Programme Area: Nuclear

Project: System Requirements for Alternative Nuclear Technologies

Title: Presentation - Approach and Findings

Context:

The purpose of the System Requirements for Alternative Nuclear Technologies project was to capture the high level technical performance characteristics and business-case parameters of small thermal plants, which will be of value to the potential future of the UK's energy system. The project included small nuclear reactors, enabling comparison with other small-scale plants, such as those powered by bio-mass. The project outputs will help enable the subsequent contrast of a range of specific technologies.

System Requirements for Alternative Nuclear Technologies

ANT Project: Approach & Findings

December 2014

energy technologies institute

Rolls-Royce

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Objective

What will Small Modular Reactors need to 'achieve' in the future, technically and economically, to be deployed at scale in the UK?

- SMR Requirements Specification
- "Frame the energy system requirements and expected cost envelope"
- To inform future assessments of SMRs technologies

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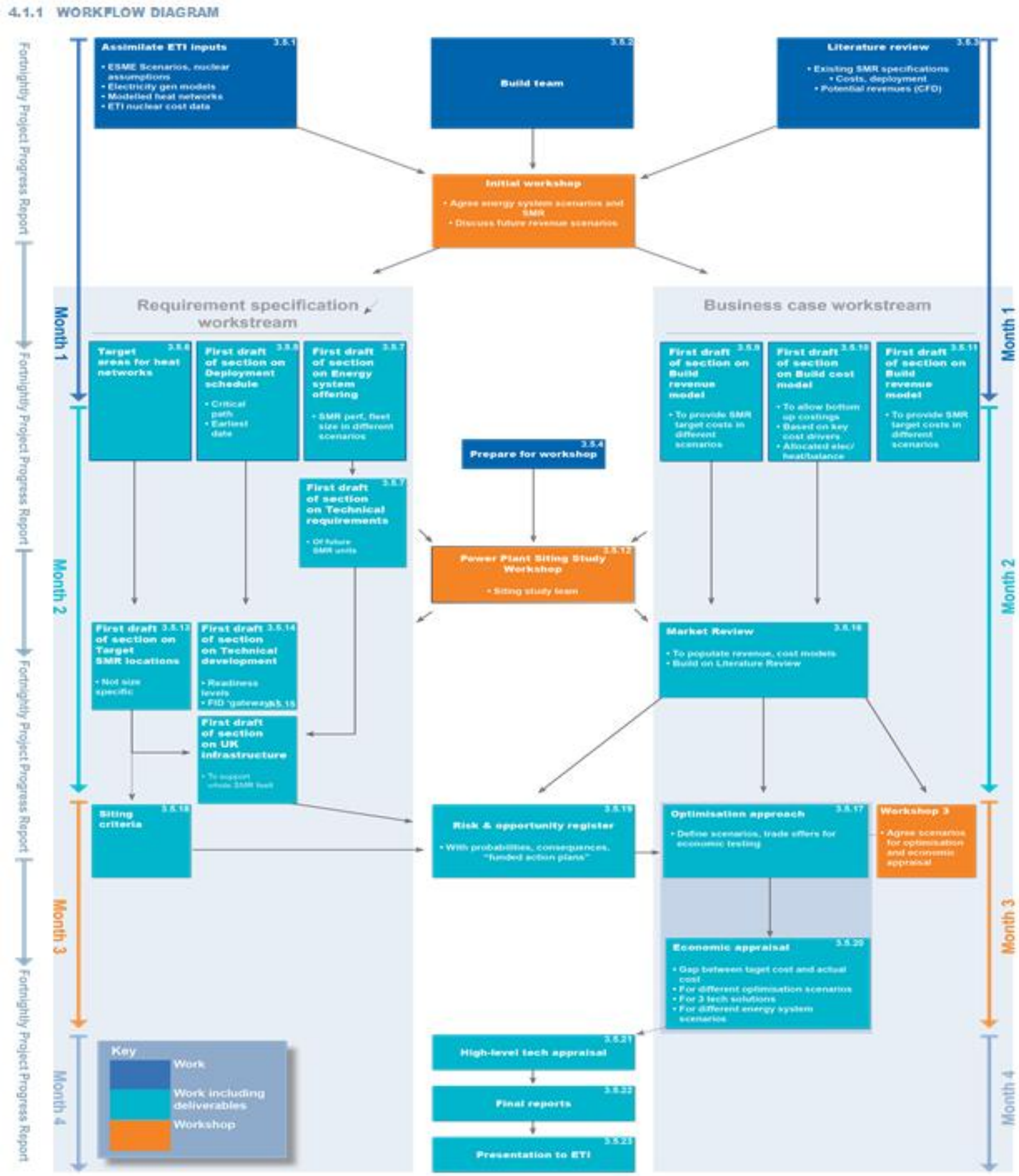
Work structure



- August-December 2014
- Two work-streams:
  - Technical
  - Economic
- 20+ tasks
- Integrated with Power Plant Siting Study
- Complementary to DECC / NLL Feasibility Study

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Project Team

Mike Middleton – ETI lead

Guy Doyle – Chief Economist
Bob Ashley – CHP & heat specialist
Sam Friggens – Project coordinator & economist
Plus engineering, power plant & consenting specialists

David Dodd – Chief Design Engineer, Civil Nuclear
Martin Goodfellow – Nuclear Engineer

This presentation

1. Objective, Work Structure & Team

2. Introduction to SMRs

3. UK energy system to 2050

4. Technical work-stream

- Service offerings
- Technical readiness
- Deployment
- Locations
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- Infrastructure
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5. Economic work-stream

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- Cost reductions
- UK economic benefits

6. Conclusions

7. Questions & Answers (40 minutes)

An Introduction to SMRs

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What is a Small Modular Reactor?

- <300MWe
- Modular
- Factory build
- Mass production
- Transported to site

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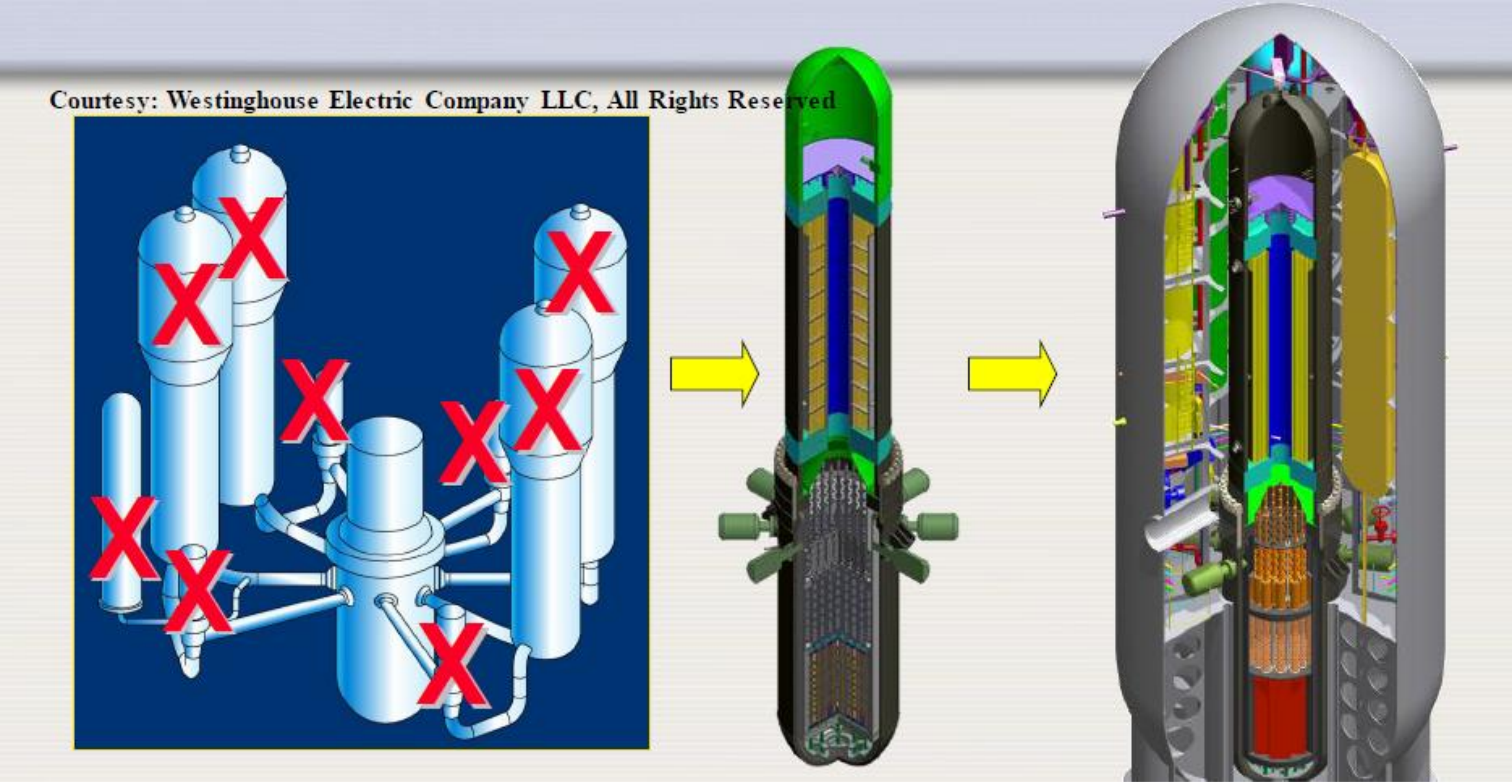
Integral design (passive safety)



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Compared to…

Potential SMR advantages

- Low carbon electricity, heat and flexibility
- Less water + less land = more sites
- Closer to demand
- Incremental deployment
- Lower total CAPEX, risk & financing costs
- Economies of multiples and mass production

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Technologies – from near term…

- 'Near term' PWR technologies:
  - mPower (180MWe)
  - NuScale (45MWe)
  - SMART (100MWe)
  - Etc.

- Chinese CNP-300 already operating
- KLT-40S in build

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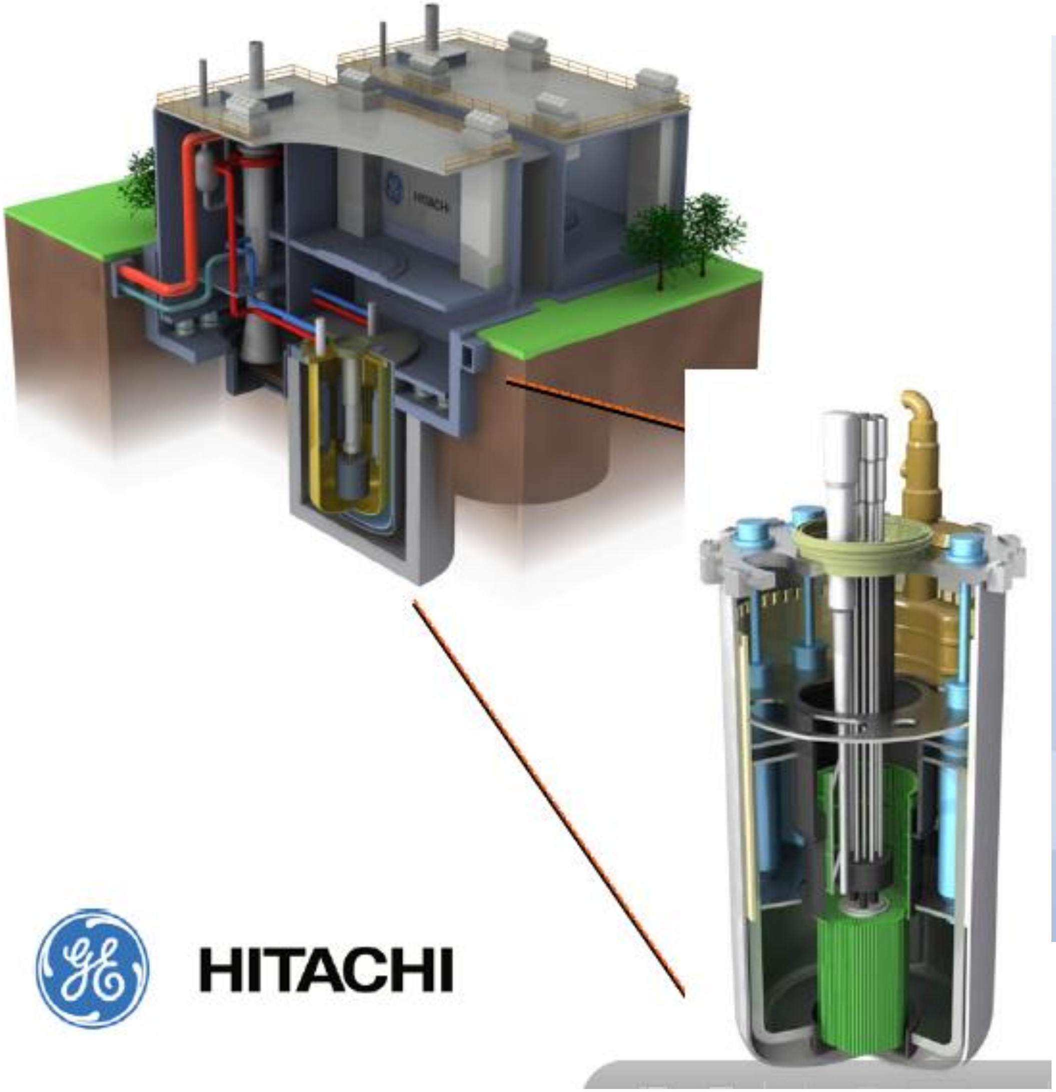
…to longer-term, revolutionary concepts



- For example:
- GE Hitachi PRISM 311MWe reactor
  - Liquid sodium-cooled fast-breed reactor
  - Fuelled using present day waste
- U-Battery 5-10MWe
  - Small transportable power batteries

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But…

- SMR concept around for decades
- No commercial deployment yet in the West
- Can we have confidence in vendor claims?
- Will the economics stack up?
- Can SMRs be competitive?

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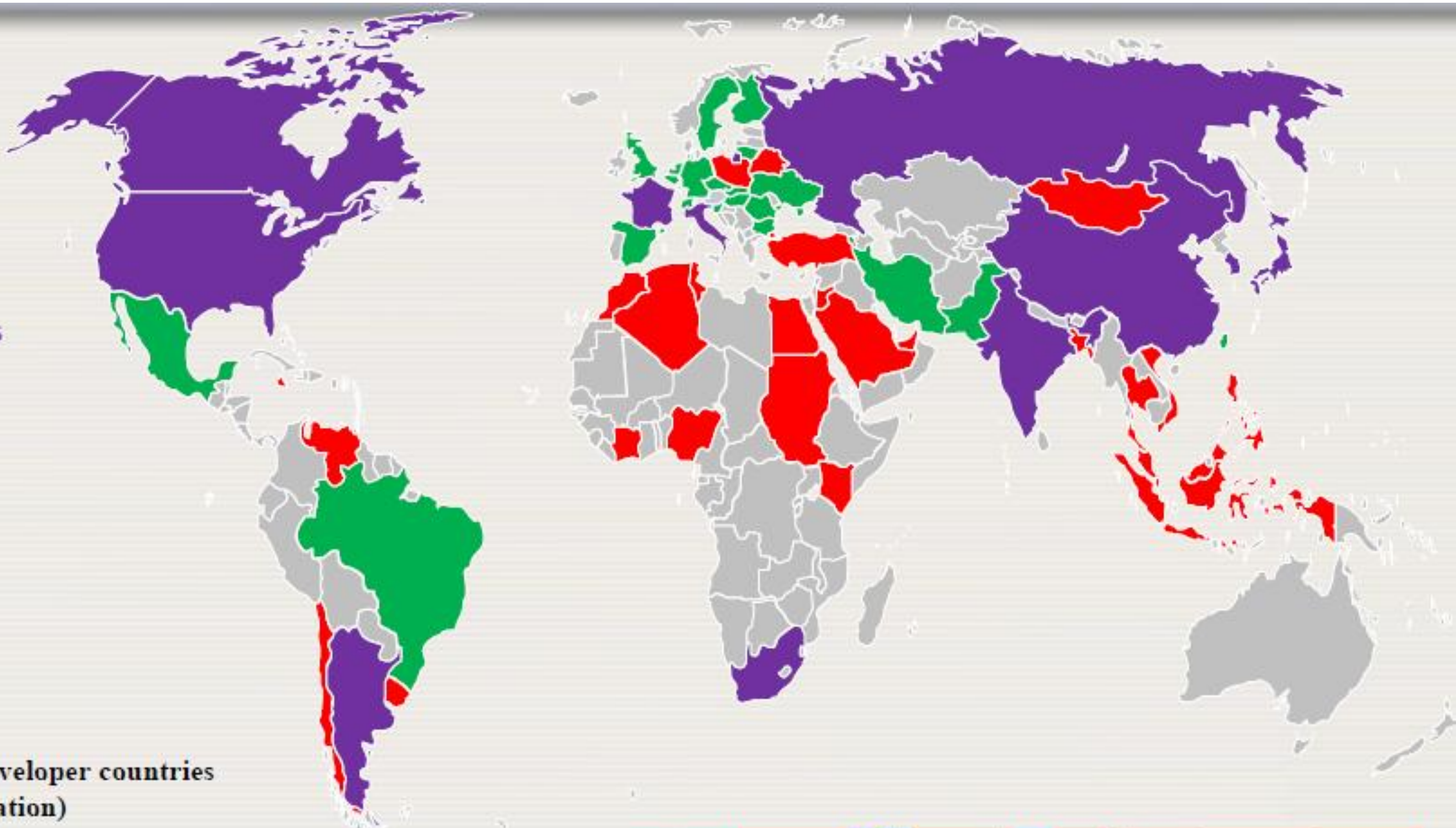
Potential global market



Which countries deploy SMRs?

