IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Webinar # 2

The Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

5 April 2023

Webinar Series on Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

The webinar is recorded

Materials and recording will be posted on the webinar web-page

Q&A

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Objectives

- Increase understanding of the economic aspects related to repurposing retired or operating coal-fired power plants with nuclear power plants to support the climate change mitigation

- Exchange thoughts and ideas with members of academia and industry currently working in this area

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

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Our speakers today

Ms Aline des Cloizeaux
Director of Nuclear Power Division, IAEA

Mr Henri Paillere
Head of Planning and Economic Studies Section, IAEA

Ms Kirsty Gogan
Founder and management partner of TerraPraxis
UK

Mr Lukasz Bartela
Associate Professor
Silesian University of Technology
Poland

Mr Yaoli Zhang
Associate Professor
College of Energy, Xiamen University
China

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Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Opening Remarks

Ms Aline des Cloizeaux

Director of Nuclear Power Division, IAEA

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Webinar Series: Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

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Mr Henri Paillere

- Over 27 years of experience in the nuclear energy sector
- Head of the IAEA's Planning and Economic Studies Section since February 2020
- Senior Analyst, Deputy Head of the Division of Nuclear Technology Development and Economics at the OECD Nuclear Energy Agency (Paris, 2011-2019)
- Head of Technical Secretariat for the Generation IV International Forum, and the International Framework for Nuclear Energy Cooperation
- Ph.D. from Universite Libre de Bruxelles (Belgium), and engineering degree from Ecole Nationale Superieure de techniques Avancees (France)

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Economic and climate benefits of repowering coal with nuclear energy

Henri PAILLERE,
Planning and Economic Studies Section

The Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants
Webinar – Wednesday 5 April 2023 – 1.30pm-3.00pm

Outline

- Relevant work in IAEA Dept of Nuclear Energy
- Nuclear power – backbone of low-carbon electricity systems
- Coal to Nuclear (power):
  - Different options, including repowering options
  - Technical and economic considerations
  - Just Transitions
- Decarbonizing beyond power (heat, hydrogen)
- 2nd International Conference on Climate Change and the Role of Nuclear Power

Repowering Coal: Relevant work at IAEA Department of Nuclear Energy

- Division of Nuclear Power:
  - New reactor technologies – including SMRs
  - Innovative nuclear energy systems
  - Engineering expertise on operating nuclear power plants
  - Supporting newcomer countries

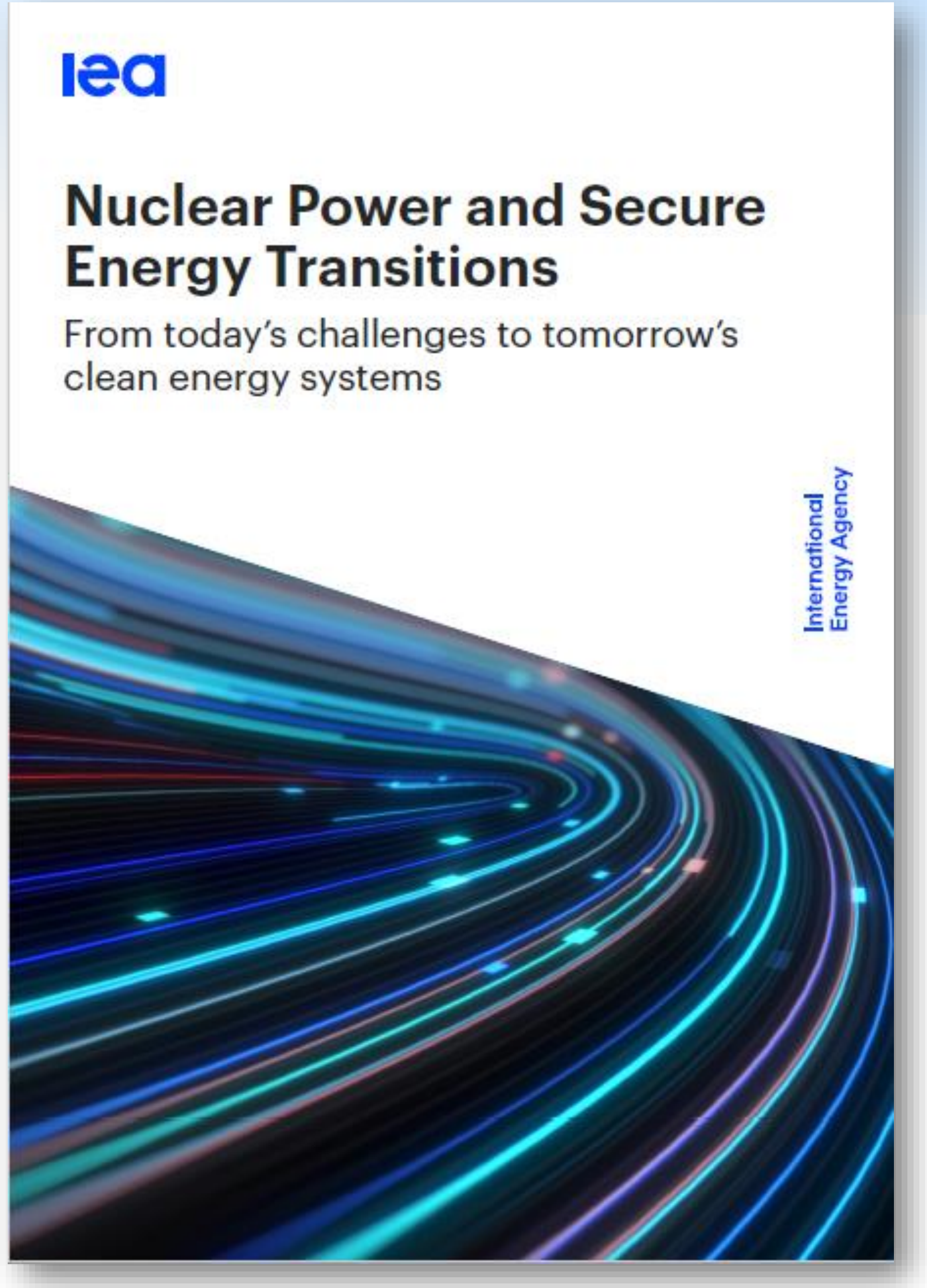
May 2022 Webinar on “Repurposing Sites of Retired Fossil Plants with Advanced Nuclear Reactors for the Clean Energy Transition”

