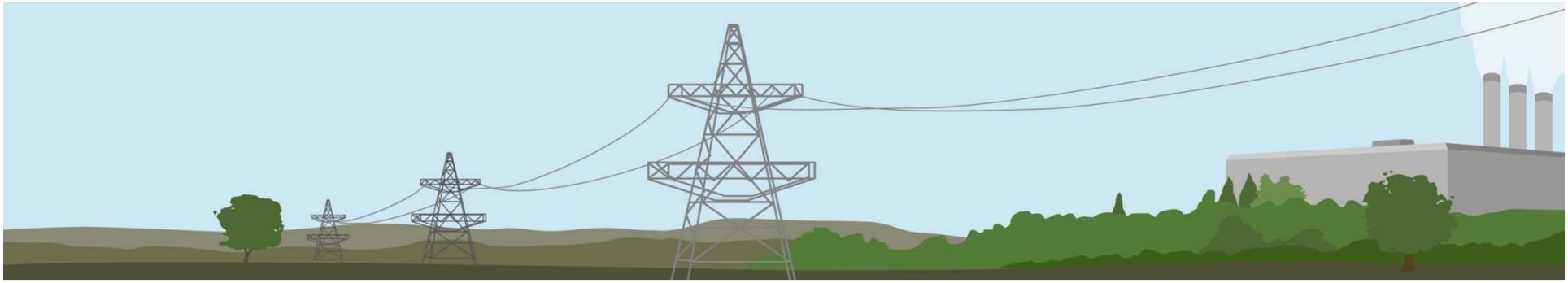
October 31st 2008, Fuel Cell Seminar, Phoenix AZ, USA



The Characteristics of Commercially Successful Fuel Cell Micro Cogeneration

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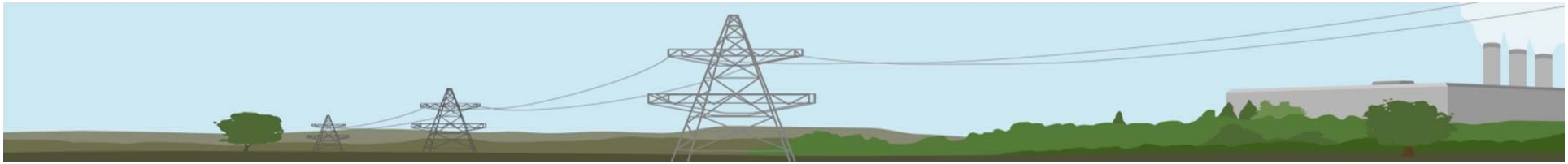

Why is this an interesting market?

- Residential sector produces more than ¼ of national greenhouse gas emissions.
- The built environment has the greatest potential of any sector for economic mitigation.
- Potential market is large – 12 million micro-CHP units installed by 2020 in Europe?
- Technology becoming available.

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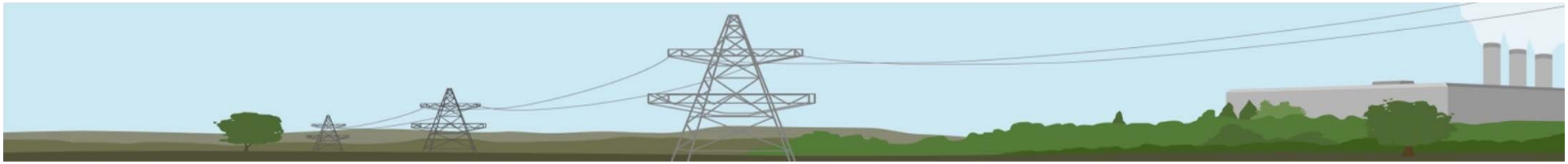

Residential Fuel Cell Cogeneration

- What factors are most important for micro-cogeneration (micro-CHP) products to reach a mass market?
  - Economic advantage (payback, IRR, reward)
  - Environmental credentials
  - Reliability and durability
  - Ease of installation and use
  - Social prestige
  - Comfort

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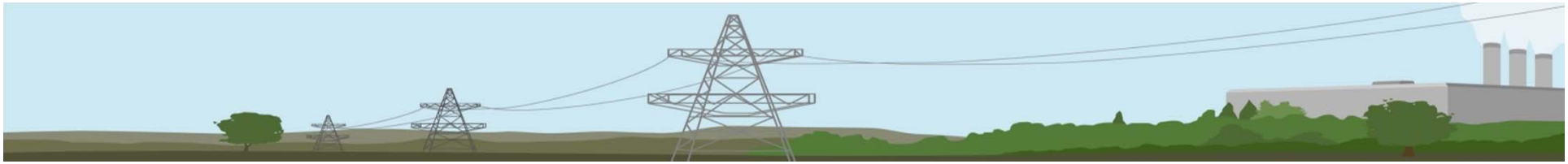

What Technical Characteristics…

- …lead to economically competitive products?
- …lead to environmentally credible products?

