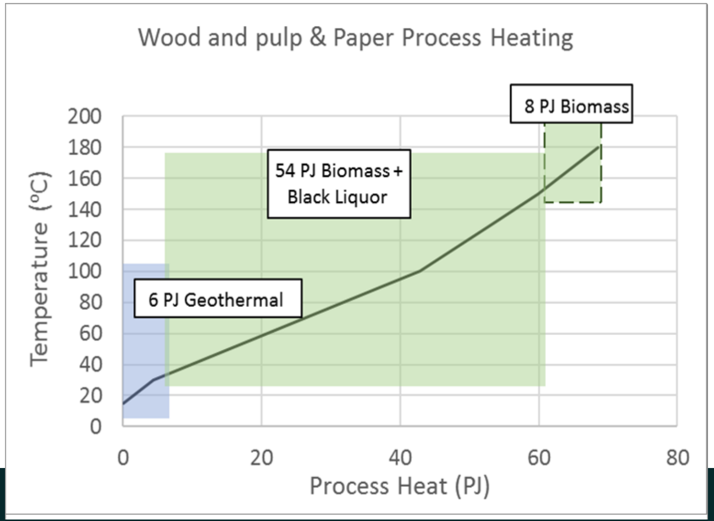

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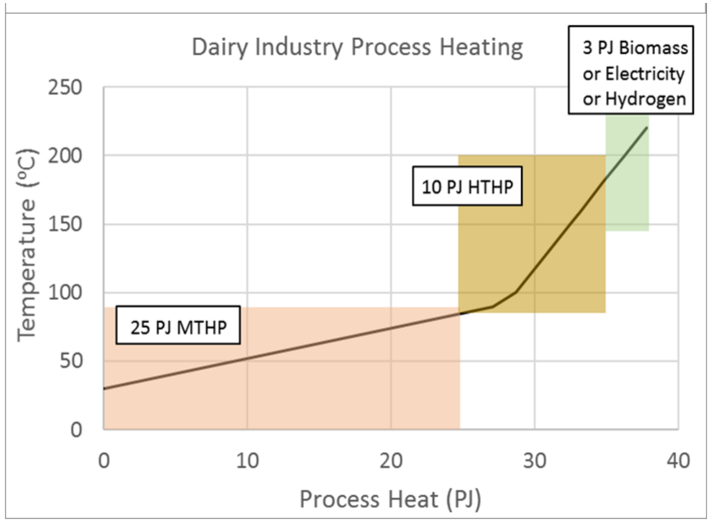
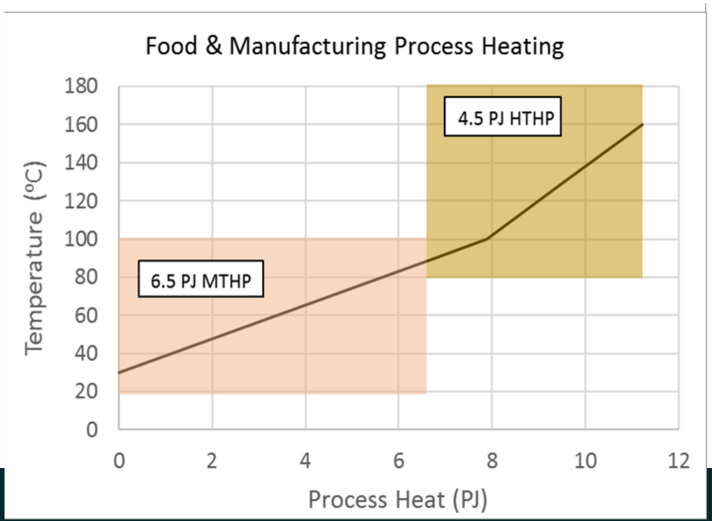
Food and fibre sector focus