- Technology developer countries (NPPs in operation)
- Countries with NPPs
- Newcomer countries

Asia

Europe

Africa

Latin America

IAEA

UK Energy System Requirements to 2050

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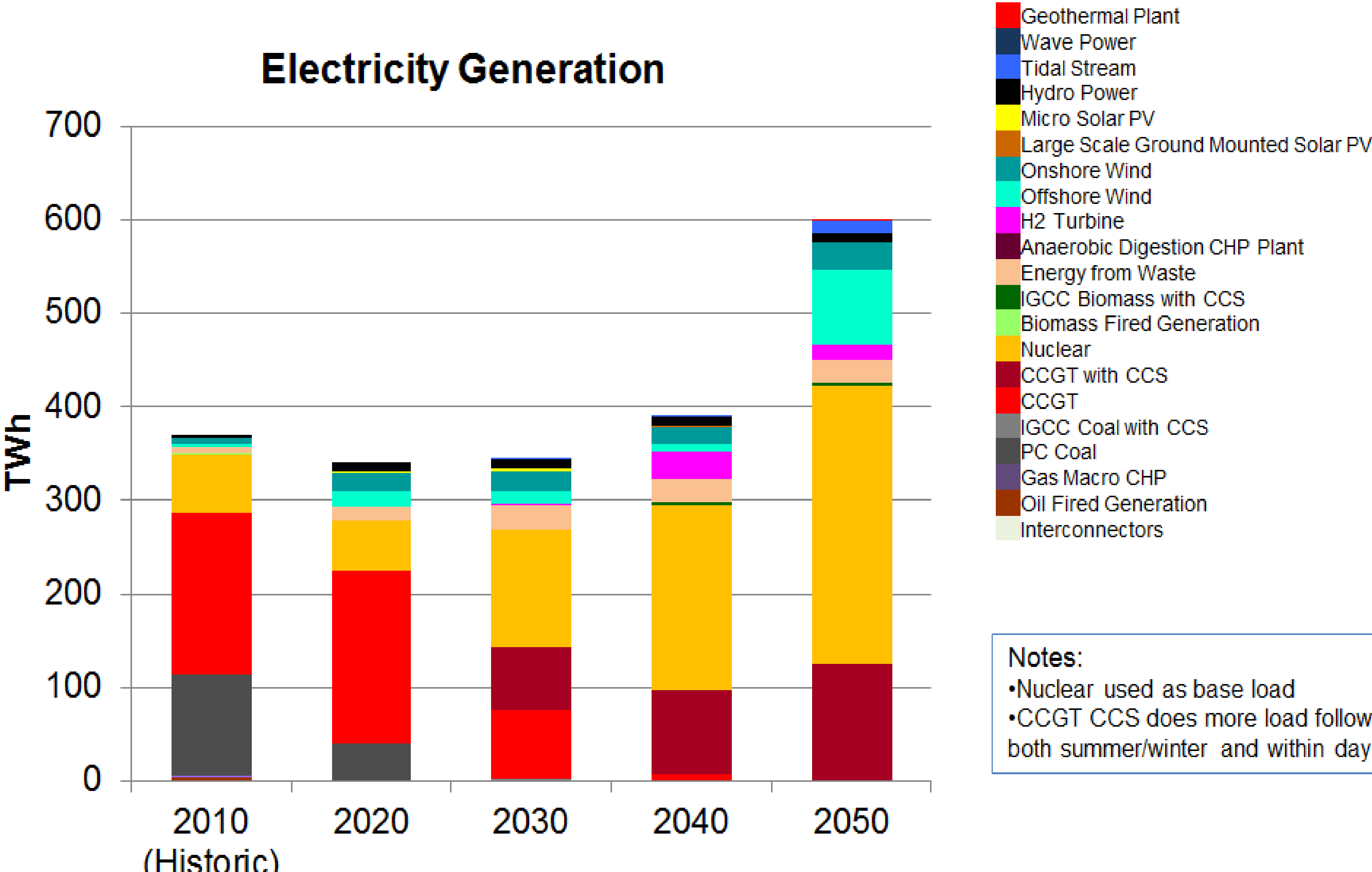
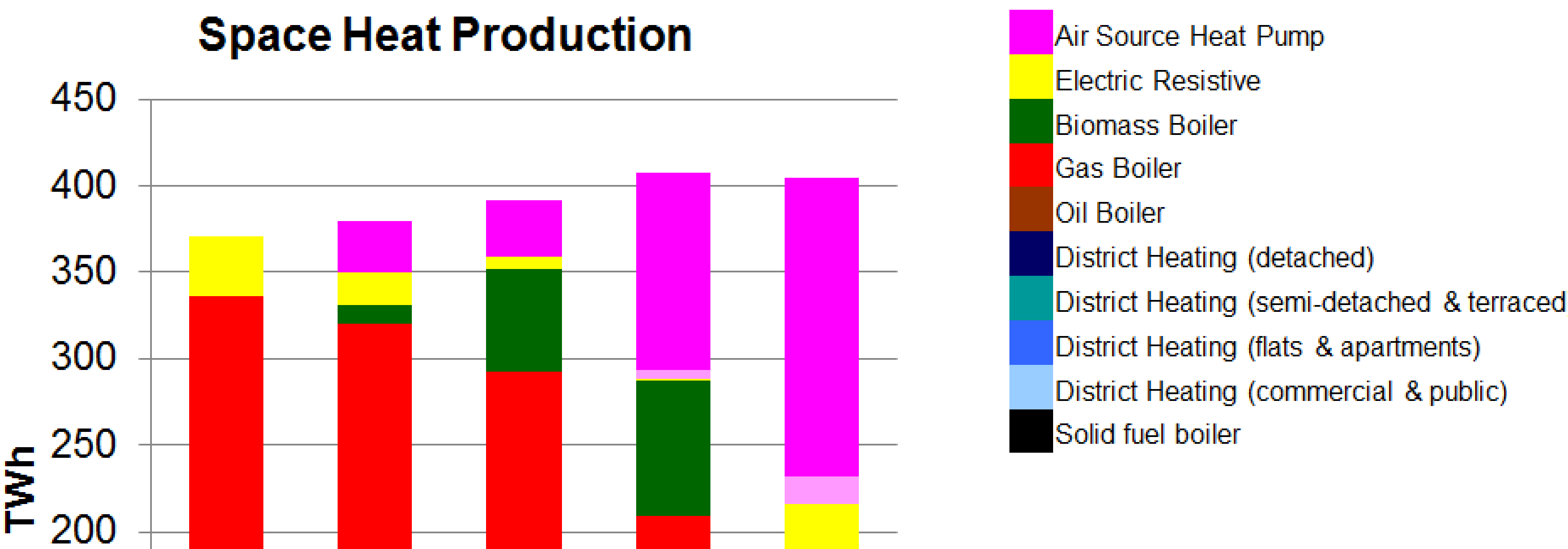


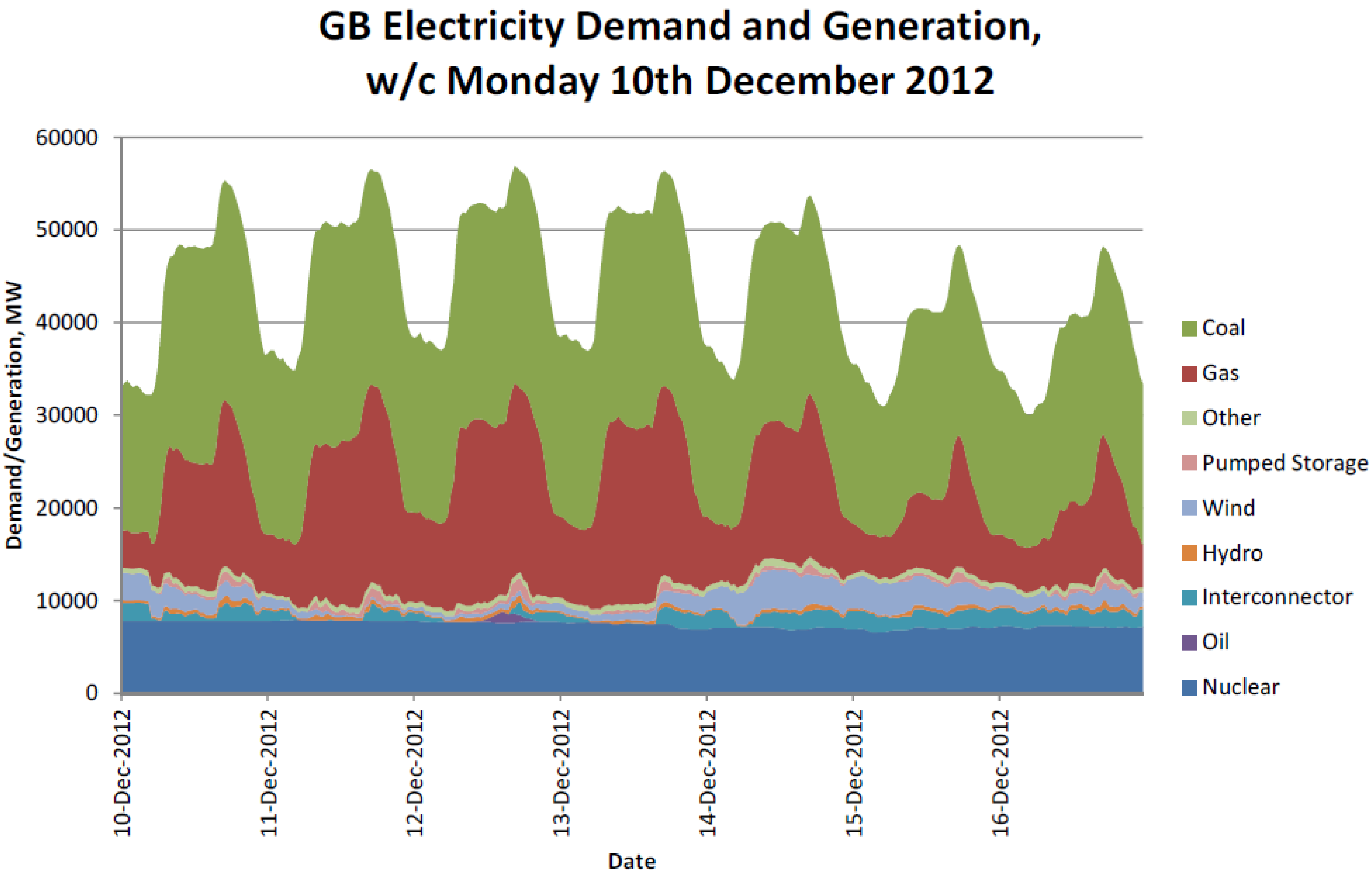
Notes:
- Nuclear used as base load
- CCGT CCS does more load following, both summer/winter and within day



Notes:

- Significant role for both district heating and heat pumps, although some uncertainty over exact balance between the two
- First choice (i.e. least cost) heat for the DHN is usually heat from large power stations (see Sankey diagram). DHN is still selected even if this is not possible, but will instead get heat from marine heat pumps, geothermal and CHP.

Flexibility



Technical Work-stream

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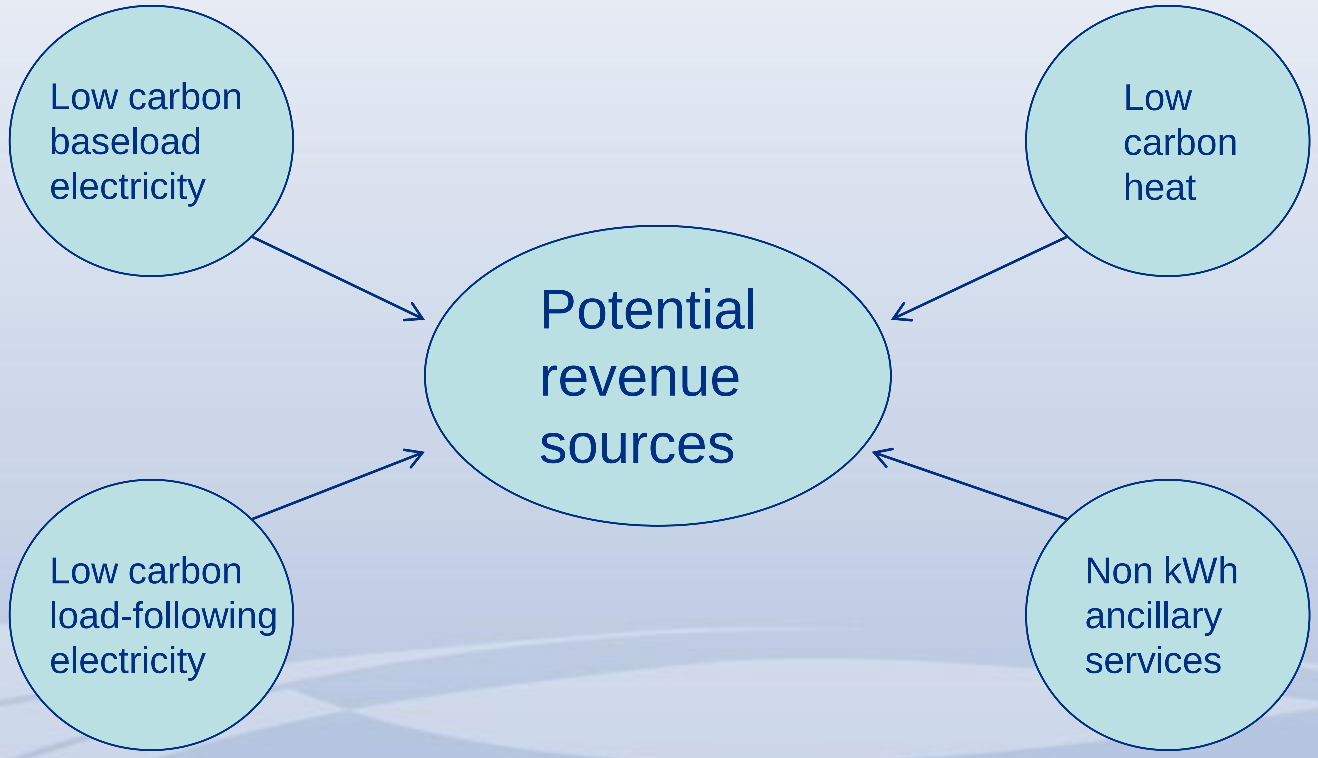
Representative SMR service offerings

		Baseload	Flexible	Extra-flex
	Electricity only SMR power plant	Baseload power (runs continuously)	Operated in load-following mode	(Slightly) reduced baseload power with extra storage & surge capacity
	Combined Heat & Power (CHP) plant	As above but with heat	As above but with heat	As above but with heat