- High level technical representations of:
  - Capacity
  - Overall efficiency (i.e. heat + power)
  - Heat-to-power ratio
  - Start-up/Shutdown performance
  - Turndown ratio
  - Ramping rate

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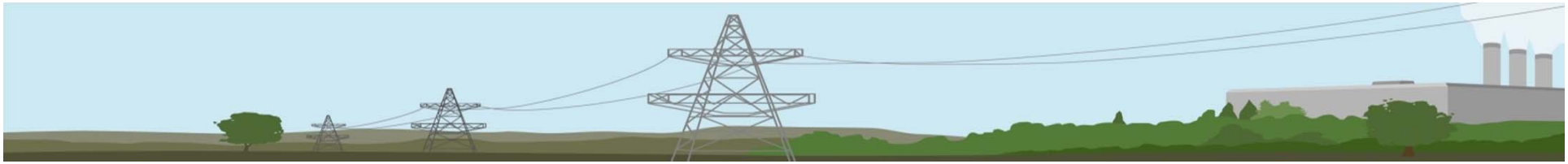

Modelling Approach – Unit Commitment

- **Simulation** – the most common micro-cogeneration modelling method – is less useful where choices exist regarding
  - Technical design
  - Control strategy

- Unit commitment **optimisation** reflects technical constraints onto the economics of the operating strategy
  - Feedback loop
  - Decision variables reflect the available choices

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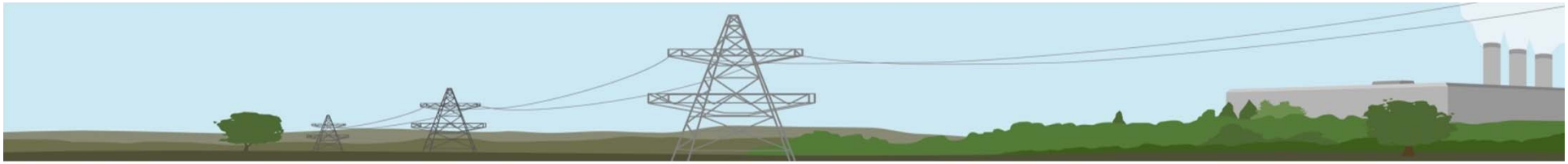

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Technical Characterisation

- Micro-cogeneration
  - Capacity (kW_e)
  - Piecewise electrical and overall efficiencies (i.e. non-linear efficiency curve)
  - 10-year lifetime
  - Minimum set point (i.e. turndown)
  - Maximum Ramp Rate (kW_e/min)
  - Start/Stop cost ($/cycle) and energy consumption (kWh/cycle)
  - *Small* thermal store
  - Degradation
- Demand/Prices
  - Five primary demand scenarios, relating the existing British housing stock.
  - Average annual demand 4,000kWh electrical, 18,000kWh thermal.
  - Demand modelled at 5-minute precision.
  - Energy prices are marginal residential tariffs in the London area.
  - Annual maintenance cost

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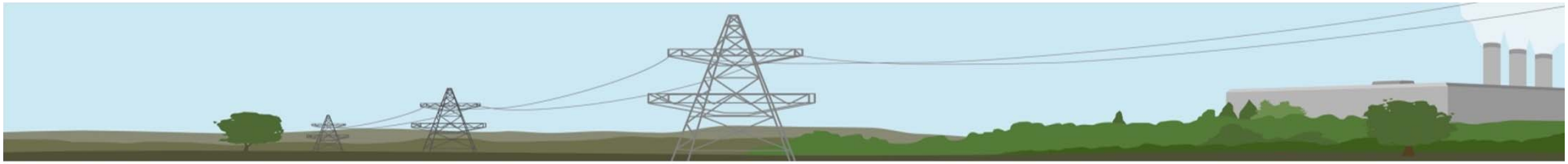