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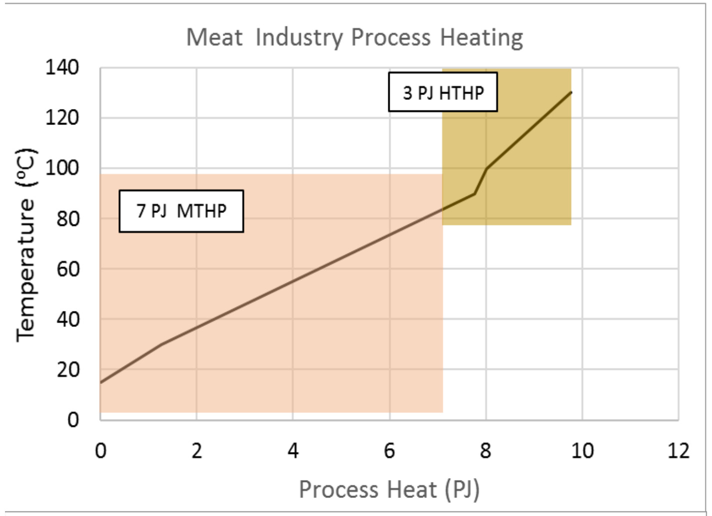
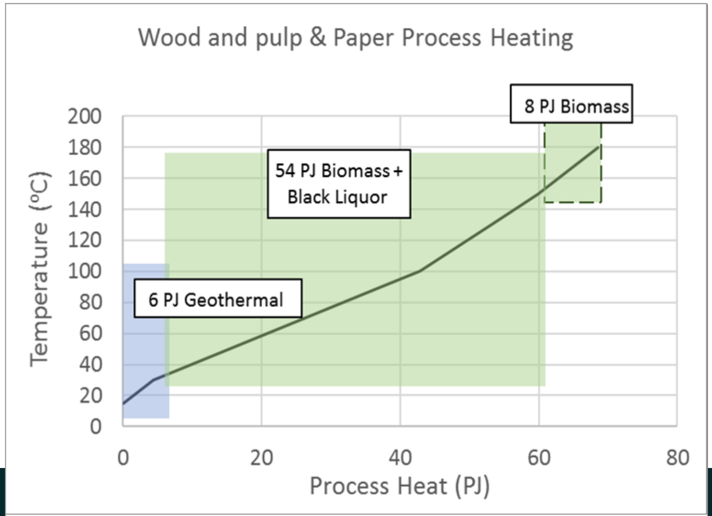
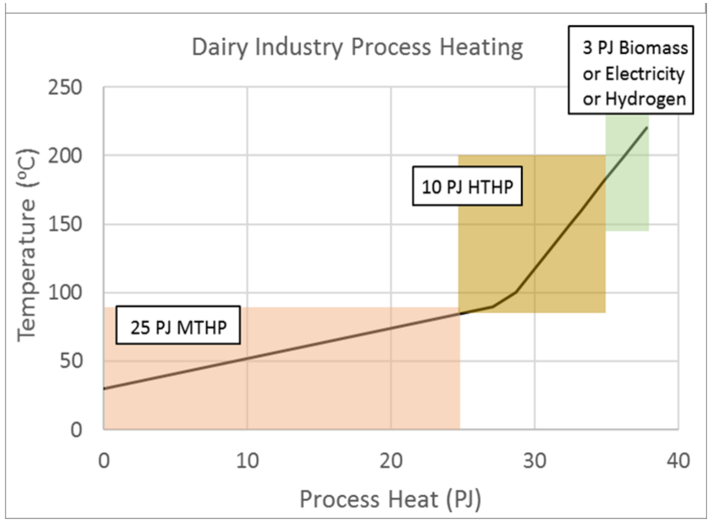
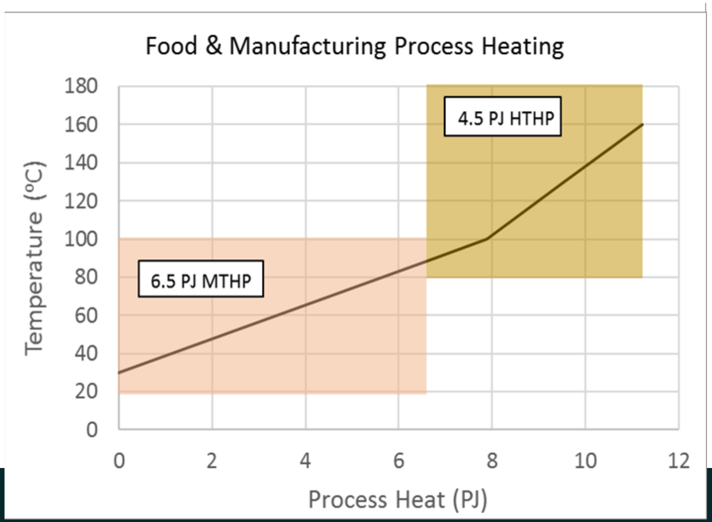