Multiple revenue sources



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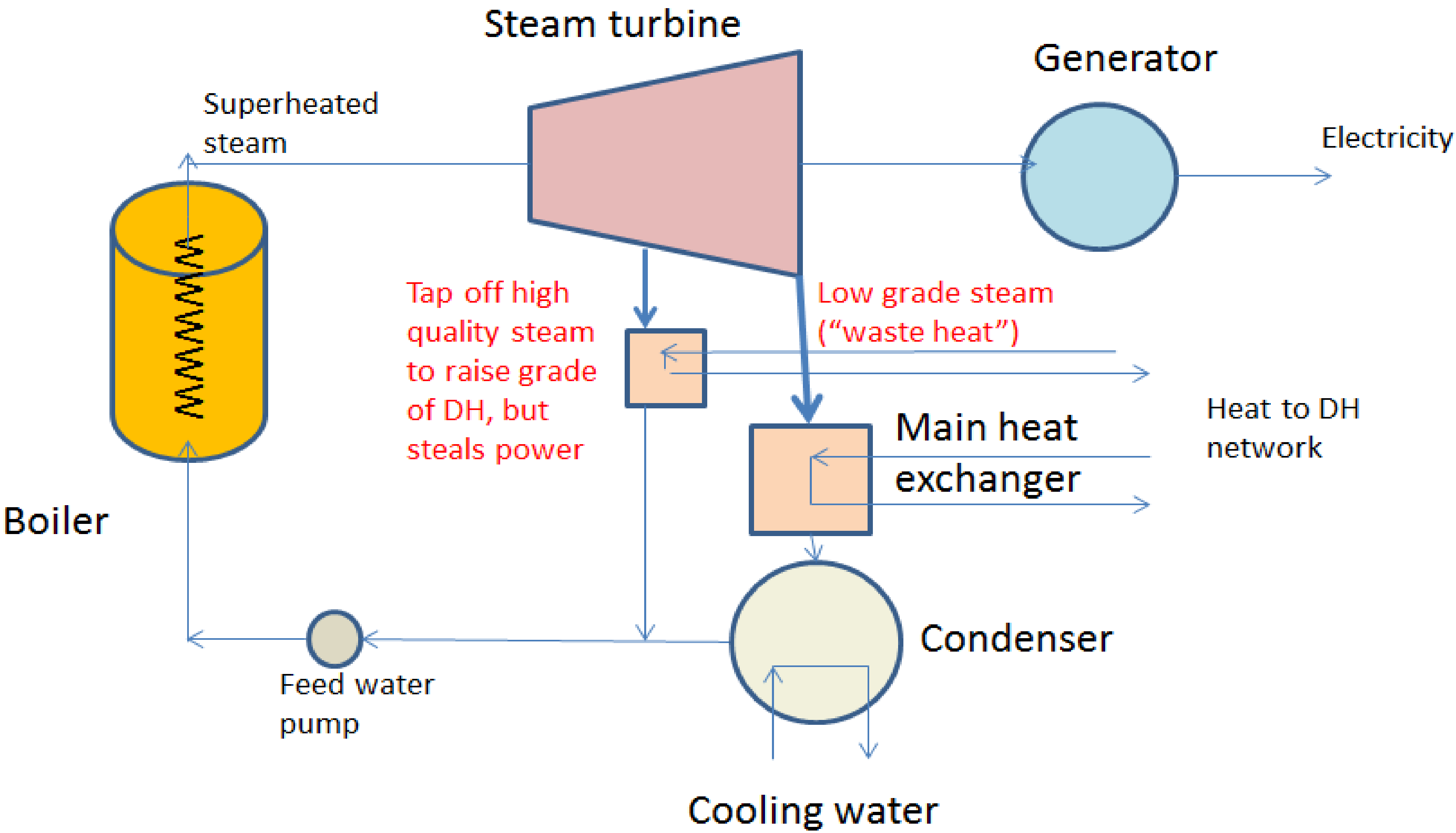
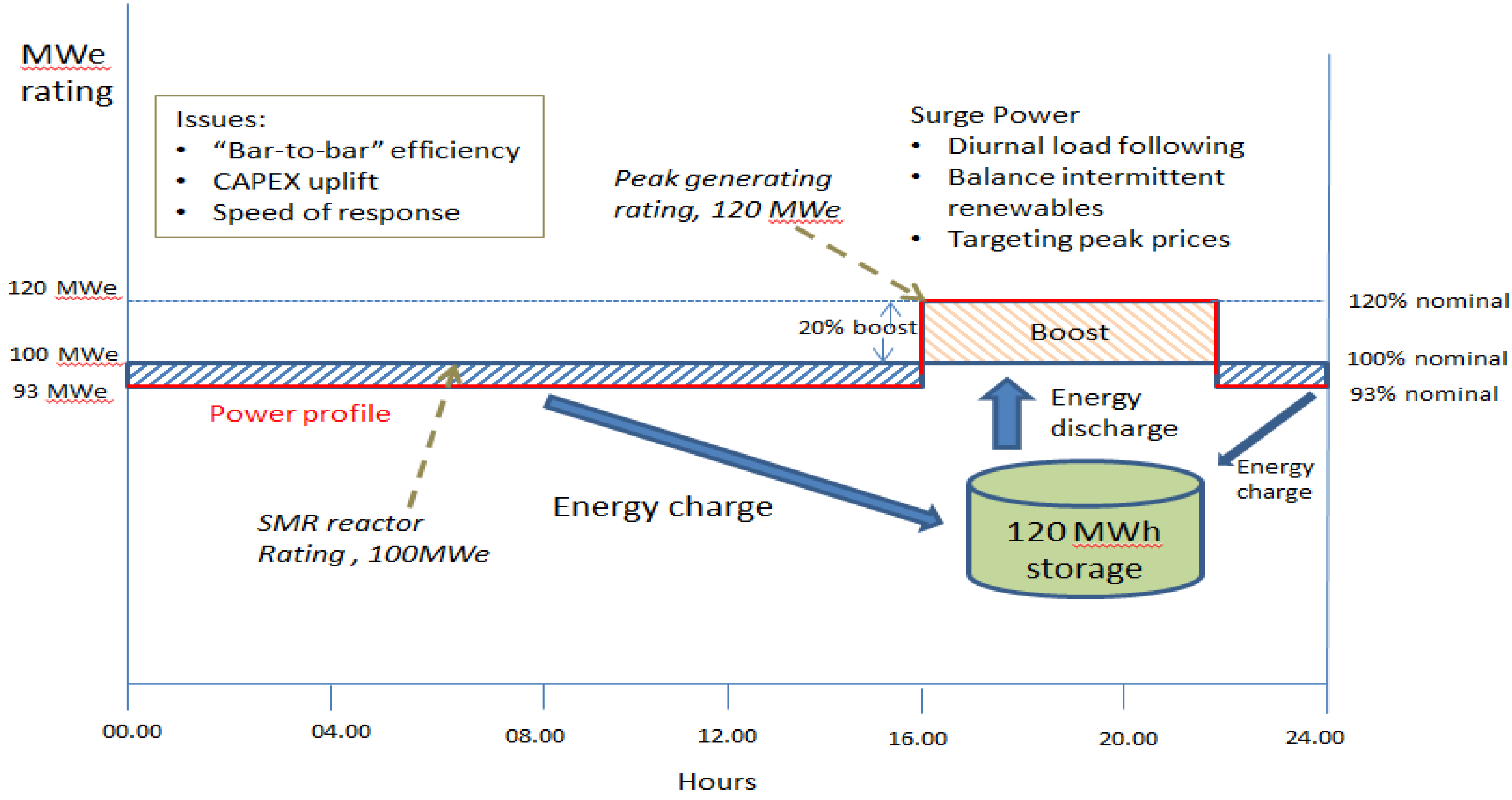
CHP – mostly waste heat; modest impact on electrical generation



Extra-flex example (+30%)



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SMR technology readiness

What stage of development are SMR technologies at?

What will it cost to develop these technologies?

- Developed an assessment framework to estimate technology maturity and cost / duration to full maturity
- Based on design maturity & Technology Readiness Levels
- Estimates for time and cost per phase
- Overall estimates based on novelty

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Technology Readiness Levels (TRLs)

TRL	Description
9	Actual system proven through successful missions (in-service)
8	Actual system completed and service qualified through test and demonstration
7	System prototype demonstration in an operational environment
6	System/sub-system model or prototype demonstration in a relevant environment
5	Component and/or partial system validation in a representative environment
4	Component and/or partial system validation in a laboratory environment
3	Analytical and experimental critical function and/or characteristic proof of concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

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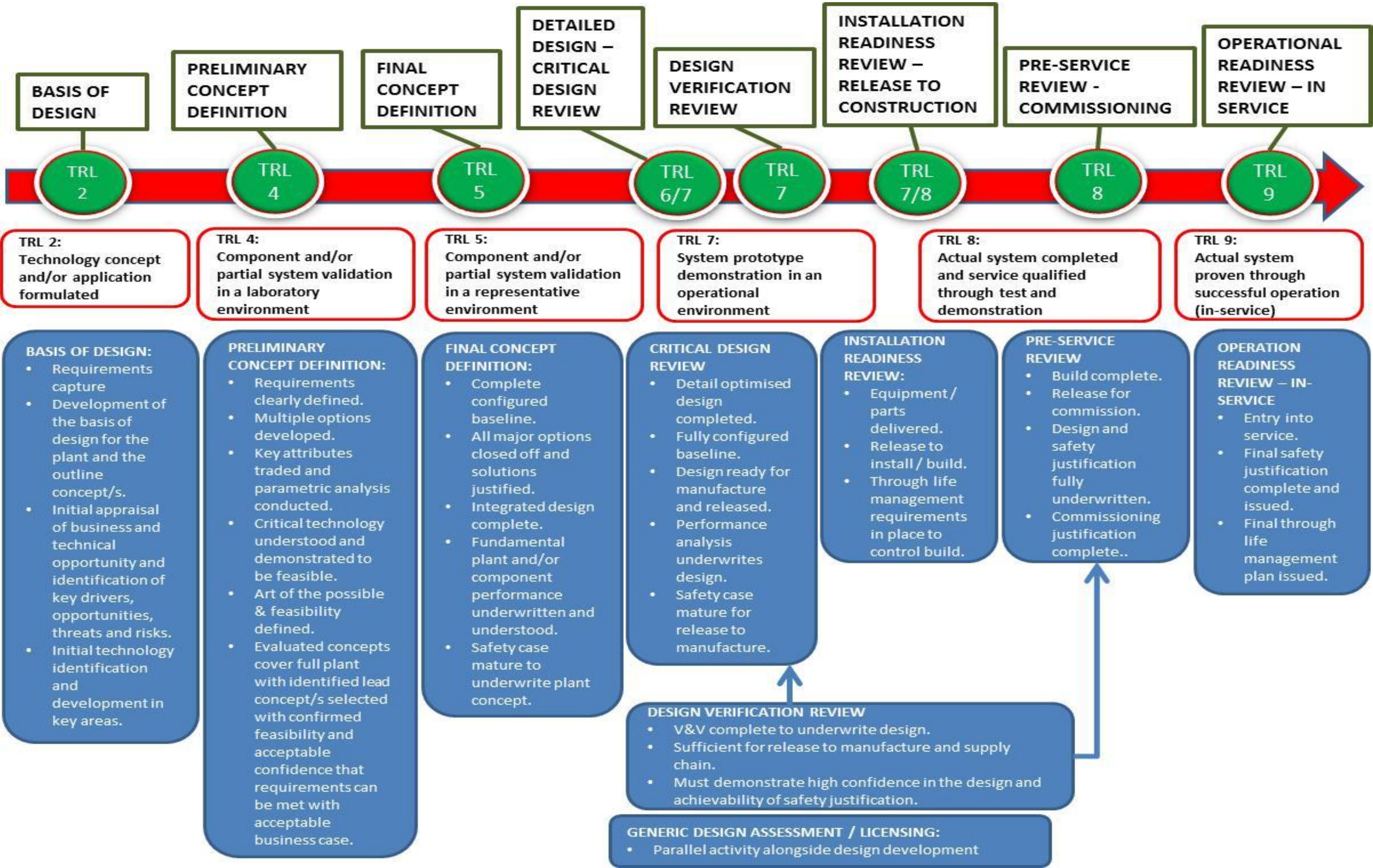
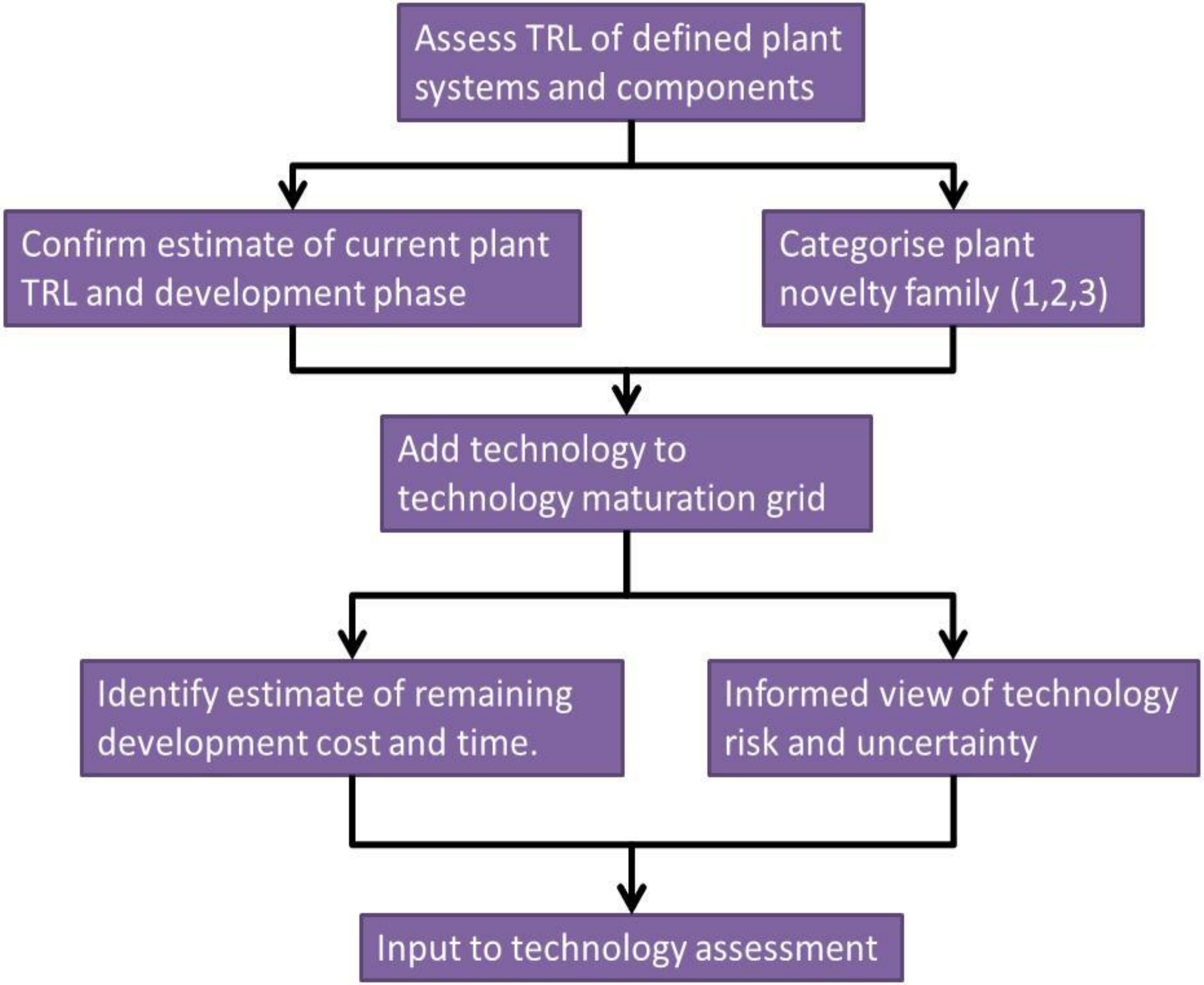
Technical development assessment framework



Assessment approach



			Reactor Technology Novelty Family		
Plant assessed to be currently at start of stage....	Typical Exit TRL		(1) Minor Evolution on well proven technology (low risk)	(2) Significant Evolution / some revolutionary aspects (moderate risk)	(3) Significant Revolutionary (high risk)
Stage 0 – Basis of Design	2	Time to maturity [yrs]	17.5	21.5	25.5
		Cost to maturity [£M]	£1,326	£1,877	£2,427
Stage 1 – Preliminary Concept Definition	4	Time to maturity [yrs]	16	19.75	23.5
		Cost to maturity [£M]	£1,320	£1,869	£2,418
Stage 2 – Full Concept Definition	5	Time to maturity [yrs]	14	17.25	20.5
		Cost to maturity [£M]	£1,289	£1,825	£2,361
Stage 3a – Product Realisation – Detailed Design - Critical Design Review	7	Time to maturity [yrs]	12	15	18
		Cost to maturity [£M]	£1,184	£1,673	£2,163
Stage 3b – Product Realisation – Design Verification Review(including parallel and additional licensing activity)	7	Time to maturity [yrs]	8	10.5	13
		Cost to maturity [£M]	£689	£979	£1,269
Stage 3c – Product Realisation – Installation Readiness Review	8	Time to maturity [yrs]	6	7.5	9
		Cost to maturity [£M]	£428	£553	£678
Stage 3d – Product Realisation – Pre Service Review	8	Time to maturity [yrs]	4	5	6
		Cost to maturity [£M]	£246	£332	£419
Stage 3e – Product Realisation – Operational Readiness Review and In service	9	Time to maturity [yrs]	2	2.5	3
		Cost to maturity [£M]	£123	£166	£209

- Determine time and cost remaining to NOAK
- 17-26 years
- £1.4-£2.5bn
- Per SMR design

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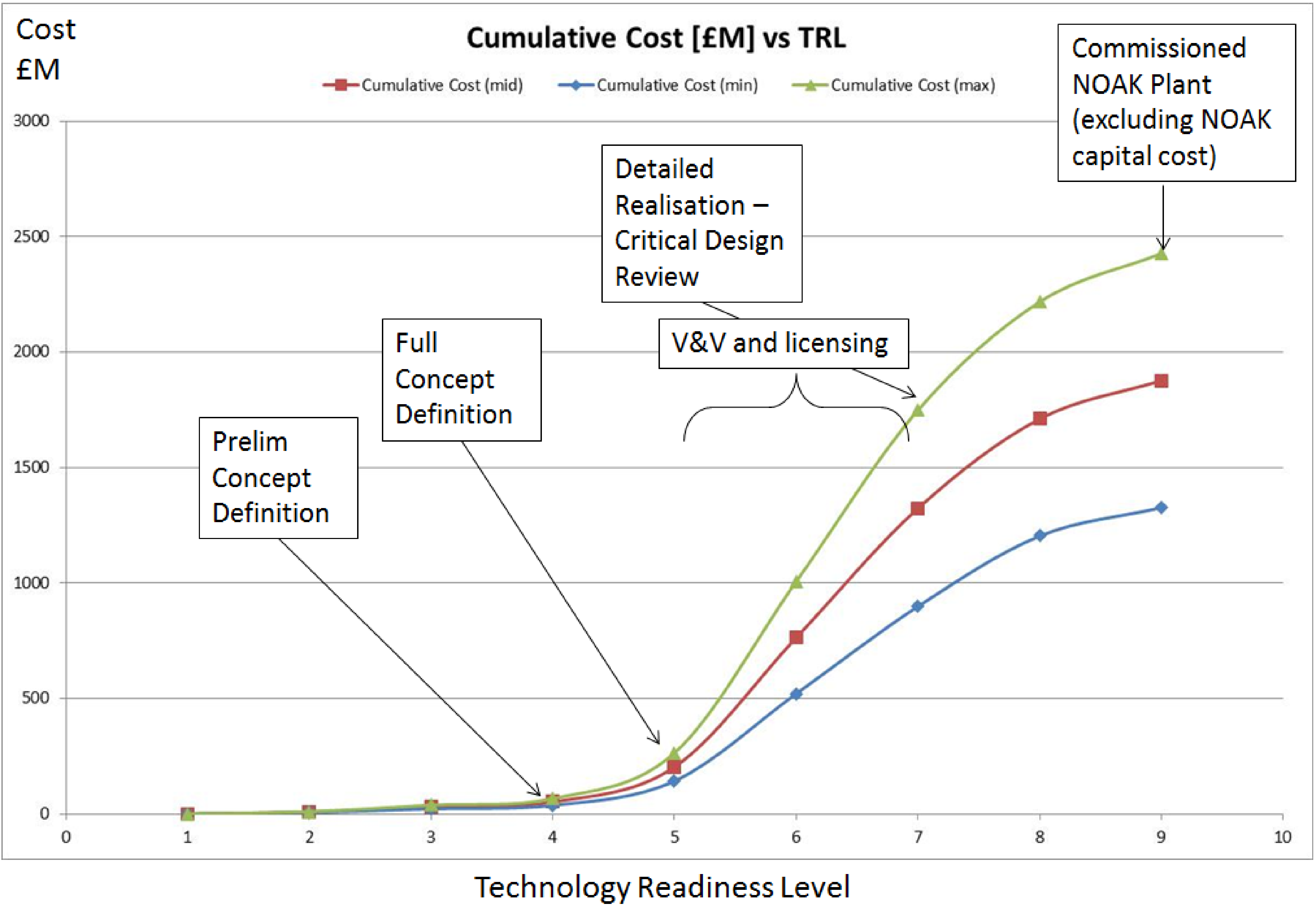

Cost £M
Cumulative Cost [£M] vs TRL
Cumulative Cost (mid)
Cumulative Cost (min)
Cumulative Cost (max)
Commissioned NOAK Plant (excluding NOAK capital cost)
Detailed Realisation – Critical Design Review
V&V and licensing
Full Concept Definition
Prelim Concept Definition
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
Technology Readiness Level

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Deployment Schedule

When could SMRs be deployed in the UK?
How much capacity is possible by 2050?