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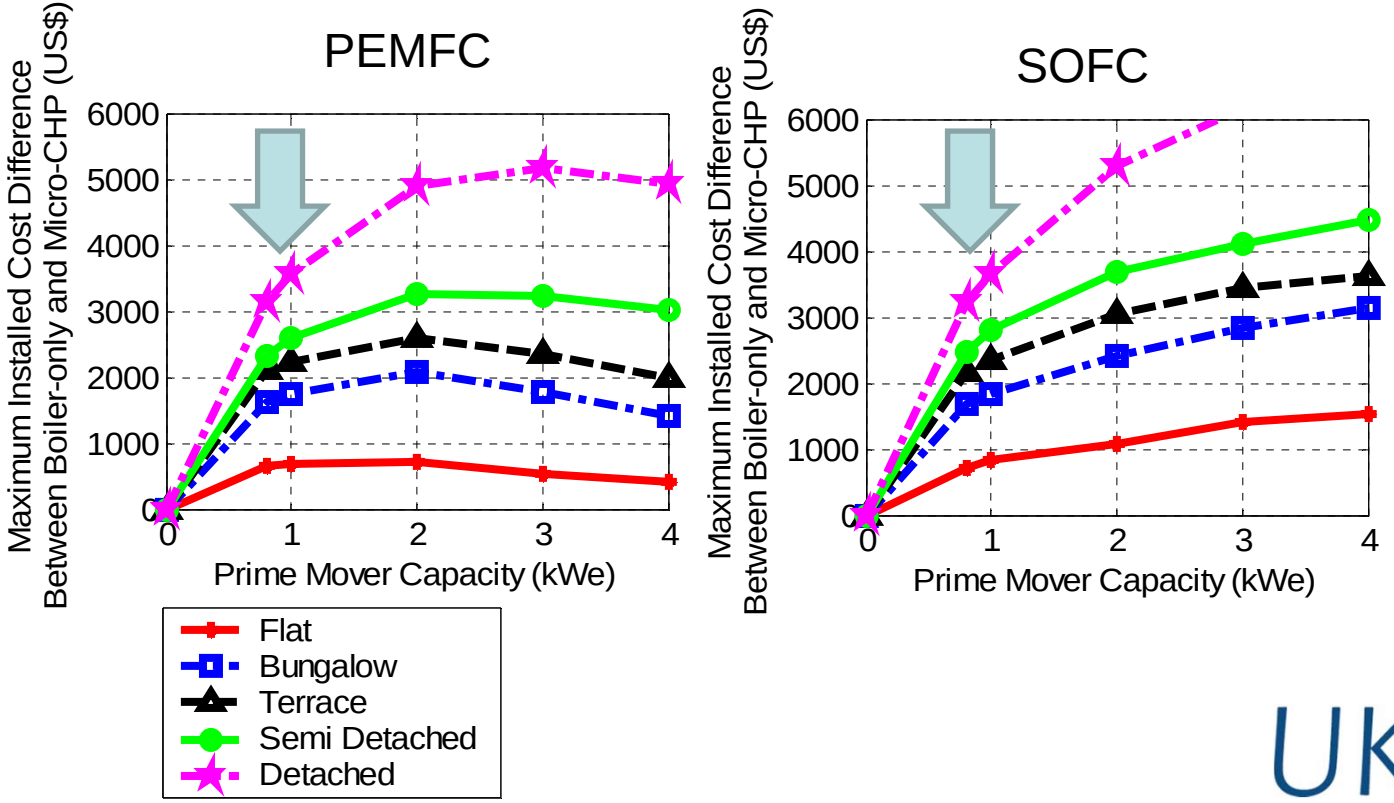
Capacity

- What capacity (kW_e) prime mover in the micro cogeneration system?



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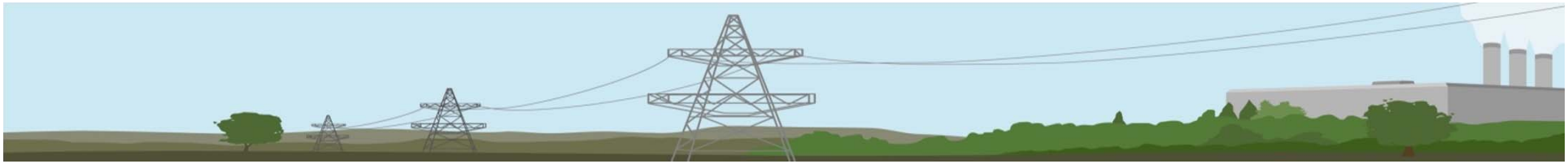