- Division of Planning, Information and Knowledge Management:
  - **Economics, Climate, Energy Planning**

- Chairing the Agency-wide SMR Platform activities

Nuclear power, backbone of low C energy systems

- Sustainable:
  - Low carbon:
    - Smallest low C footprint among low C technologies
    - 70Gt CO_2 avoided in past five decades, more 1Gt avoided each year
  - Management of back-end: → integration into EU taxonomy
- Flexible, dispatchable:
  - Supports cost-effective integration of large %share of renewables
- Security of supply:
  - Low dependency on cost fuel, widespread U resources, storage fuel on site
  - Among the low C technologies least intensive in critical minerals
- Can contribute to climate-resilient energy systems
- Can help decarbonize beyond the power sector



Without additional nuclear, the clean energy transition becomes ***more difficult and mor expensive*** **(IEA)**

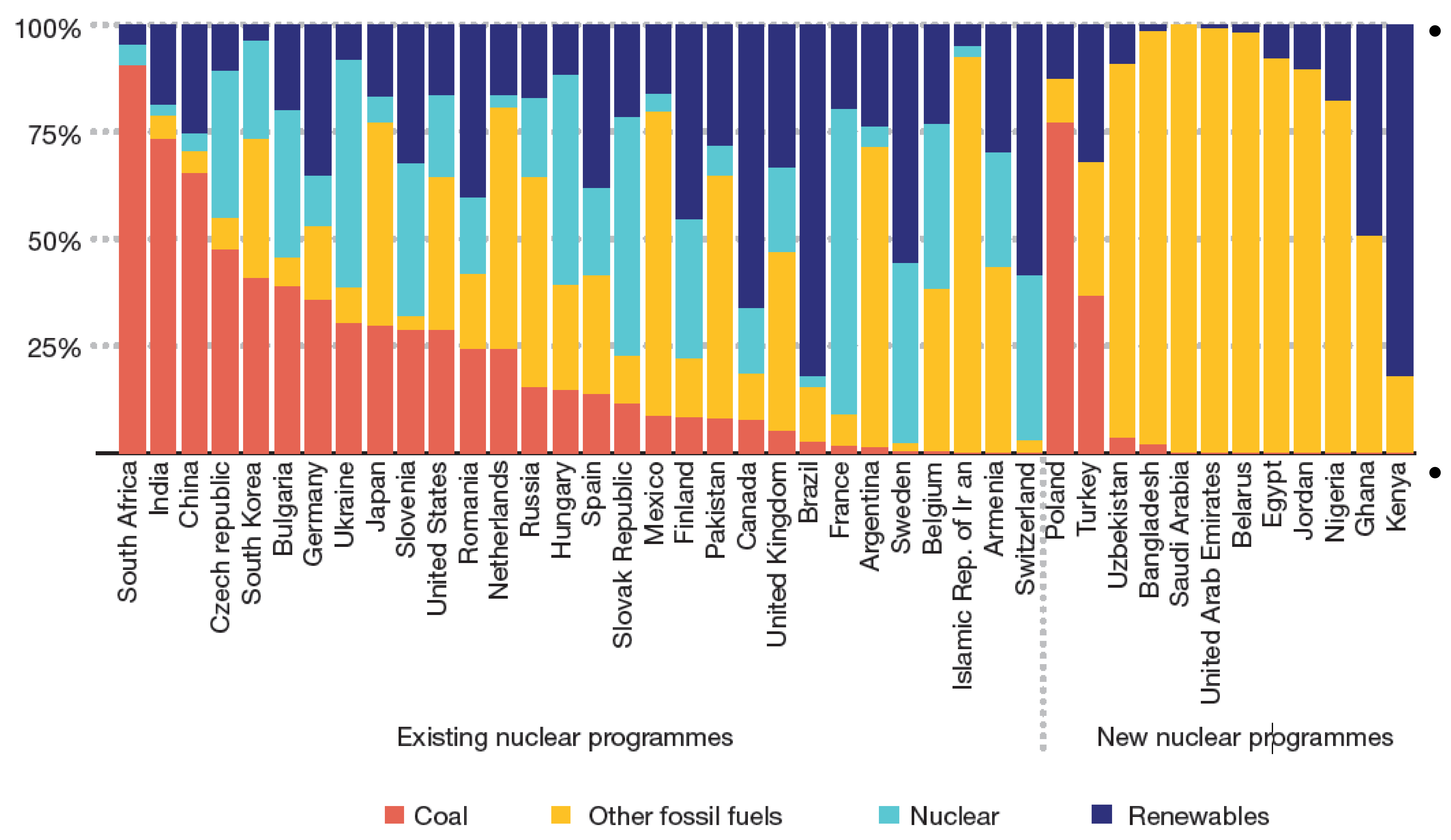
Phasing out coal to align with 1.5ºC goal

"We have a collective and urgent responsibility to address the serious challenges that come with the speed and scale of the transition. The needs of coal communities must be recognized, and concrete solutions must be provided at a very local level"

Coal to Nuclear (1)

- Coal is among the most CO_2 emissions intensive fossil fuels per unit of energy produced.
  - Combustion of coal accounts for almost 45% of energy sector
- CO_2 emissions worldwide as well as substantial local air pollution linked to millions of premature deaths every year
- Cumulative global coal use has remained roughly stable since 2011
  - In 2022, coal consumption reached a new high in 2022 as a consequence of energy crisis
- The majority of emissions from coal use arise in electricity generation,
  - Accounting for 30% of the total emissions from the energy sector.
- Given that nuclear and coal fired plants have certain similarities — e.g. they are both thermal power plants relying on similar components (and supply chains):