Tool created for analysis based on 2 supply-side factors:

- Pace of early technology development (including FOAK)
- Factory production drumbeat (NOAK)

FOAK = full-scale single module demonstrator plant (stick-built)
NOAK = subsequent multi-module plants (factory built)

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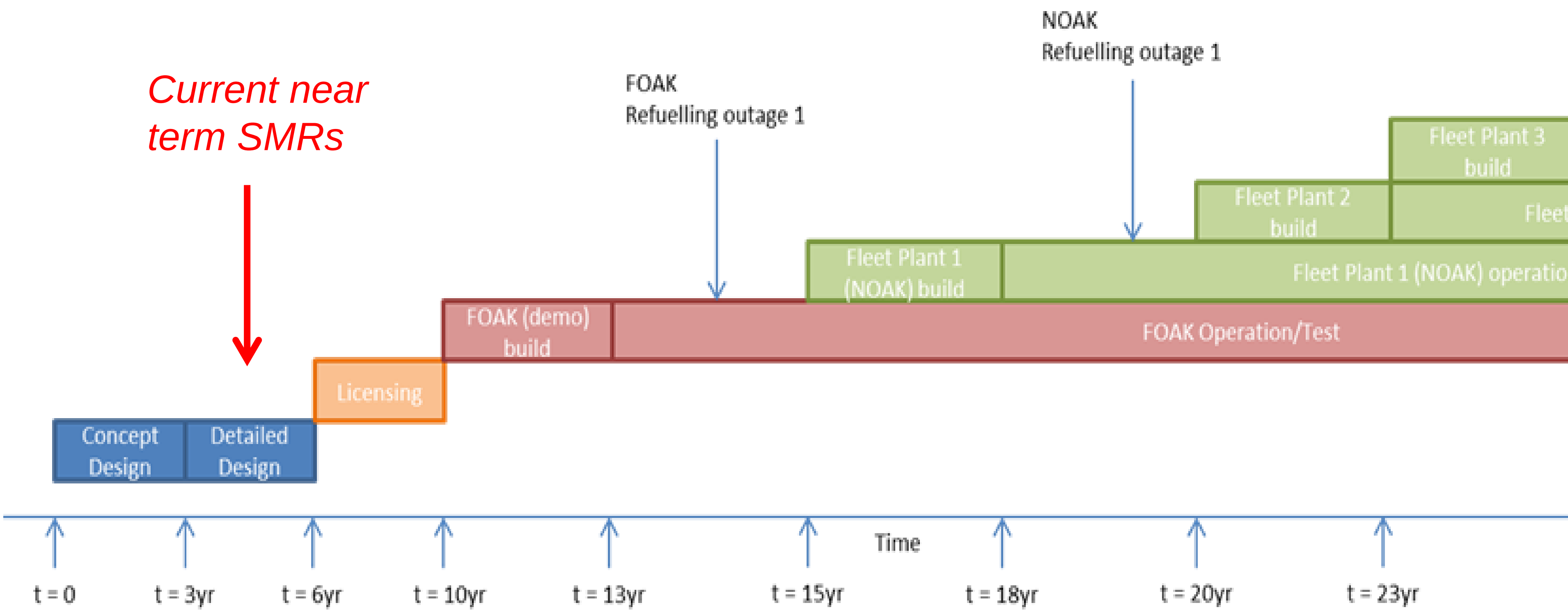
Pace of early technology development

- Concept design to FOAK plant re-fuelling
- At least 15 years for PWR based technology
- Earliest FOAK build starts in 2021



Three drumbeat scenarios

Scenario	Low SMR build rate	Mid SMR build rate	High SMR build rate
Completed Design Date	2018	2018	2018
Licensing approval	2021	2021	2021
FOAK build starts	2021	2021	2021
NOAK build starts	2025	2025	2024
Drumbeat NOAK build starts	2029	2029	2027
NOAK 'drumbeat' (2030s)	2 reactor sets per year (100MWe)	4 reactor sets per year (100MWe)	9 reactor sets per year (100MWe)
NOAK 'drumbeat' (2040s)	4 reactor sets per year (100MWe)	12 reactor sets per year (100MWe)	12 reactor sets per year (100MWe)

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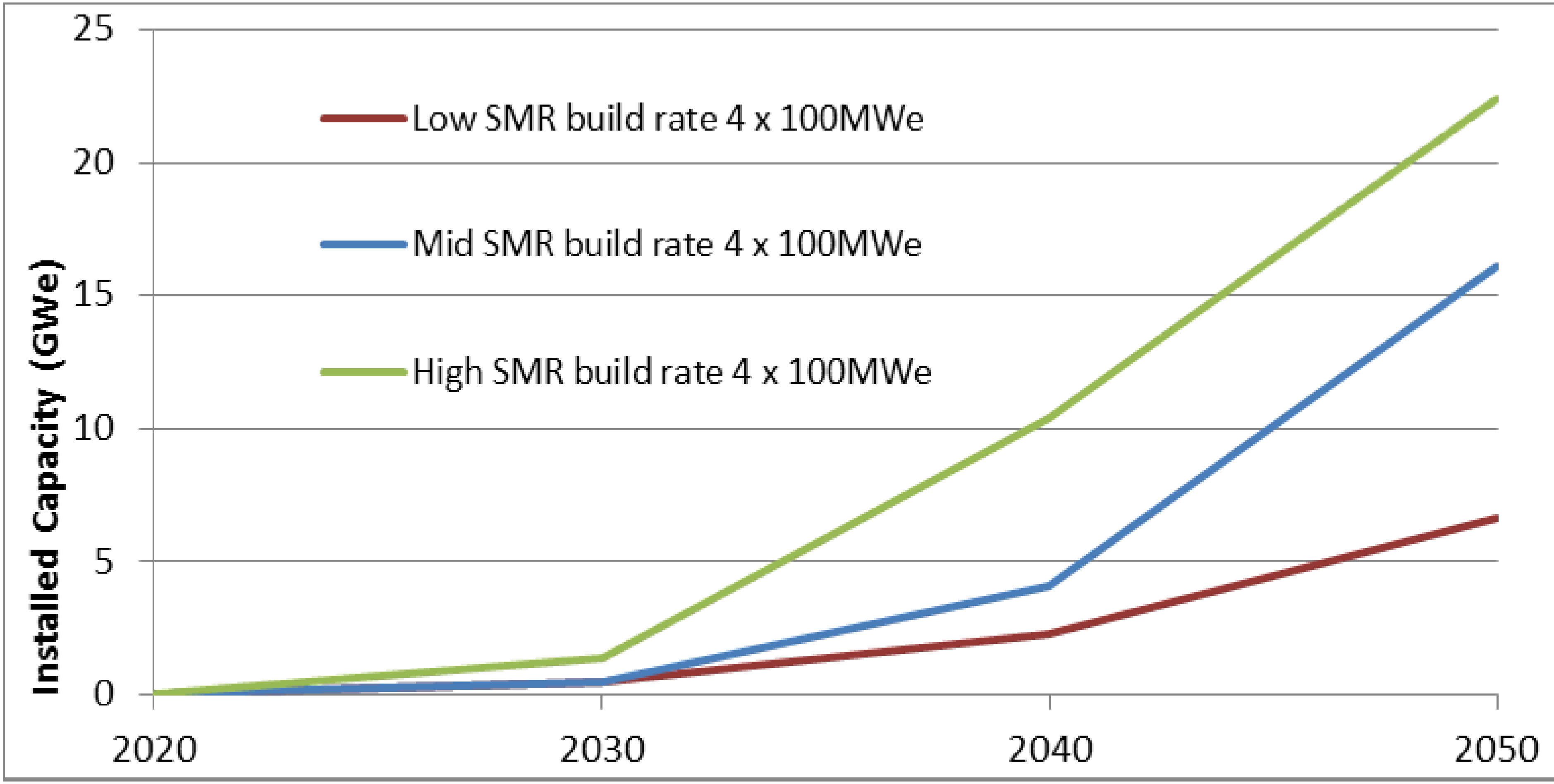
6-23GWe by 2050?



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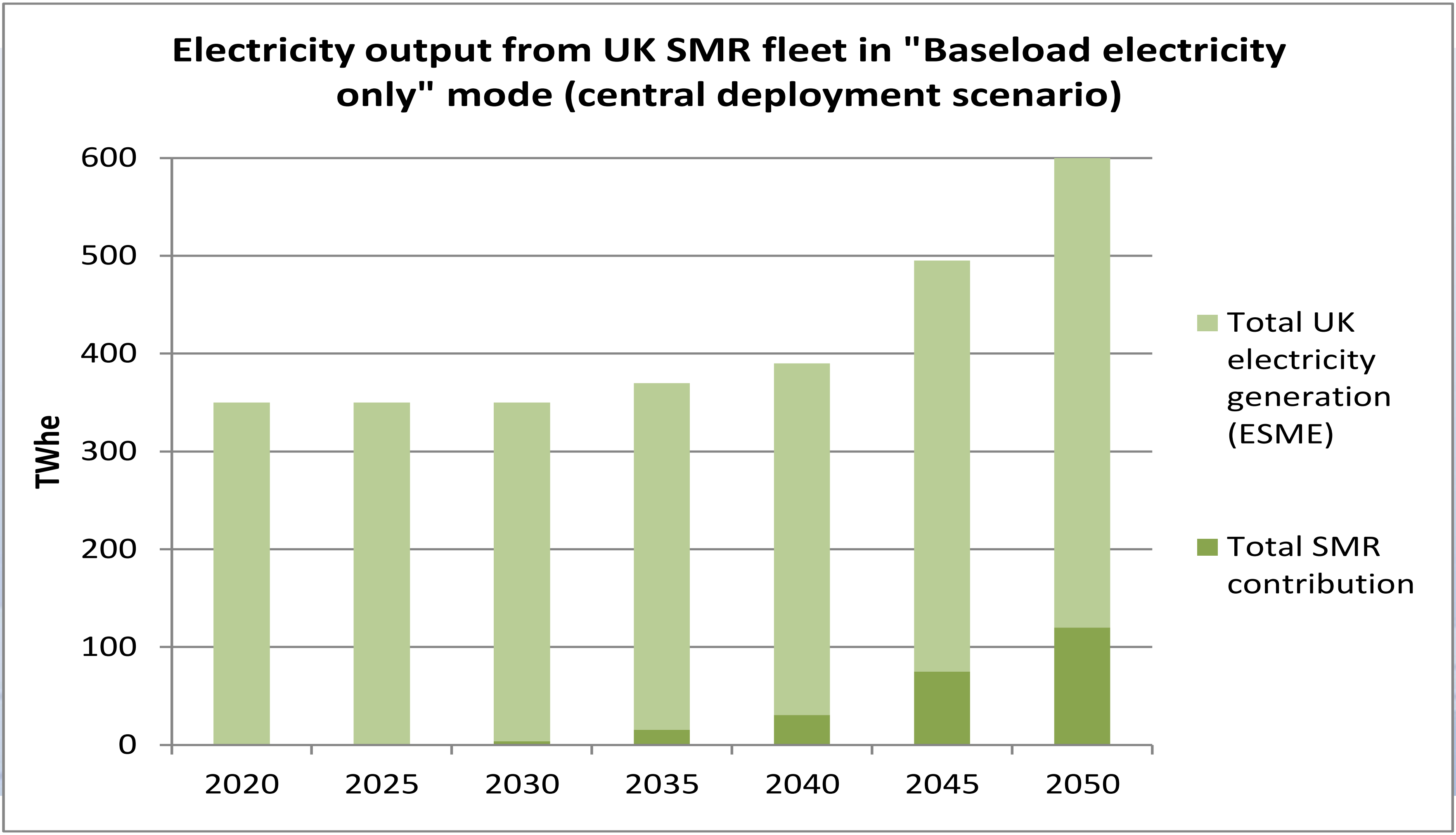
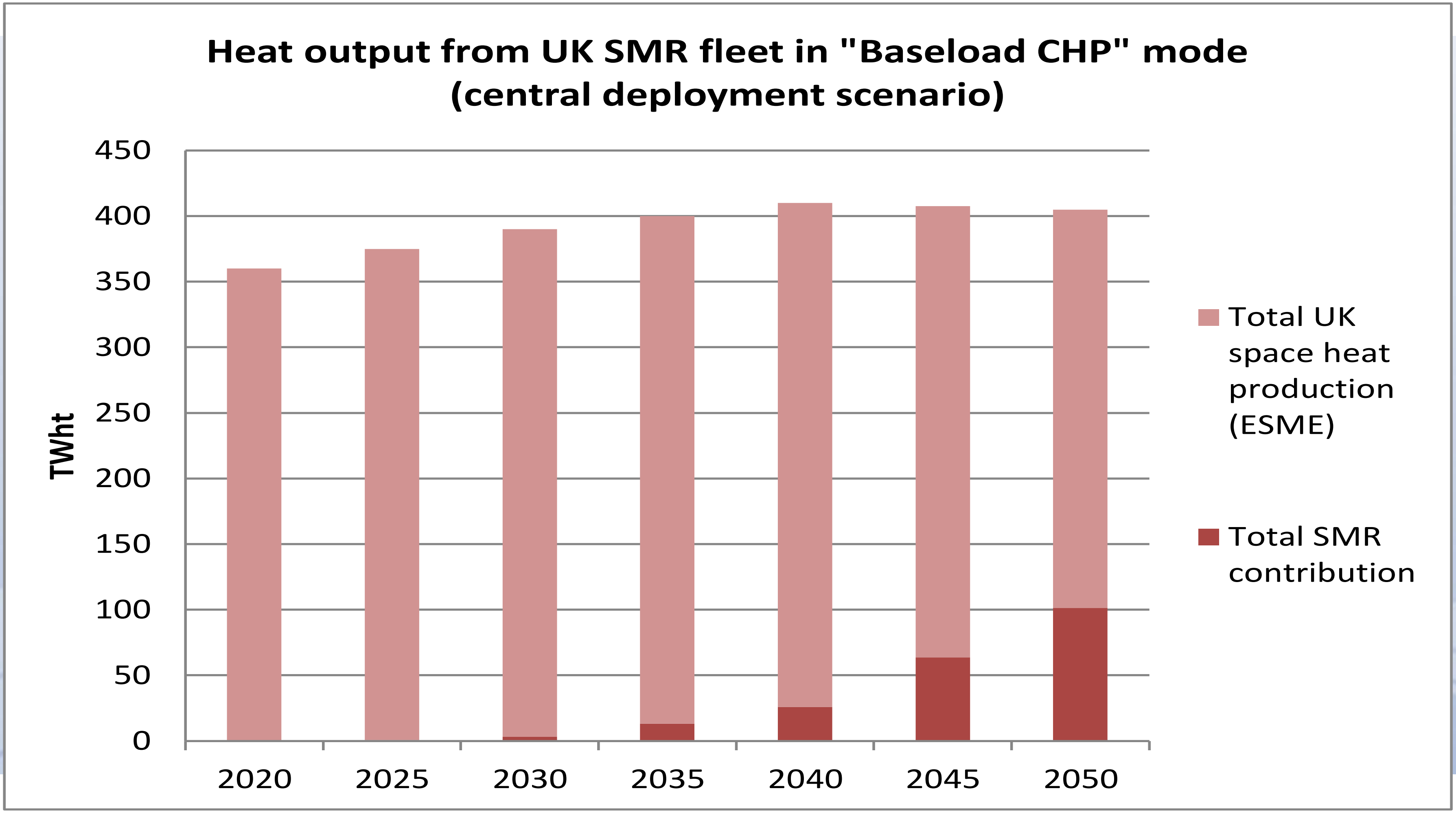
Electricity contribution to 2050



Heat contribution to 2050



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Potential locations for SMR plants

Are there locations in GB to host SMR fleet deployment?

Our analysis suggests potentially yes

Approach:

- PPSS locations for power plants <300MWe in size, plus unused capacity at existing large nuclear sites
- Assessed potential heat networks in GB
- Married two together to identify and quantify target locations

Conservative estimate

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Heat network analysis

What demand is required to utilise 40% of the annual heat output of an SMR CHP plant (min. 100MWe)

- 75% penetration
- 20% of annual demand not met
- Heat ACF can change

What is the minimum "heat load *density*" needed for a viable heat network?

- Based on Danish heat load networks

Which areas in GB meet these criteria?