Food and fibre sector focus

60 PJ heat = 6.7 TWh ele
(+15.9% ele)





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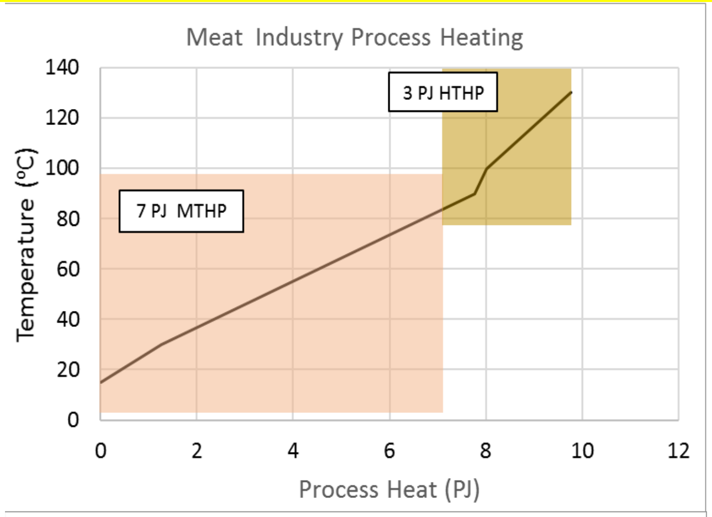

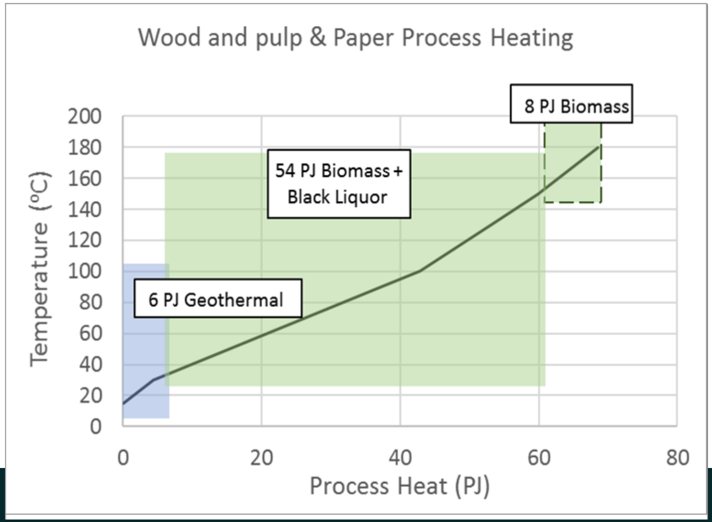

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Key technology gap: Air-sourced hot water heat pump