  - nuclear power can be a **suitable replacement for coal on the path to net zero**

Coal to Nuclear (2)



- 85% of the world's coal generation in countries that already have nuclear → infrastructures in place to support a relatively rapid switch from coal to nuclear energy,
- Replacing 20% with 250 GW of nuclear generation would reduce emissions by 2 Gt CO_2 (or around 15% of power sector emissions).

Nuclear Energy for a Net Zero World (IAEA, 2021)

Coal to Nuclear (3)

- Nuclear: potential to decarbonize beyond power:
  - besides generating around 2550 TW·h of low carbon electricity (about 10% of global electricity generation) in 2020, nuclear power plants in 10 countries also supplied heat used for district heating, industrial processes or desalination
- Among the 42 countries using nuclear power or in the advanced stages of adoption,
  - 22 also utilize coal for heat generation.
  - Surplus heat from large nuclear power plants could potentially replace much of the coal used for low temperature applications.
  - Higher temperature requirements could potentially be supplied by some small modular reactors (HTGRs)

Coal to Nuclear (4)

Nuclear reactor design		Plant output: Electricity	Plant output: Low temperature heat (300°C) (district heat, industry, H_2)	Plant output: High temperature heat (600-700°C) (industry, H_2)	Coal replacement applications	Technological and commercial maturity
Nuclear reactor design	Large water cooled	✓	✓		Multi-unit power plant	Mature; more than 300 units in operation
	SMR, water cooled	✓	✓		Single unit, power or CHP	Demonstration; pre-commercial; conventional nuclear licensing process widely applicable
	SMR, advanced (gas/sodium cooled)	✓	✓	✓	Single unit, power, CHP, industrial boiler, H_2	Design phase; demonstrated technology; pre-commercial
	SMR, advanced (salt or lead cooling; micro-reactors)	✓	✓	✓	Single unit, power, CHP, industrial boiler, H_2	Research, development and demonstration

Table 1. Categorizing selected nuclear technologies suitable for replacing coal.