= central nodes of future SMR energised district heat networks

- Using GIS

Estimate total number of SMR energised heat networks, and theoretical SMR fleet capacity to energise these networks

- ETI heat data (contemporary)
- Residential & tertiary
- 8000+ Mid Level Super Output Areas (MSOAs) in GB
- GIS

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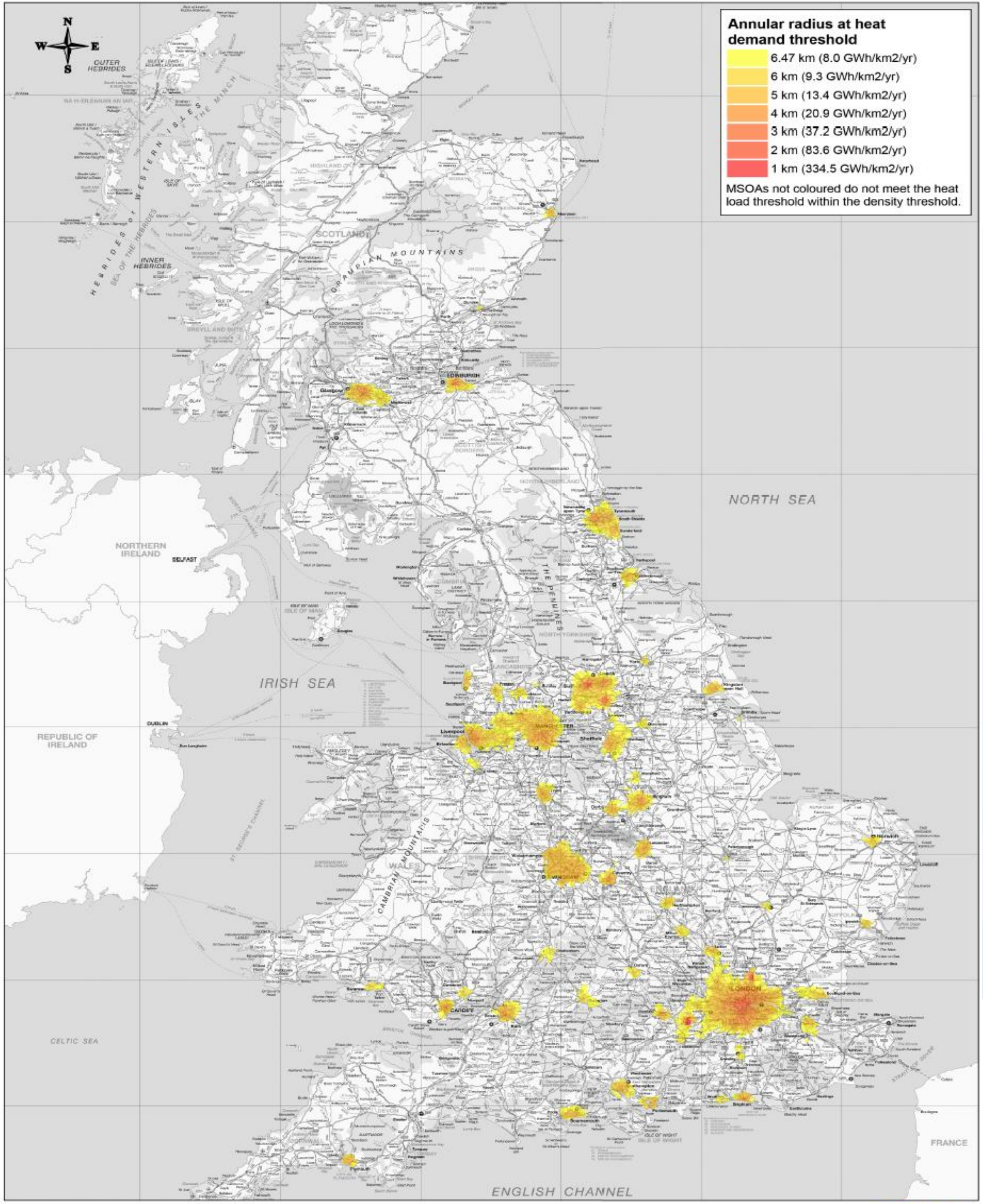
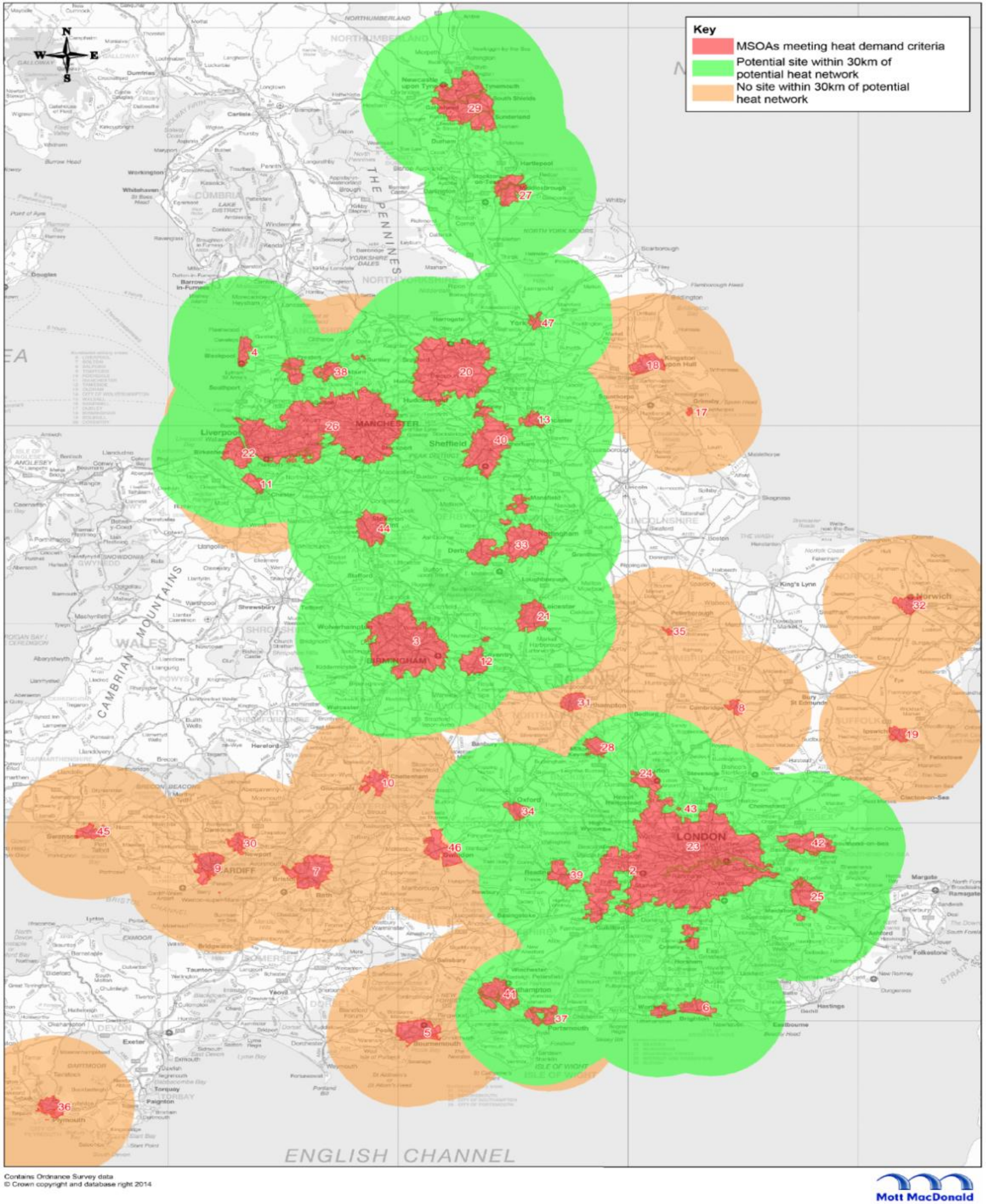


- Almost 50 GB urban conurbations with sufficient heat load to support SMR energised heat networks
- Would theoretically require 22.3GWe CHP SMR capacity



- Many potential heat networks within 30kms of PPSS SMR location
- Of 9.9GWe capacity possible at PPSS locations, 7.4GWe could be CHP
- Heat market = economic advantage for SMRs

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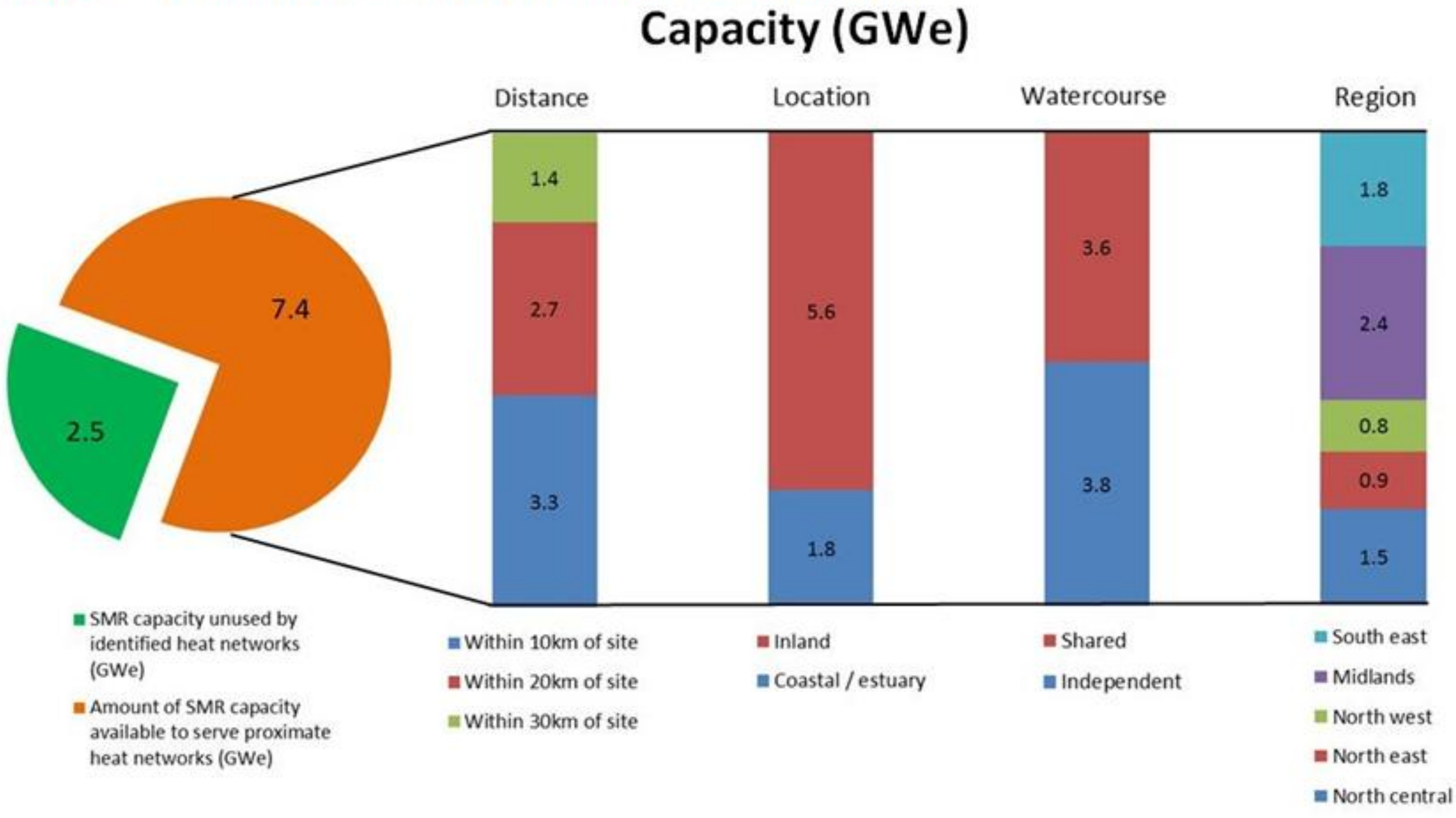
Target locations

Figure 2.6: Graphical representation of SMR location capacity breakdown



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Siting criteria

Unlocking SMR siting potential will be key to facilitating deployment

Existing siting criteria expected to form basis for SMRs

But SMRs are fundamentally different from LR in some ways

So how would these differences impact on existing criteria

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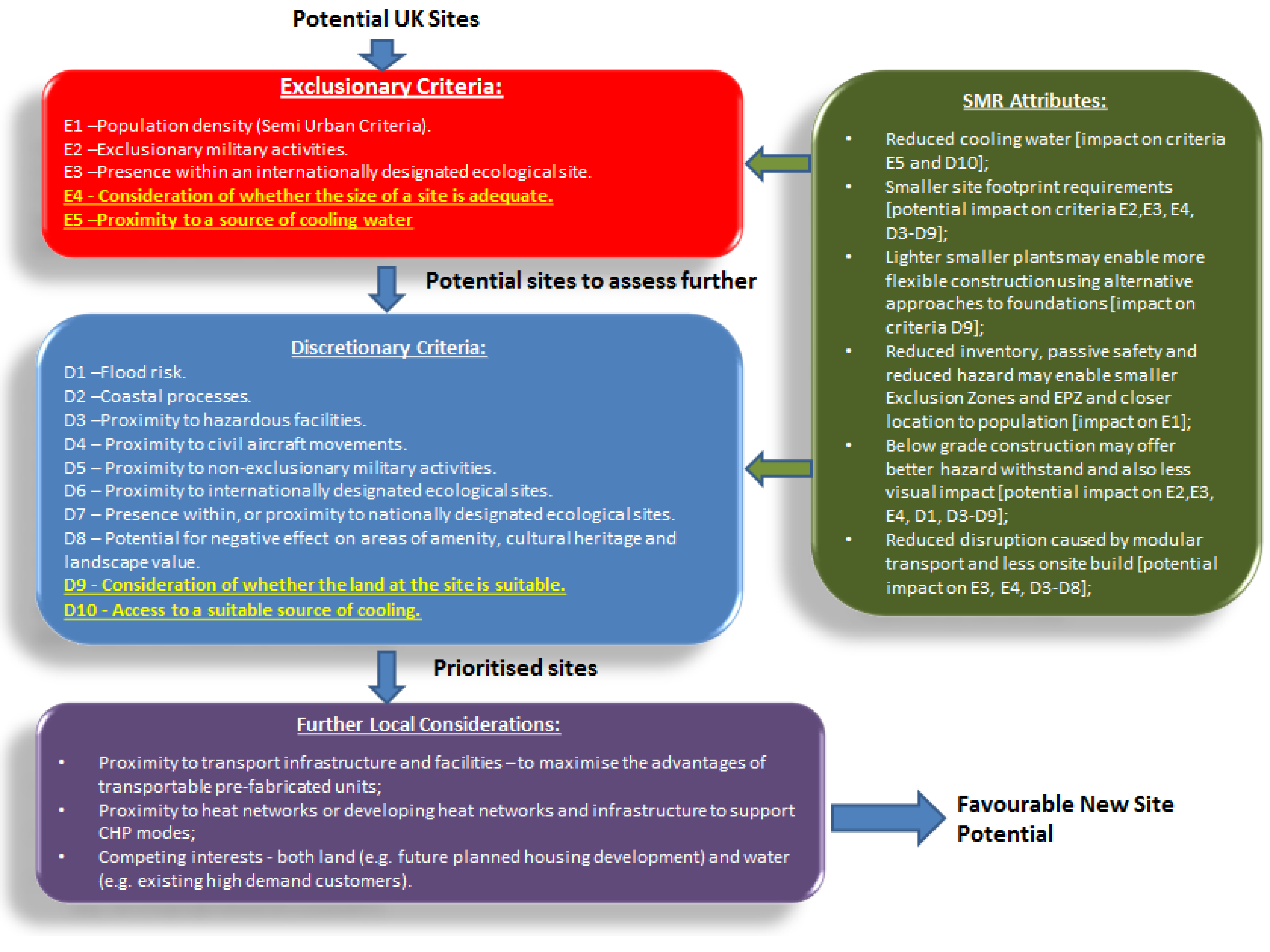
Potential UK Sites
Exclusionary Criteria:
E1 –Population density (Semi Urban Criteria).
E2 –Exclusionary military activities.
E3 –Presence within an internationally designated ecological site.
E4 - Consideration of whether the size of a site is adequate.
E5 –Proximity to a source of cooling water
Potential sites to assess further
Discretionary Criteria:
D1 –Flood risk.
D2 –Coastal processes.
D3 –Proximity to hazardous facilities.
D4 – Proximity to civil aircraft movements.
D5 – Proximity to non-exclusionary military activities.
D6 – Proximity to internationally designated ecological sites.
D7 – Presence within, or proximity to nationally designated ecological sites.
D8 – Potential for negative effect on areas of amenity, cultural heritage and landscape value.
D9 - Consideration of whether the land at the site is suitable.
D10 - Access to a suitable source of cooling.
SMR Attributes:
Reduced cooling water [impact on criteria E5 and D10];
Smaller site footprint requirements [potential impact on criteria E2,E3, E4, D3-D9];
Lighter smaller plants may enable more flexible construction using alternative approaches to foundations [impact on criteria D9];
Reduced inventory, passive safety and reduced hazard may enable smaller Exclusion Zones and EPZ and closer location to population [impact on E1];
Below grade construction may offer better hazard withstand and also less visual impact [potential impact on E2,E3, E4, D1, D3-D9];
Reduced disruption caused by modular transport and less onsite build [potential impact on E3, E4, D3-D8];
Prioritised sites
Further Local Considerations:
Proximity to transport infrastructure and facilities –to maximise the advantages of transportable pre-fabricated units;
Proximity to heat networks or developing heat networks and infrastructure to support CHP modes;
Competing interests - both land (e.g. future planned housing development) and water (e.g. existing high demand customers).
Favourable New Site Potential

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UK national nuclear infrastructure

What would be the impact of SMR deployment on nuclear infrastructure?