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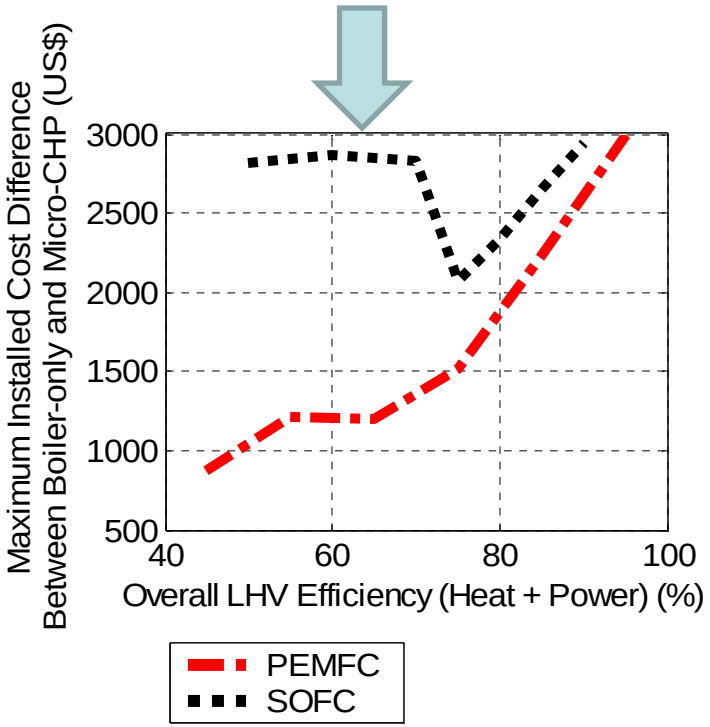
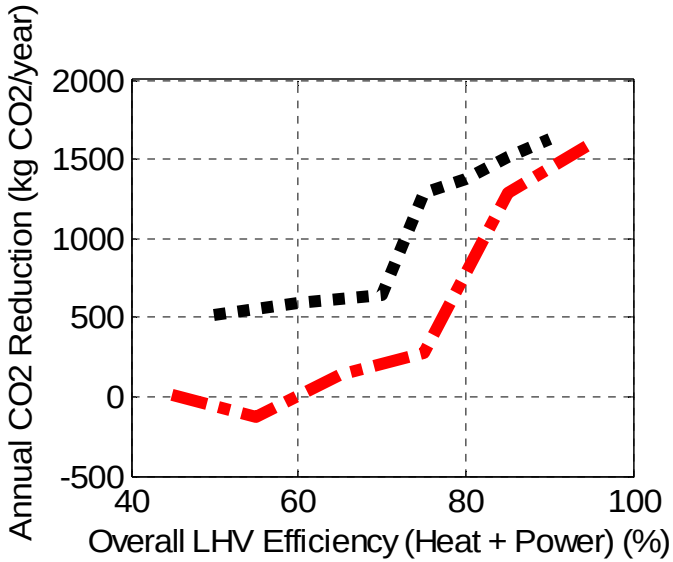
Overall Efficiency

- How important is Heat + Power efficiency?





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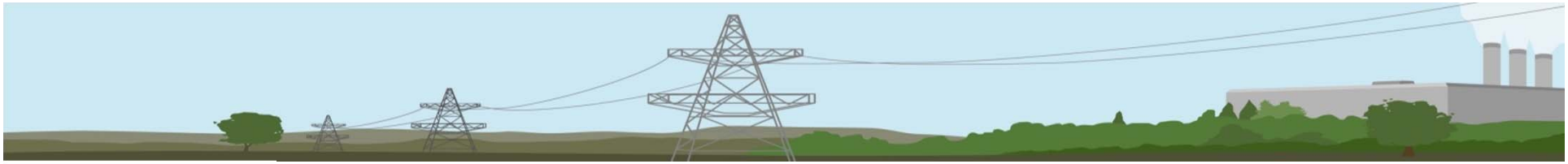