Potential 42.5 PJ process heating up to about 80°C

COP >3

Mass production

Standard units

Installed Costs < $500/kW

-10 – 20°C air source

Key technology gap: High temp, cogeneration heat pump

Potential 60 PJ process heating up to about 200°C

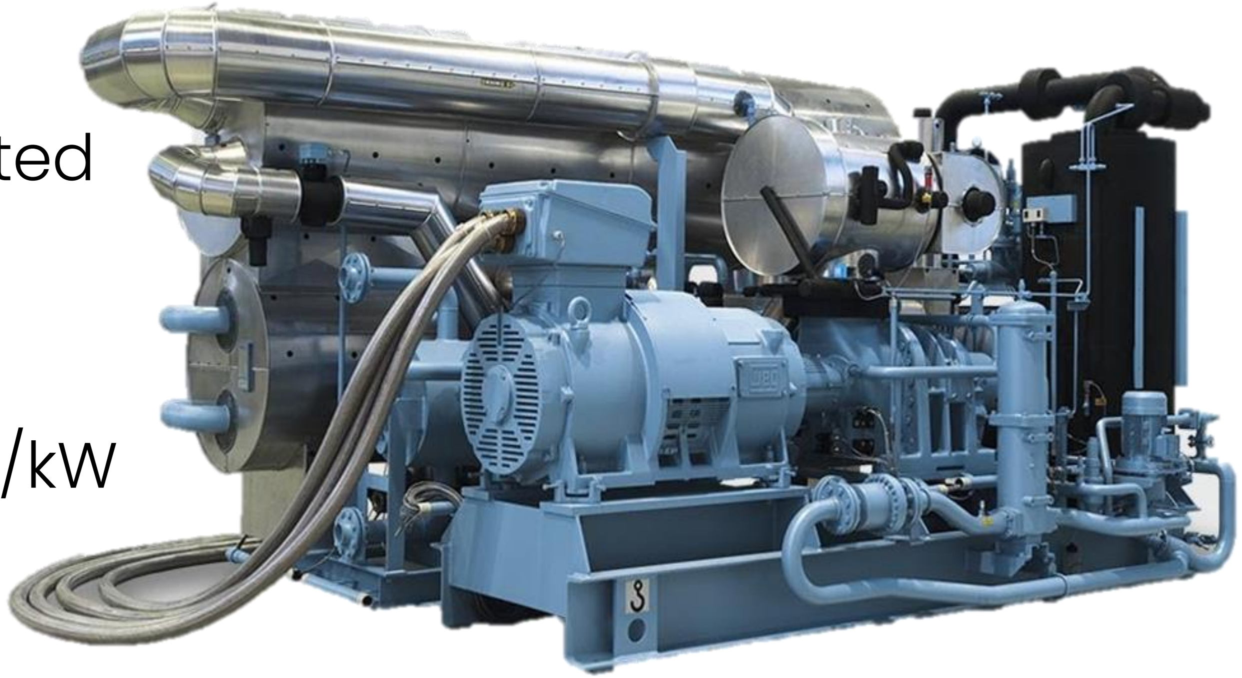
COP <3

Cogeneration, integrated

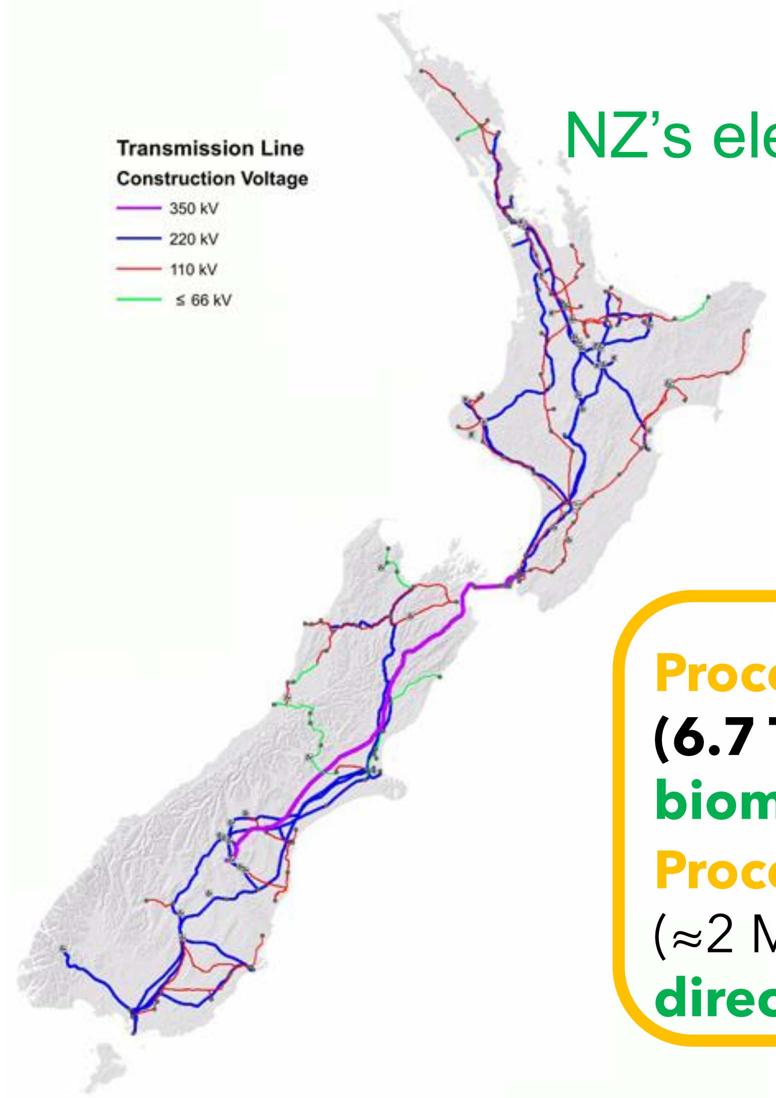
Configurable units

Installed Costs > $1000/kW