Our approach:

- Acknowledges UK's existing infrastructure & plans
- Identified infrastructure for each part of SMR life cycle
- Considered aggregate impacts of a fleet of SMRs

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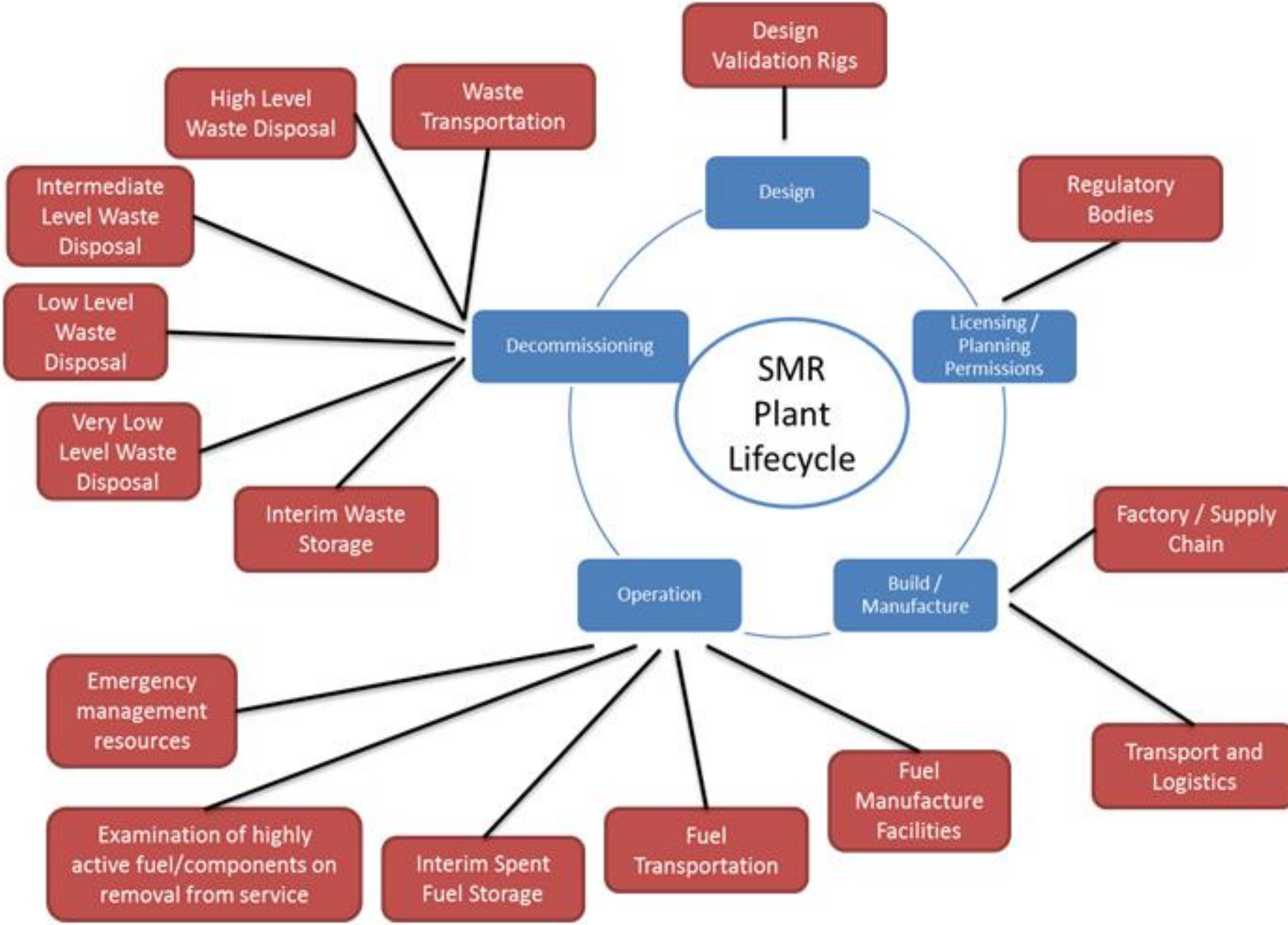

SMR Plant Lifecycle
Design
Licensing / Planning Permissions
Build / Manufacture
Operation
Decommissioning
Design Validation Rigs
Regulatory Bodies
Factory / Supply Chain
Transport and Logistics
Fuel Manufacture Facilities
Fuel Transportation
Interim Spent Fuel Storage
Examination of highly active fuel/components on removal from service
Emergency management resources
Interim Waste Storage
Very Low Level Waste Disposal
Low Level Waste Disposal
Intermediate Level Waste Disposal
High Level Waste Disposal
Waste Transportation

UK national nuclear infrastructure

Key infrastructure requirements relate to:

- Additional capacity for nuclear waste handling and disposal
- Compatibility between SMR and existing infrastructure
- Development of, and capacity in, the factory module manufacturing supply chain
- Validation and verification facilities to enable/enhance value added offering from UK in SMR design and development

Cost and timescales confirm importance of aligning SMR development to existing infrastructure

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Technical requirements: Objective

What are key technical requirements for SMR technologies & power plants that are different from large reactors?

Important to integrate a wide range of stakeholder inputs across the whole plant lifecycle

Within the scope and constraints of the project, its was only feasible to define a very high level set of design requirements with a focus on differentiation between large and small reactors

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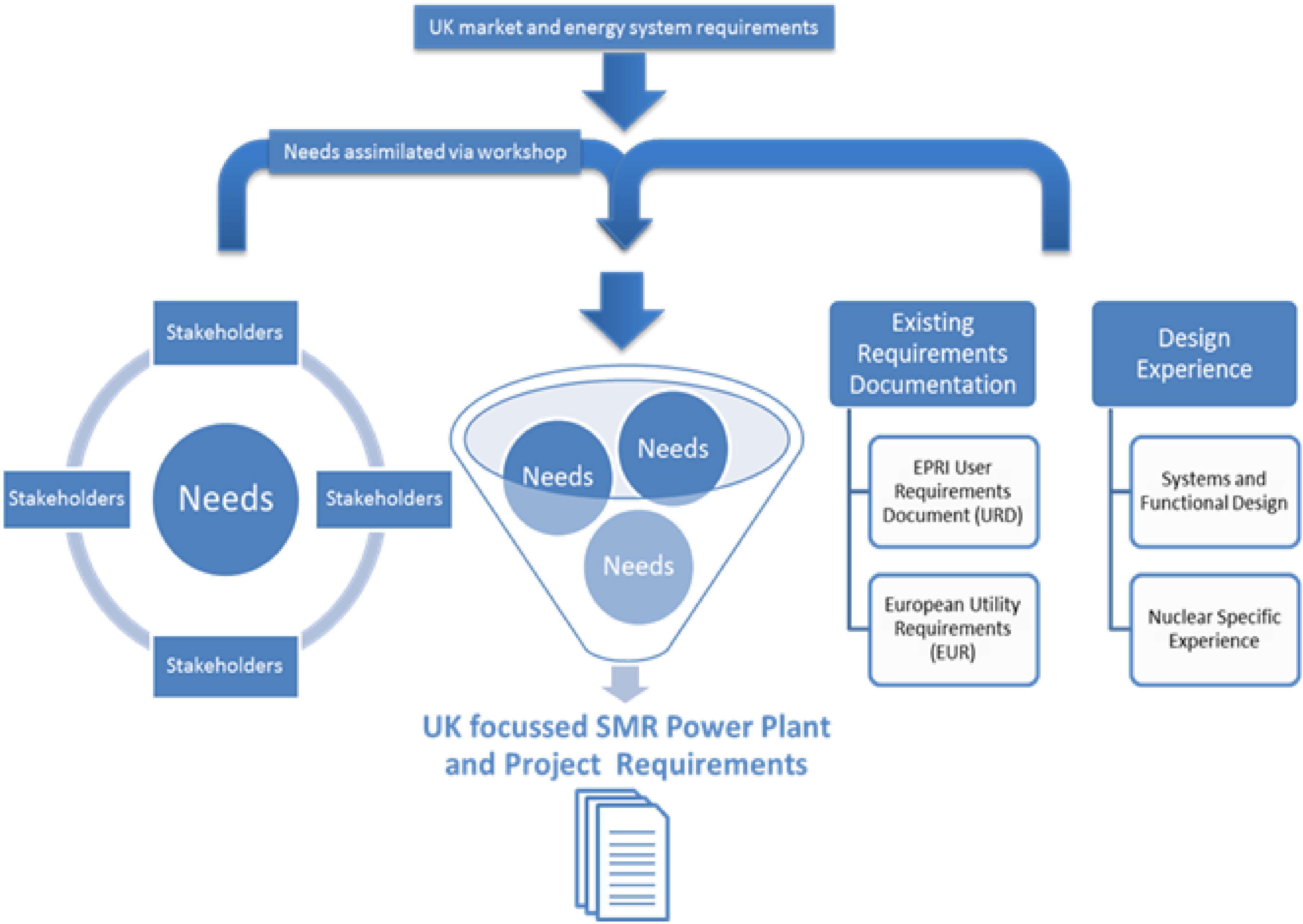
UK market and energy system requirements
Needs assimilated via workshop
Stakeholders
Stakeholders
Needs
Stakeholders
Stakeholders
Needs
Needs
Needs
Existing Requirements Documentation
EPRI User Requirements Document (URD)
European Utility Requirements (EUR)
Design Experience
Systems and Functional Design
Nuclear Specific Experience
UK focussed SMR Power Plant and Project Requirements

Key Technical Requirements (1/3)

Over 100 technical requirements generated. Regulatory oversight is assumed to be as is currently the case for large nuclear plants; key differentiating requirements include:

- SMR power plant output defined between 100MWe and 1000MWe, with multiple SMR power modules allowable to make up the total output
- Desirable for SMR to perform in a secondary mode to compliment their primary performance purpose (e.g. grid electricity production complimented by district heat output)

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Key Technical Requirements (2/3)

- Whole plant modular construction to be maximised in order to reduce on-site build cost and duration
- SMR to be able to operate in diurnal load-following mode (30-100% nominal power with 0.5% per minute ramp rate)
- SMR plants to incorporate latest developments in passive safety

Key Technical Requirements (3/3)

- SMR power plant designs with individual power modules to be managed to facilitate online refuelling and flexibility around incremental operation/start-up during modular build
- SMR modules to be designed to maximise compatibility with existing infrastructure routes
- SMR power plants to be designed and located so that ground works are minimised; up to and including removing the bedrock anchor

Economic Work-stream

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Aims of economic appraisal

- To investigate the economic case for SMR deployment in the UK

- Power plant level:
  - Target costs for SMR plants to be viable
  - Our own projections of costs

- National level:
  - Costs & benefits to UK PLC

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Caveat

- High uncertainty
- Many assumptions
- Multi-decadal timescale
- Treat results with caution
- Indicative only

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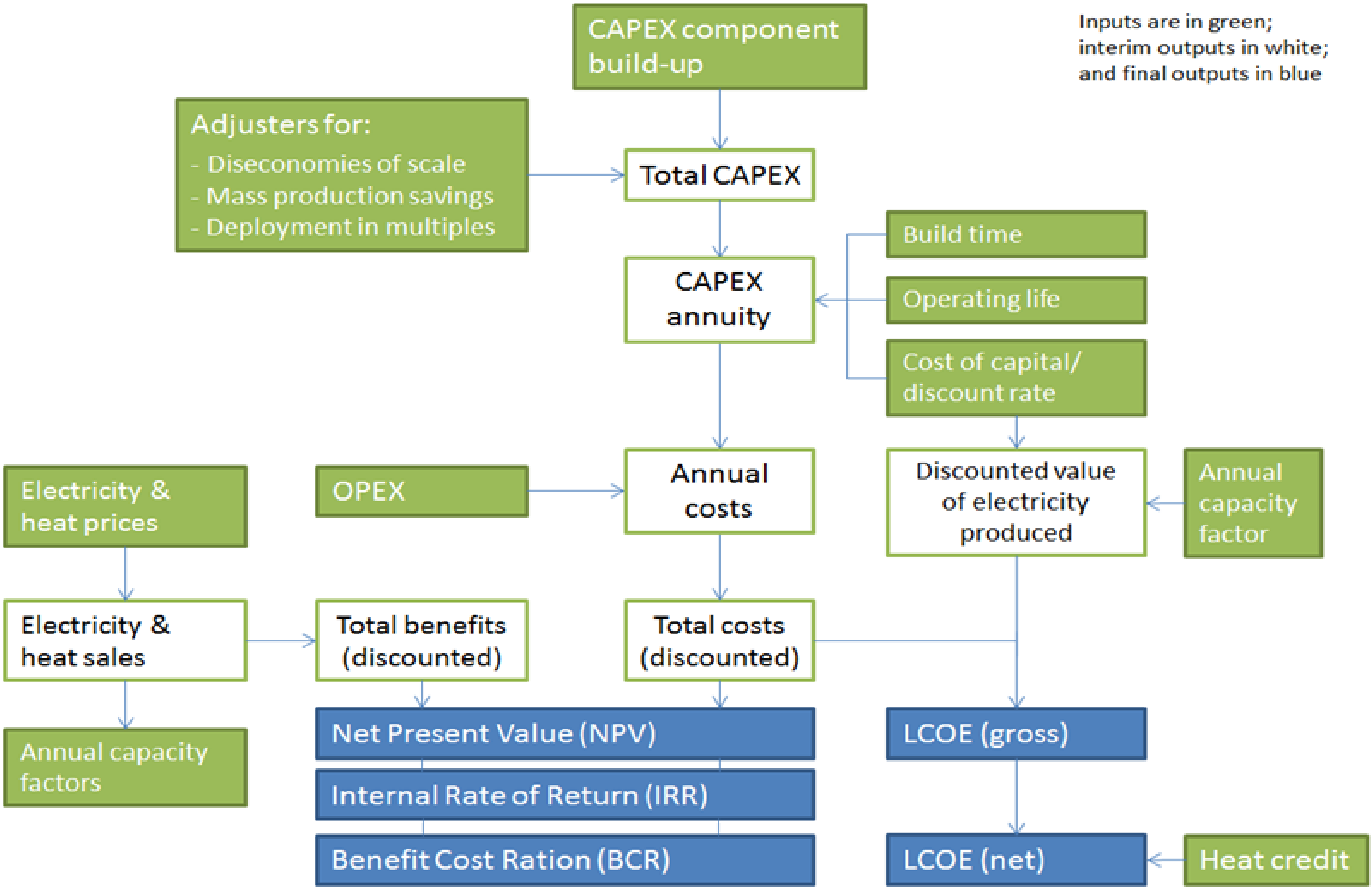
Economic model



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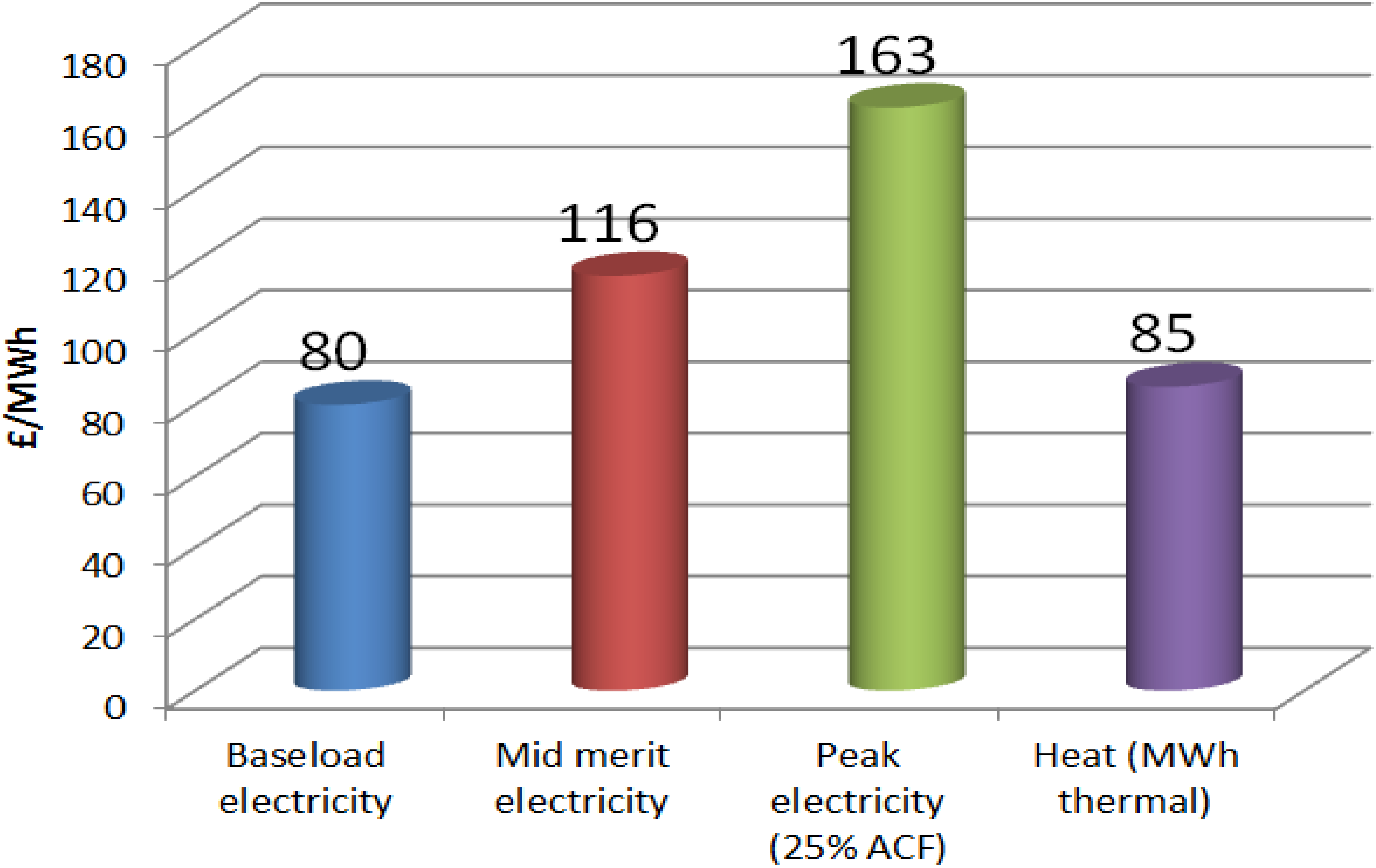
Assumptions: Prices



Assumptions: Capacity factors

	Electricity-only SMRs			CHP SMRs		
	Baseload	Flexible	Extra-flex	Baseload	Flexible	Extra-flex
Electricity ACF	85%	55%	85%	75%	50%	75%
Heat ACF	0%	0%	0%	40%	30%	40%

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Assumptions: Other

	Assumption
Discount rate	10% (12% for FOAK)
Construction period	4 years
Project life	60 years
CfD term	35 years
Fuel cycle cost	£20-£30/kW p/a (NOAK-FOAK)
Total OPEX	£130-£190/kW p/a (NOAK-FOAK

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1. Objective, Work Structure & Team

2. Introduction to SMRs

3. UK energy system to 2050

4. Technical work-stream

5. Economic work-stream

6. Conclusions

7. Questions & Answers (40 minutes)

Service offerings
Technical readiness
Deployment
Locations
Siting criteria
Infrastructure
Technical requirements

Economic appraisal
Assumptions
Target costs
Projected costs
Cost reductions
UK economic benefits