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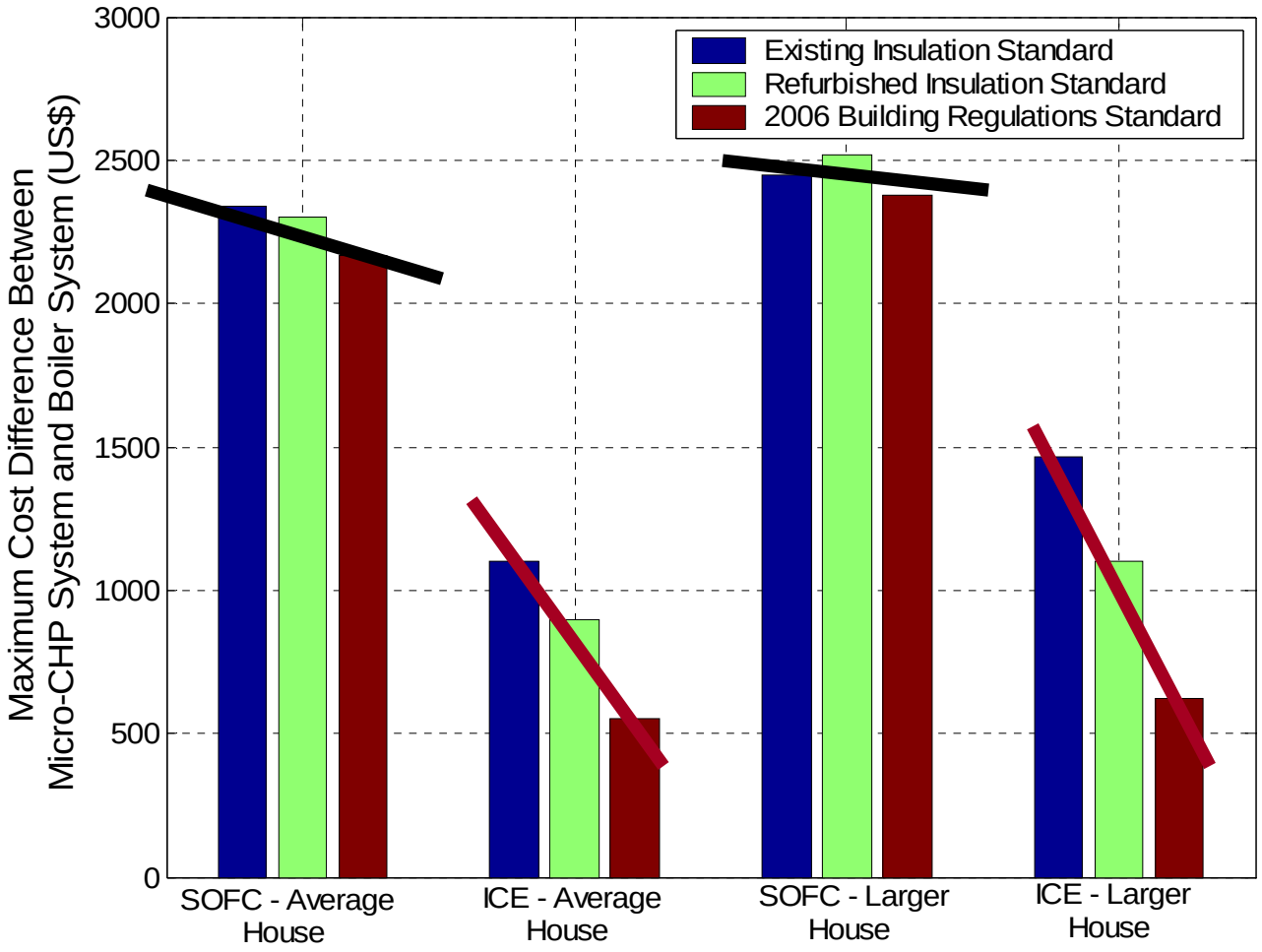
Heat-to-Power Ratio