Waste process heat source



We need more grid-edge renewable gen



NZ’s electricity supply = 42 TWh in 2019

68% expansion of renewable **electricity** maybe required for heat, power & growth by 2050 (**+28 TWh$_{ele}$**)*

Process Heat < 200°C : 60 PJ/y (**6.7 TWh$_{ele}$**) of **heat pumps (& biomass)**

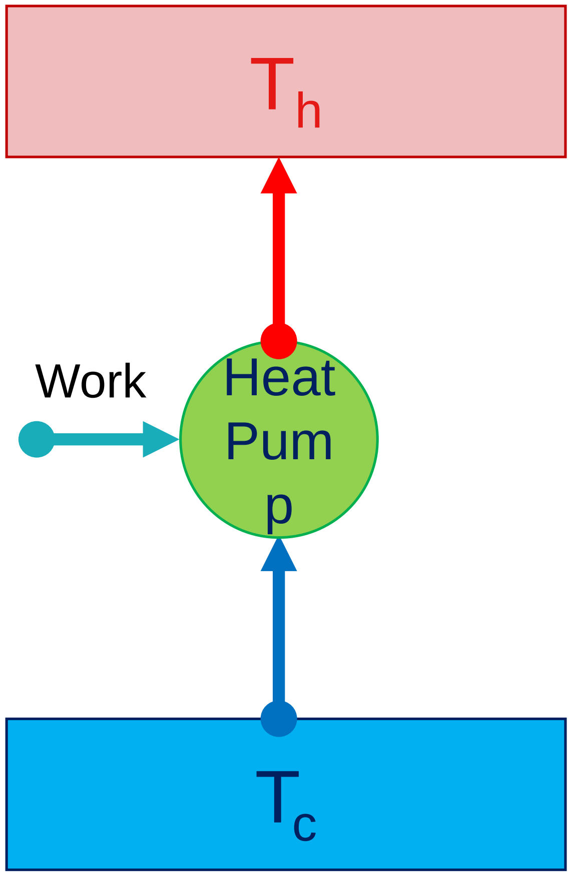
Process Heat >200°C : 22 PJ/y (≈2 M tonnes/y) **biomass (& direct ele.)**