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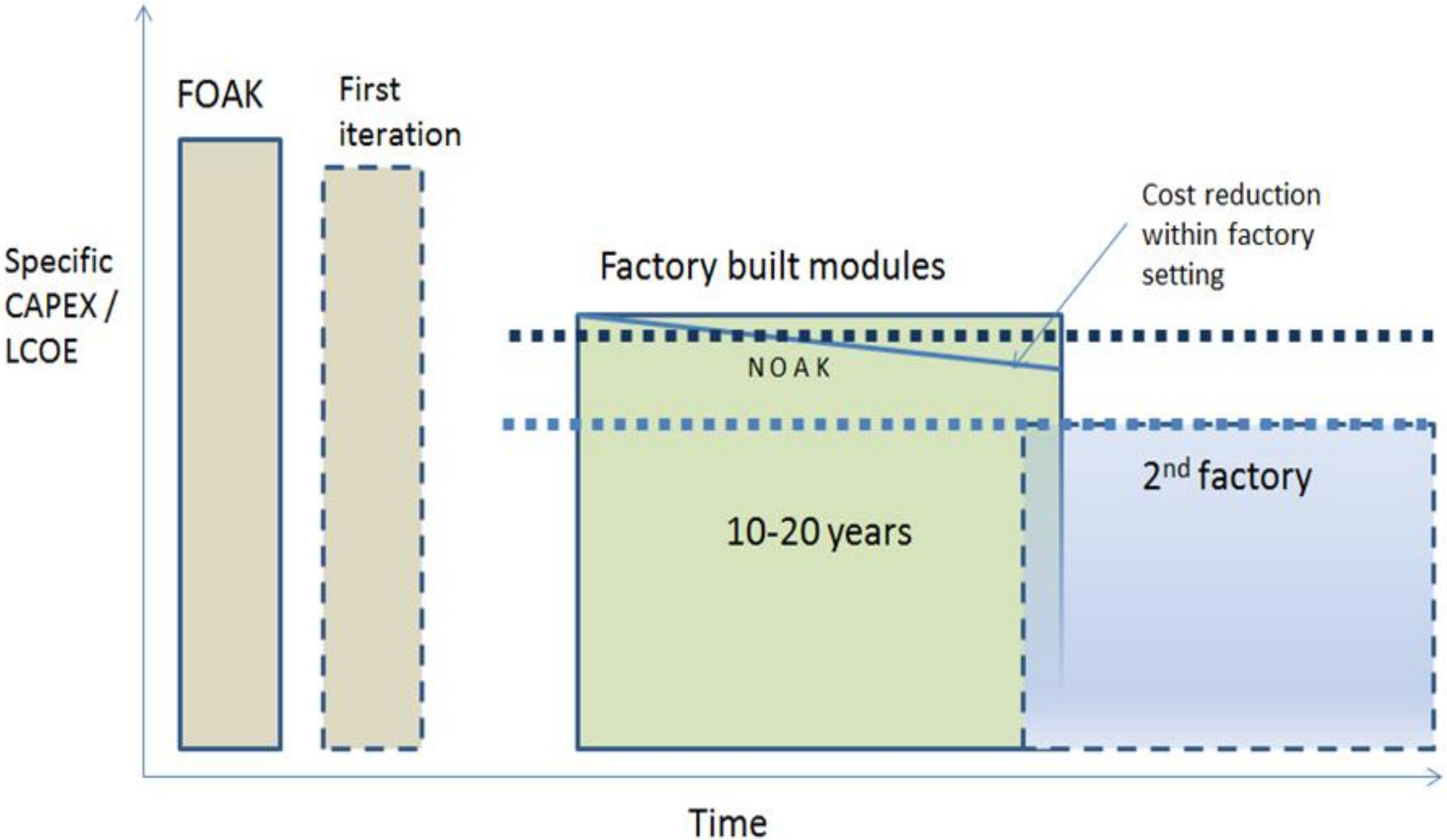
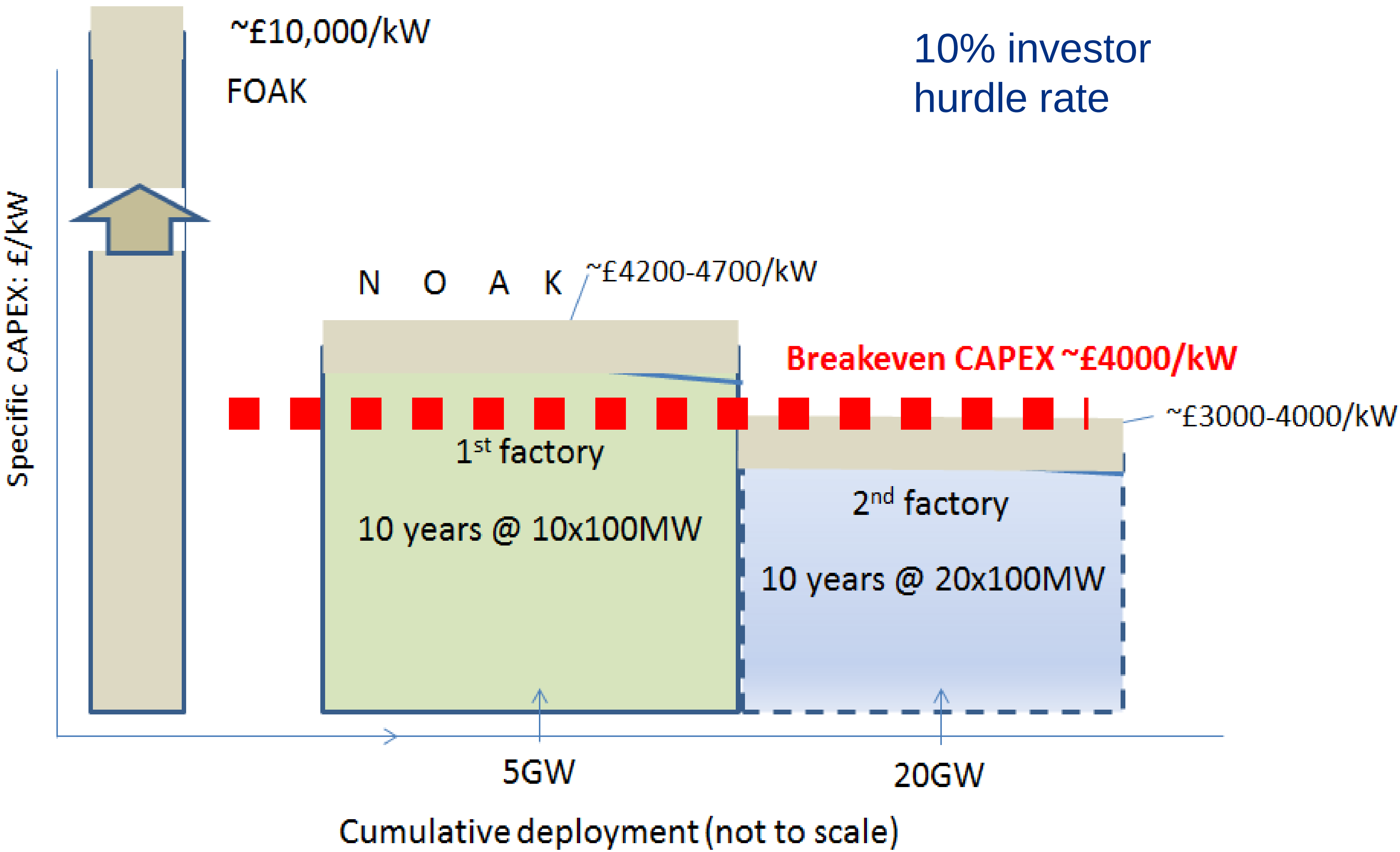
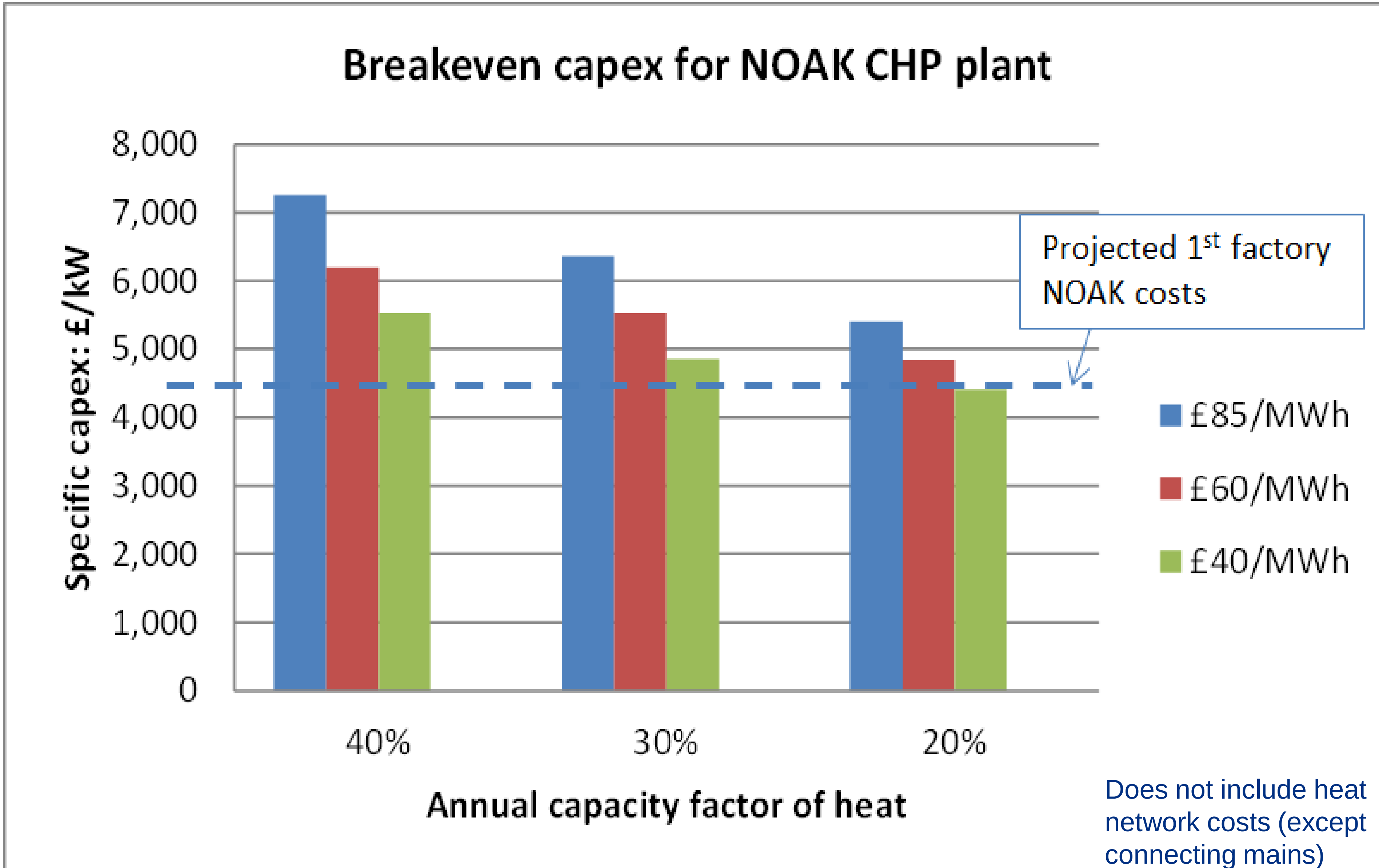
Stepped cost reduction pathway



Target CAPEX: Baseload electricity SMR

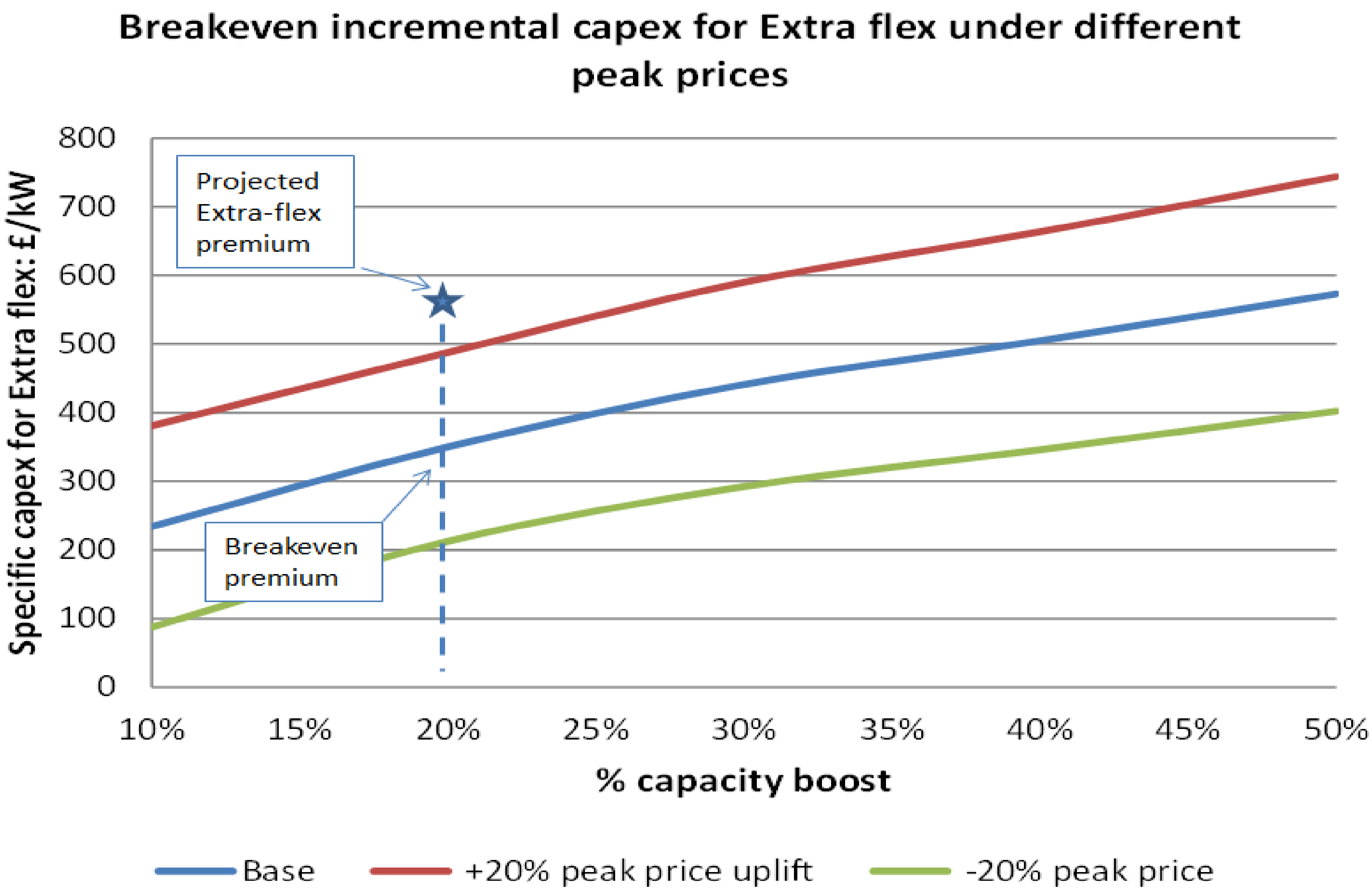


Target CAPEX: CHP SMR



Does not include heat network costs (except connecting mains)

Target CAPEX: Extra-flex SMR uplift



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Our own cost projections

Methodology:

- FOAK cost based on Hinkley C, adjusted for diseconomies of scale

- NOAK costs via application of cost driver assumptions
  - Factory mass production
  - Traditional learning
  - Deployment in multiples
  - Cost of capital
  - Heat credit for CHP SMRs
  - CAPEX uplift for Extra-flex