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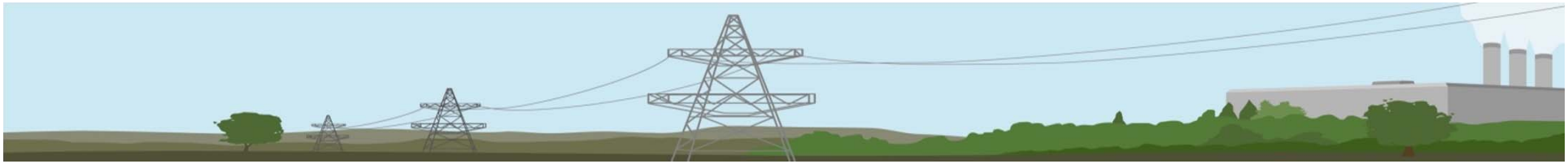
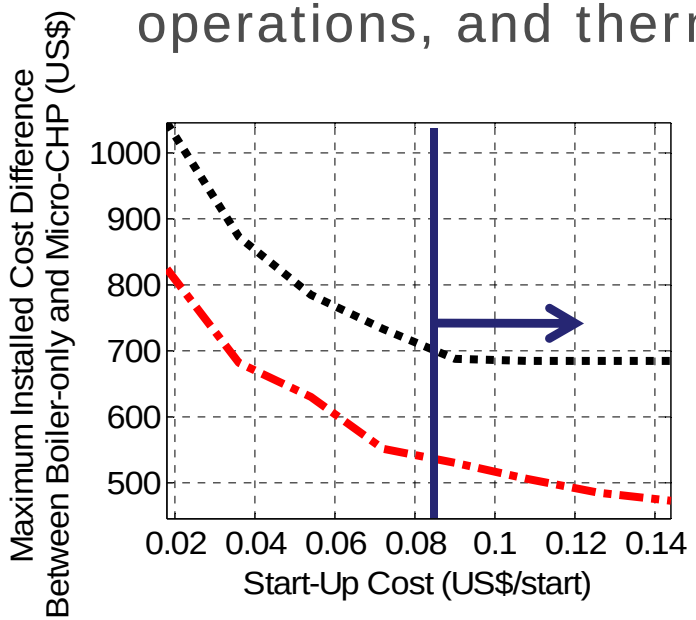
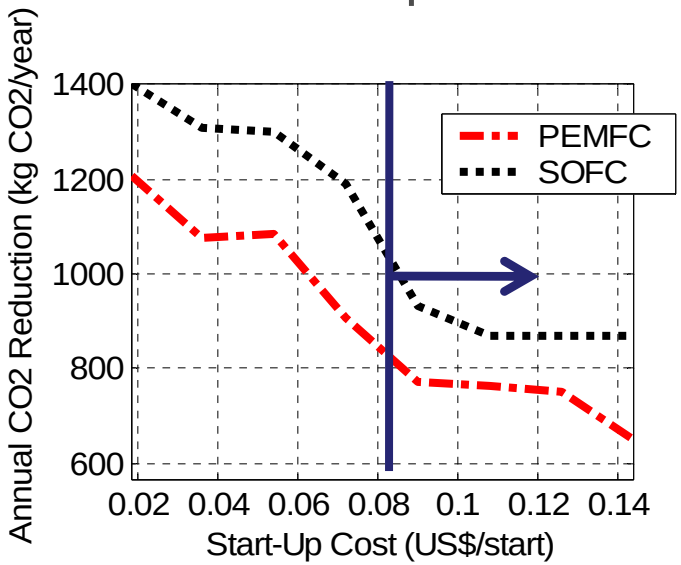


Start-Up and Shutdown Performance

- Energy consumed during start-up and shutdown operations, and thermal mass of components.





NB/ Small dwelling demand – e.g. 1 bed flat, single occupancy

	Minimum Start / Stop Cost	Maximum Start / Stop Cost
PEMFC	365 cycles/year	61 cycles/year
SOFC	425 cycles/year	0 cycles/year

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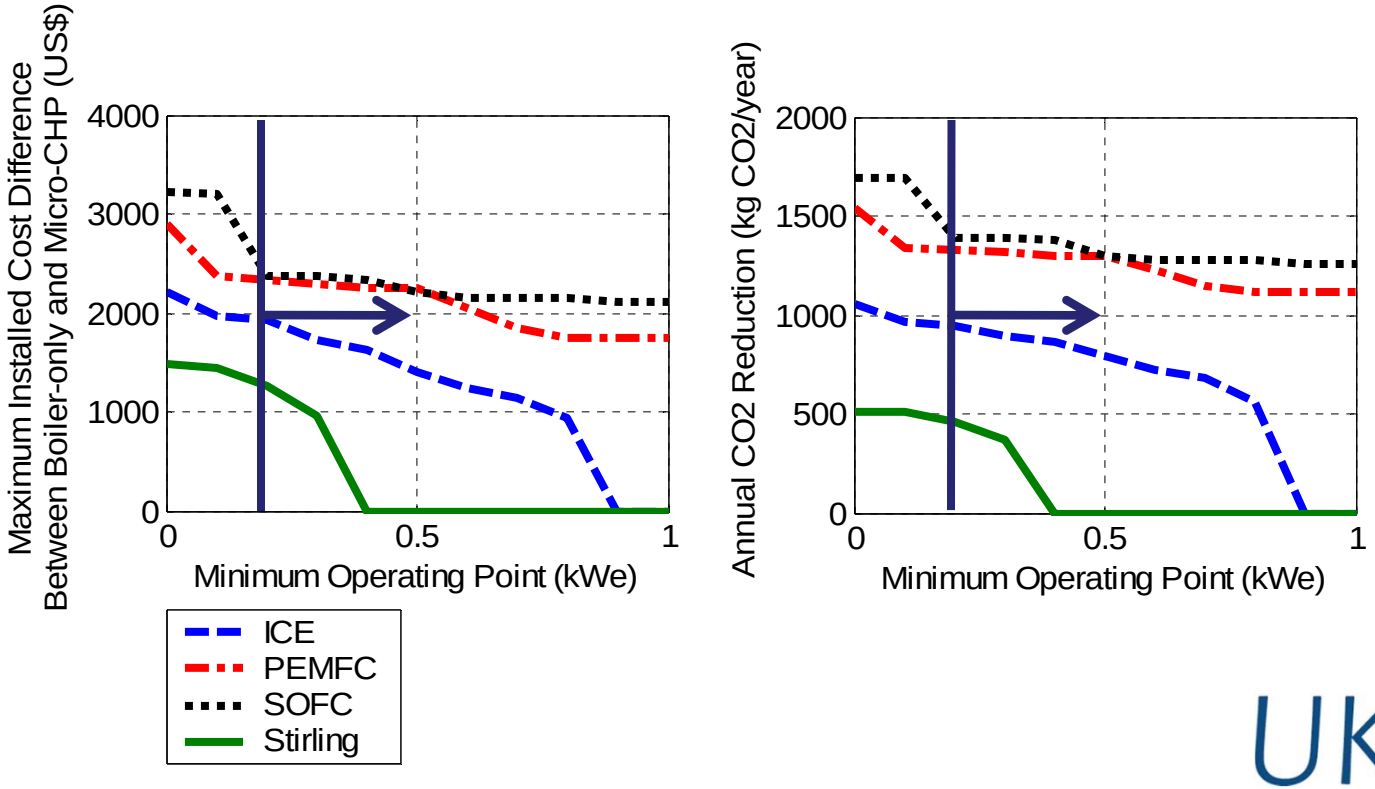
Turndown Ratio