Light Vehicles +28% expansion (**11.7 TWh$_{ele}$**) of **electricity**

Heavy Vehicles +10% expansion (**4.2 TWh$_{ele}$**) of **electricity**

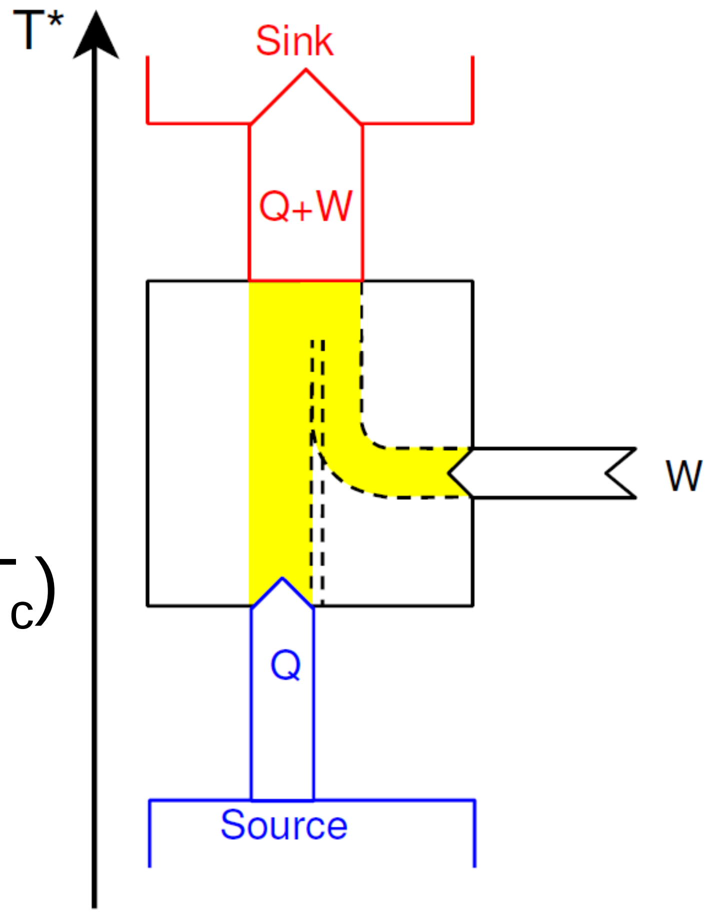
* Transpower report, Empowering our Energy Future, March 2020