- Benchmarked against previous estimates

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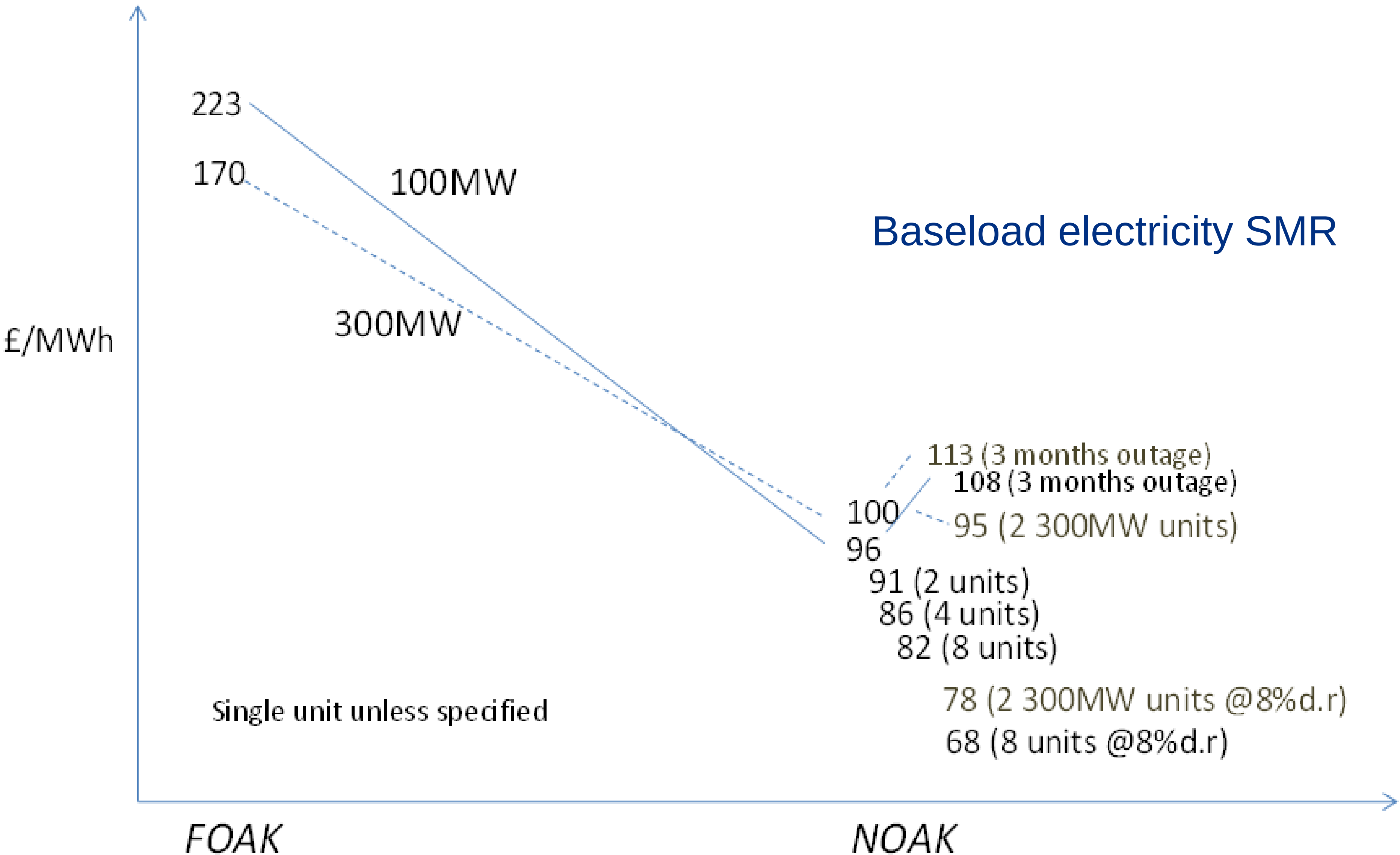
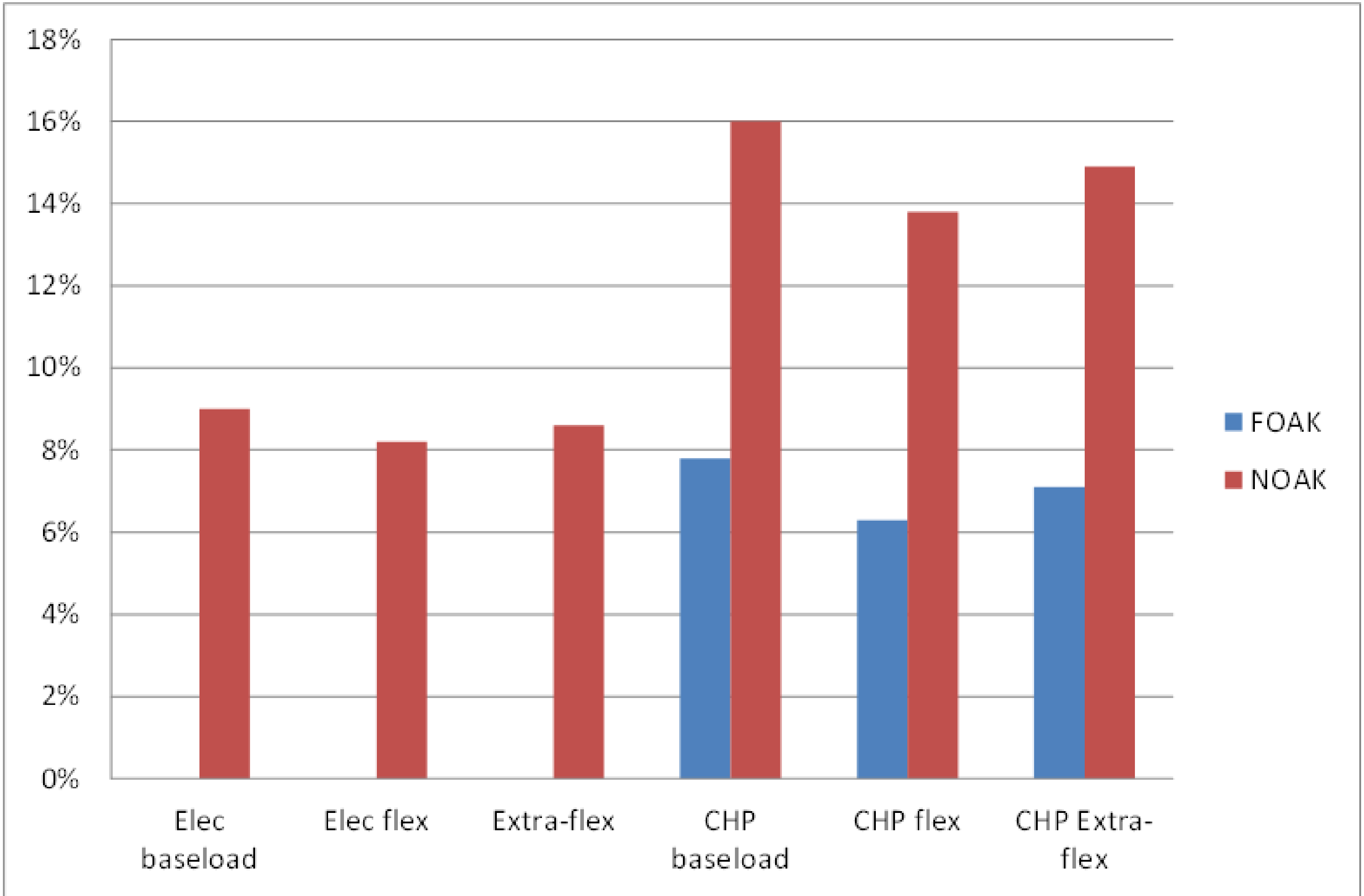
Levelised Cost of Electricity (LCOE)



Internal Rates of Return (IRR)



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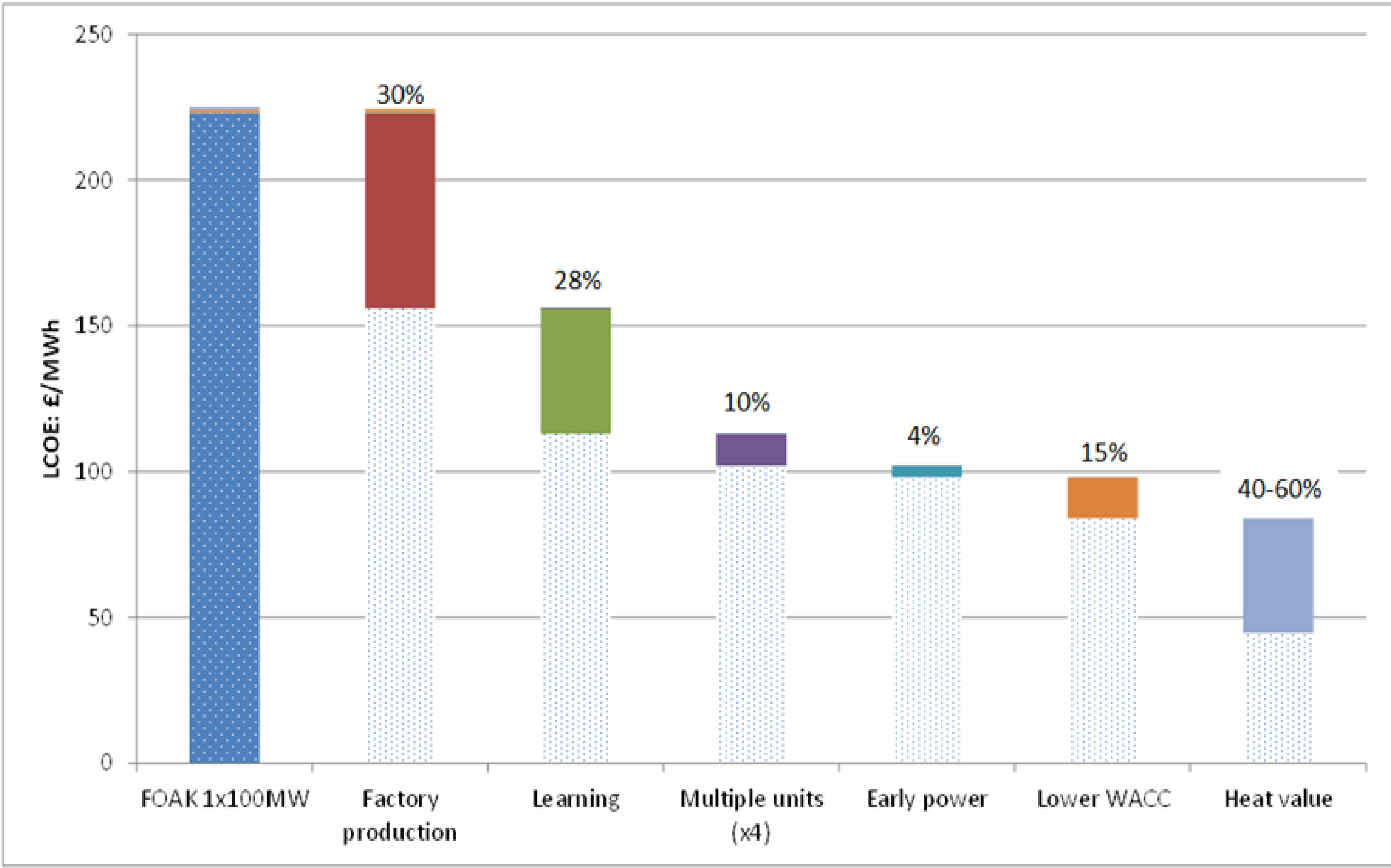
Cost reduction drivers



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Costs & benefits to UK PLC

Three scenarios to stimulate debate

	Development costs	1st factory NOAK CAPEX (£/kW)	Supply chain capture
Wait & See	£0	£3,750	~25%
Prime Mover	£2.5bn* (100%)	£4,250	~75%
Cooperation	£1.25bn* (50%)	£3,750	~50%

* Costs "from scratch". Could be less if development process already underway

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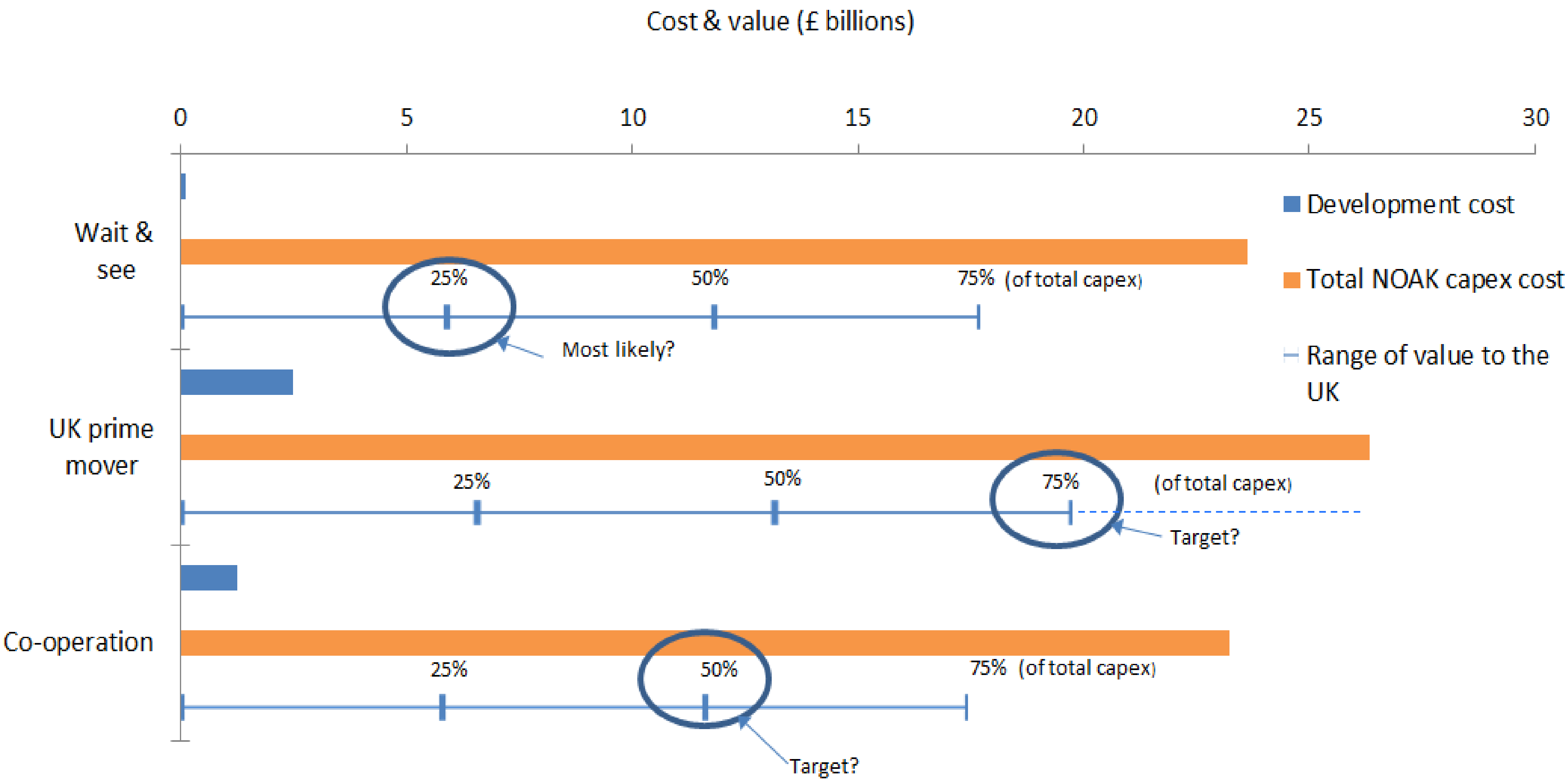
UK supply chain capture (low deployment scenario)



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Conclusions

Conclusions - opportunities

- If SMRs do what proponents say they will, SMRs could be a significant contributor to the UK's future energy system
- Widespread deployment possible from 2030 onwards
- More siting opportunities over and above large reactors (9GWe+ identified to date)
- Technical potential to supply heat as well as electricity, and potentially large district heat market in the future

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Conclusions - challenges

- Currently high uncertainty on performance, costs
- Factory mass production = unusual ‘stepped’ cost reduction pathway
- Near-term vs Revolutionary technologies – a trade-off?
  - Deployment readiness
  - Impact of infrastructure
  - Public acceptability
- Range of issues to be investigated and quantified, related to UK context: E.g. Transport infrastructure; Heat infrastructure; Modularisation/Factory mass production benefits

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Conclusions – economics

- Electricity only SMRs marginal viability
- CHP SMRs appear highly economic attractive
- Extra-flex concepts face challenges in achieving competitive costs
- Significant upfront technology development costs
- Potential wider economic benefits for UK PLC, but risks as well as opportunities

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Questions?

energy technologies institute

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Next Steps

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Next Steps – PPSS & ANT

	2014		2015							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Power Plant Siting Study										
Small Sites Update - Atkins			■	■	■					
IPR Nos. 1 & 2 - Initial Review			■	■						
IPR Nos. 1 & 2 - Final Review						■				
Alternative Nuclear Technologies										
Motts ANTPhase 2 Update			■	■	■					
IPR Nos. 3, 4 & 5 - Initial Review			■	■						
IPR Nos. 3, 4 & 5 - Final Review						■				
ESME Update - Nuclear										
Split nuclear to 4 lines		■	■							
Sensitivity Studies using PPSS data			■	■						
Sensitivity Studies using ANT data			■	■						
Sensitivity Studies using combintn.			■	■						
Combintn update with Phase 2 data						■				
Nuclear Strategy Insight Document										
Initial Draft					■					
Update with Phase 2 report output						■				
Verify with IPR and ESME							■			
Publish through comms end Jun '15							■	■		

Dissemination – June 2015

ETI Insight Report			
↑	↑	↑	↑
PPSS Summary Report	**ANT Summary Report**	**EMSE Sensitivity Modelling**	**Report Interfaces**
↑	↑	PPSS Results	ETI ESME Scenarios
PPSS Independent Peer Review	ANT Independent Peer Review	ANT Results	ETI Smart Heat Programme
		PPSS with ANT	ETI Energy Storage & Distribution
		New nuclear uptake; large and small. Impact on the mix?	NNL SMR Feasibility Study

Back up slides

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High Level Technology Appraisal

- Based on criteria / requirements generated through project
- Identified a comparison matrix framework to assess a range of technology
- SMR technology that covered a broad range of maturity, technology approaches and attributes
- Goal: to identify key positive and negative attributes of SMR technology
- Not definitive BUT applies learning and tests the framework

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Overview of Assessment

Broad Range of Technology

1. Gas CCS
2. Large Biomass
3. US NuScale
4. US B&W mPower
5. US Westinghouse SMR
6. Chinese CNNC ACP-100
7. UK Urenco U-battery
8. Chinese HTR-PM
9. Russian KLT-40S

Informed Assessment Criteria

1. Economic Viability
2. Technology maturity
3. Safety
4. Security
5. Infrastructure compatibility
6. Modularity
7. License-ability
8. Siting Potential
9. Flexibility of operation / application (e.g. CHP)

Technology Comparison

Positive SMR Attributes

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Compact Integral reactors; maximise factory module production to minimise site construction activity and open up siting potential

PWR technology; proven experience and capability, existing key infrastructure, less novel to regulators, confidence on GDA process success.

Modular size within transportation limits; maximise factory production capability to commoditise and drive standardisation and cost reduction.

Scalable multiple SMR power module options; to take advantage of and realise economy of multiples.

Minimise cooling water demands; to maximise siting potential

Simplicity; to deliver cost competitiveness on unit cost and life cycle basis.

Positive SMR Attributes

Supportive state backing, funding and commercial backing

Long refuelling periods within other constraints to reduce costs and hazards

Novel siting options

Flexible applications e.g. process heat and district heating

Mature technology with appropriate use of innovation and novel technology

Load following capability

Maximise passive safety and remove need for back-up power systems

Minimise site footprint; maximise potential sites and reduce costs.

Comply with expectations of the ONR GDA

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Non-kWh services

- Reserve and response of different types
- Equivalent to ~2% of energy sales value
  - Mainly procured through Balancing Mechanism
- Expectation that AS need will increase
- But limited role for (conventional) nuclear
  - As not suited to active participation in BM
  - Strong competition from flexible generation, smart demand and storage
  - Extra flex may offer greater scope

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