- The minimum set-point at which the unit can operate at efficiently (for a 1kWe system)



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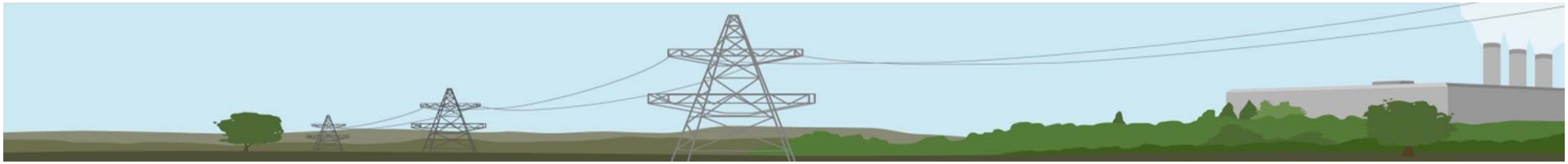
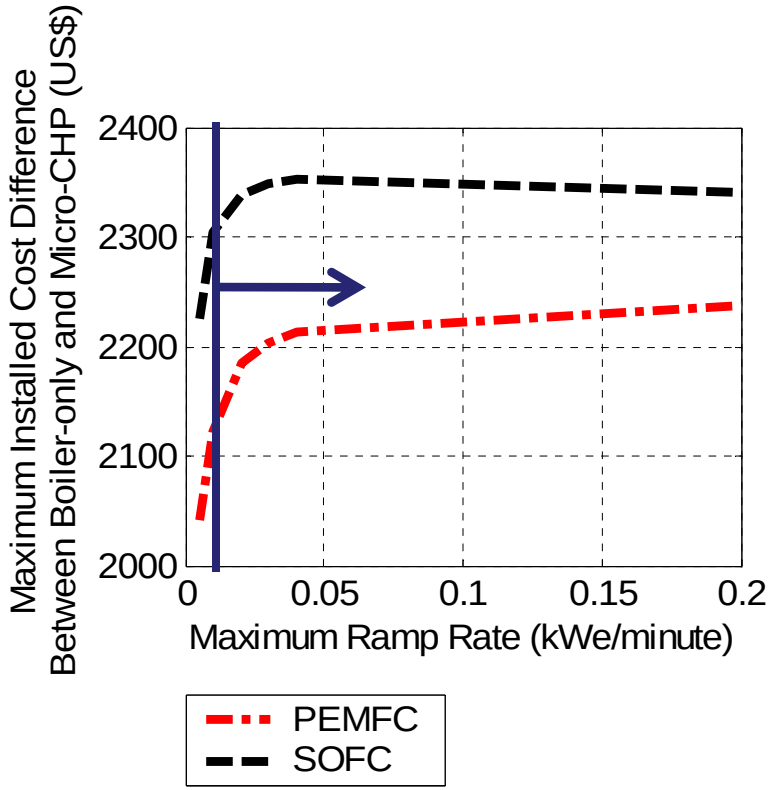
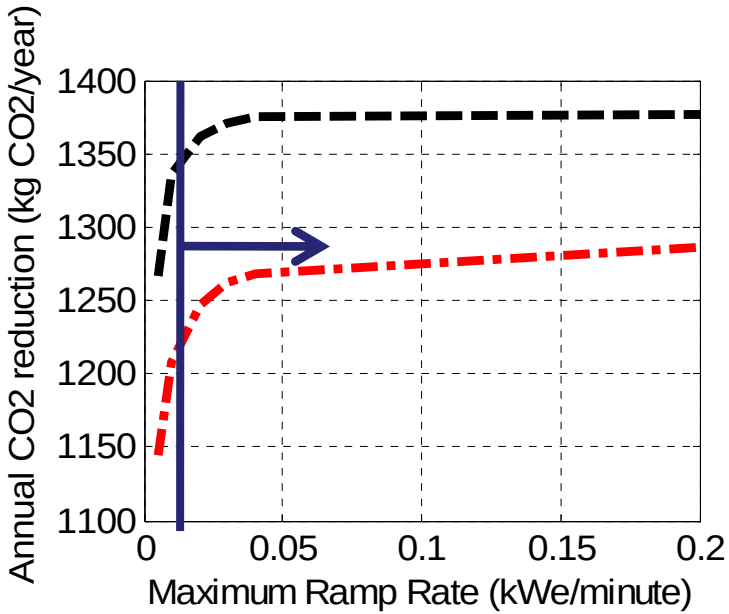