Let's look into heat pumps more: Back to the basics



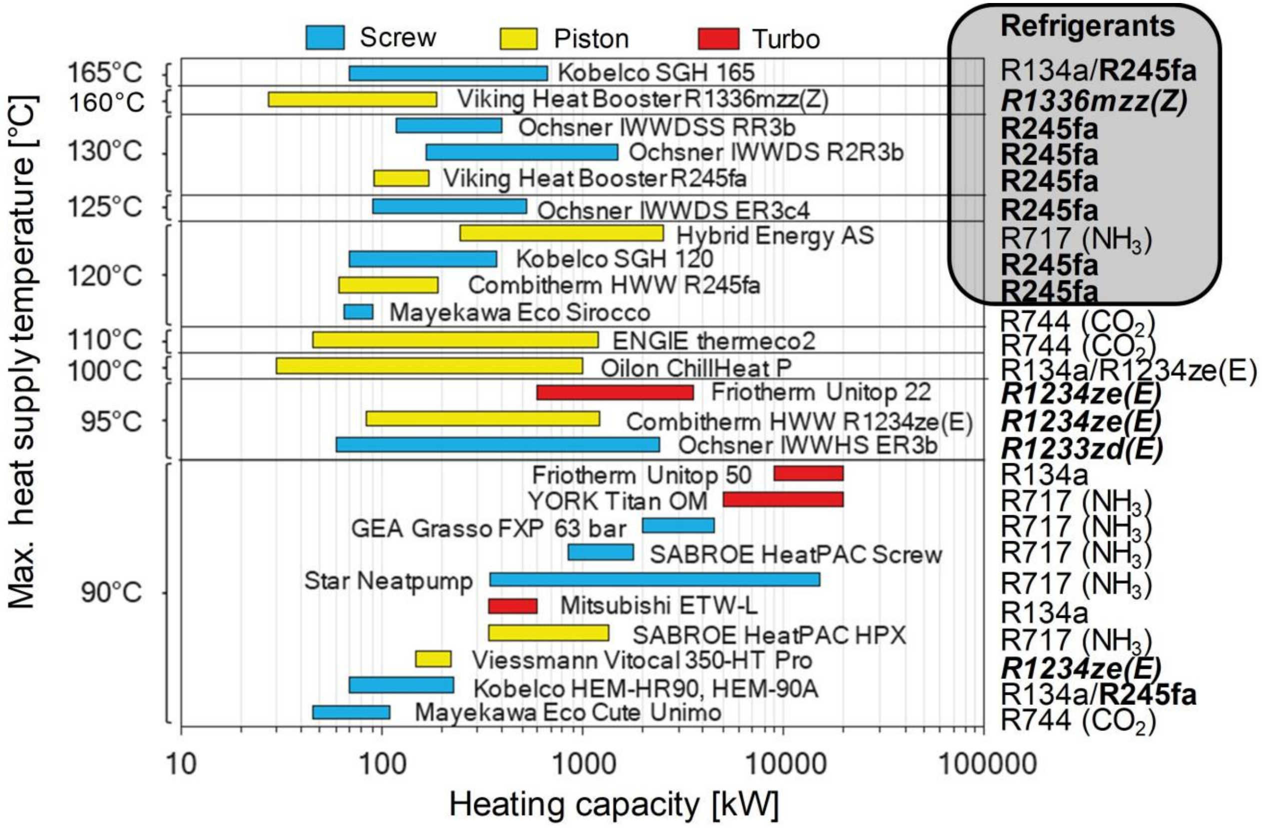
$$COP = (Q+W)/W$$

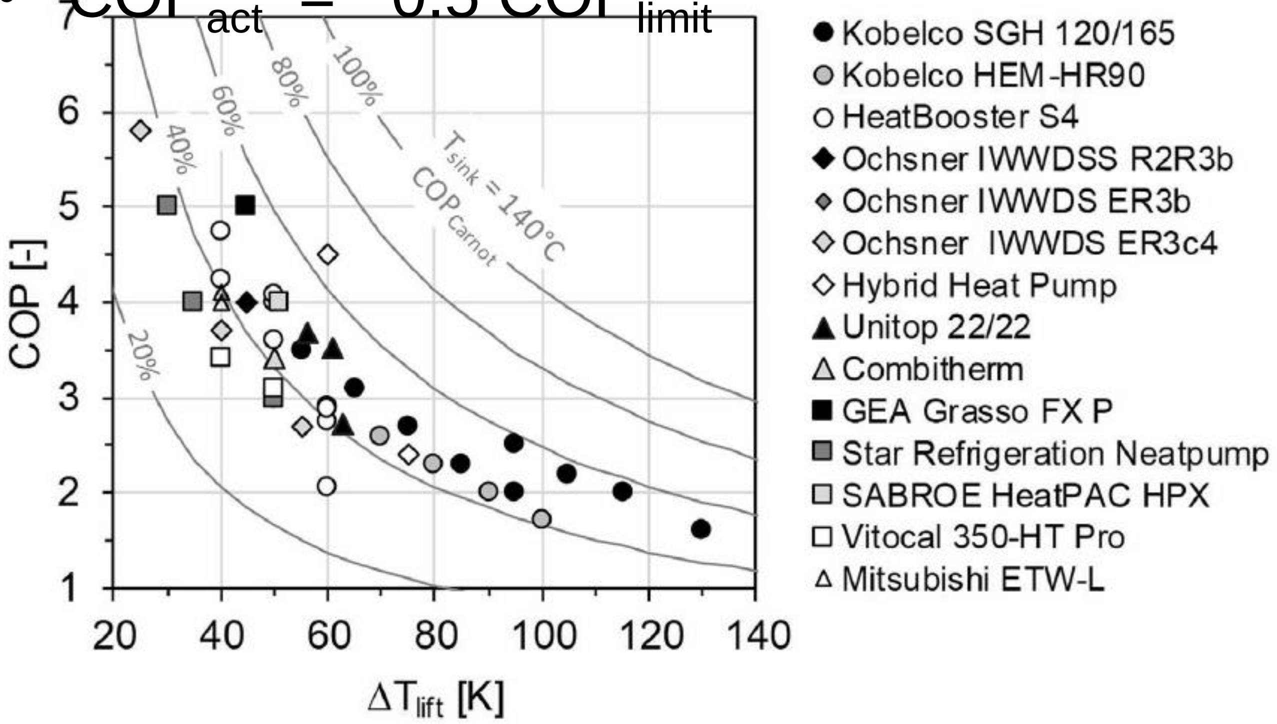
$$COP_{limit} = T_h / (T_h – T_c)$$



Real high-temp heat pump systems
(Aspagaus et al, 2018)

- Temperature lifts < 80°C for COP_{actual} > 3
- Seldom is waste heat >60°C
- COP_{act} = ~0.5 COP_{limit}





Min COP for heat pump consideration

COP min = (Biomass price / Heating system efficiency) / Electricity price

		Electricity prices [2]				
Biomass prices [1]		$/MWh (Purchased)				
$/GJ (Fuel supply)	$/MWh (Heat demand)	**80**	**100**	**120**	**140**	**180**
12	60	1.33	1.67	2.00	2.33	3.00
13	65	1.23	1.54	1.85	2.15	2.77
14	70	1.14	1.43	1.71	2.00	2.57
15	75	1.07	1.33	1.60	1.87	2.40
16	80	1.00	1.25	1.50	1.75	2.25
17	85	0.94	1.18	1.41	1.65	2.12
18	90	0.89	1.11	1.33	**1.56**	2.00
19	95	0.84	1.05	1.26	1.47	1.89
20	100	0.80	1.00	1.20	1.40	1.80

Targets for maximum heat pumping temperature

$T_h = T_c \, (COP_{min} / (COP_{min} - 1))$

Biomass prices [1]		Electricity prices [2] $/MWh (Purchased)				
$/GJ (Fuel supply)	$/MWh (Heat demand)	**80**	**100**	**120**	**140**	**180**
12	60	188	138	111	94	73
13	65	212	154	122	102	78
14	70	239	170	134	111	85
15	75	269	188	146	120	91
16	80	303	207	159	130	97
17	85	342	228	173	141	104
18	90	385	251	188	**151**	111
19	95	436	276	204	163	118
20	100	495	303	221	175	126

Conventional heat pump wisdom

- What makes a good refrigerant?
  - Large heat of condensation compared to compression work
  - Operated well below critical point temperature (e.g., 50 K)
  - Fully condense fluid, limited subcooling opportunity
  - Low swept volume
  - Non-flammable, low GWP, no ODP

- We analysed 237 different fluids in REFPROP using a simple vapour compression cycle model to confirm these rules of thumb

Emerging high temp heat pump wisdom

- ☒ Large heat of condensation compared to compression work
  - ✓ **More important to obtain close temperature profile matches**
- ☒ Operated well below critical point temperature (e.g., 50 K)
  - ✓ **Subcritical and transcritical cycles are acceptable**
- ☒ Fully condense fluid, limited subcooling opportunity
  - ✓ **Subcooling critical, often cogeneration of utility levels**
- ☒ Low swept volume
  - ✓ **New compressors enable high swept volume but remain compact**

Summary

- NZ well placed to decarbonise process heat
  - Up to 60 PJ's of HTHP (24 PJ electrical or 6.7 TWh_{ele})

- Collaboration and trust in research results are essential to accelerating decarbonisation

- Heat pumps are well-established but not for high temperatures

- High temperature heat pumps must integrate well with the industrial process

Thank you for listening.

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