Ramping Rate

- The rate at which fuel cell can change kW_e output.





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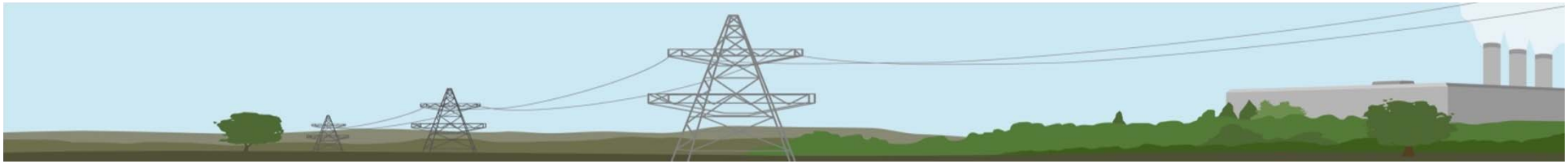

Conclusion for 1 kW_e SOFC in an Average Dwelling

Design Parameter	Range Considered	Value Range (per kW_e)	CO_2 Savings Range (kg/year)
Capacity (kW_e)	0.5 – 4.0	$2300 - $500	1200 – 1100/kW_e
Overall Efficiency	50% - 90%	$2600 - $2300	500 - 1500
Heat-to-Power Ratio	1:1 - 4:1	$2300 - $500	1300 – 400
Start/Stop Costs	0.02 – 0.14	$2600 - $1850	1400 - 900
Turndown Ratio (kW_e)	0.05 – 1.0	$3200 - $2000	1700 - 1300
Ramping Rate (kW_e/minute)	0.01 - unlimited	$2200 - $2300	1250 - 1350

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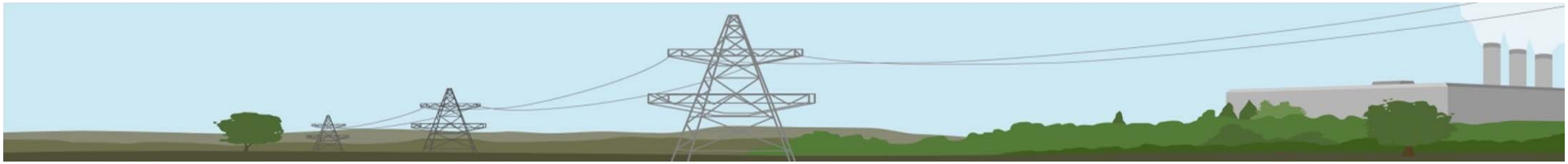

Conclusion

- Modelling approach can help focus R&D.
- A possible system development scenario:
  - For a 1kWe system:
    - Maximise Electrical Efficiency, don't worry so much about thermal efficiency unless CO_2 reduction highly valued.
    - Design control and/or thermal delivery system to avoid cycling – this avoids the need for low-energy start-up/shutdown.
    - Enable efficient turndown to near-zero output.
    - Don't worry about enabling rapid ramping – focus on intelligent control.
- Micro cogeneration greatly benefits from a low heat to power ratio:
  - Avoid start/stop cycling due to insufficient heat demand
  - Avoid turndown due to insufficient heat demand
  - Access value through producing more electricity

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