Nuclear Energy for a Net Zero World (IAEA, 2021)

Coal to Nuclear (5)

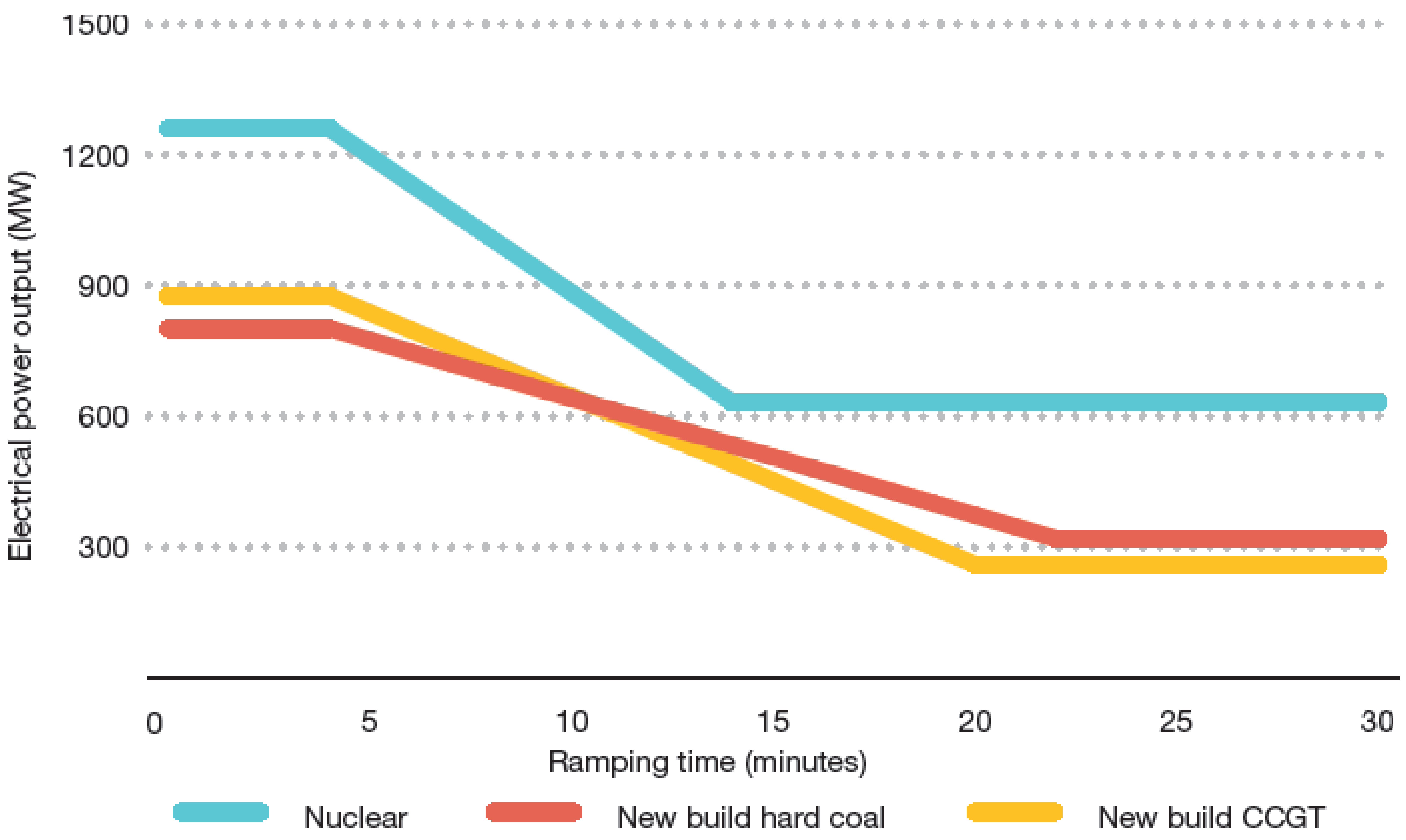


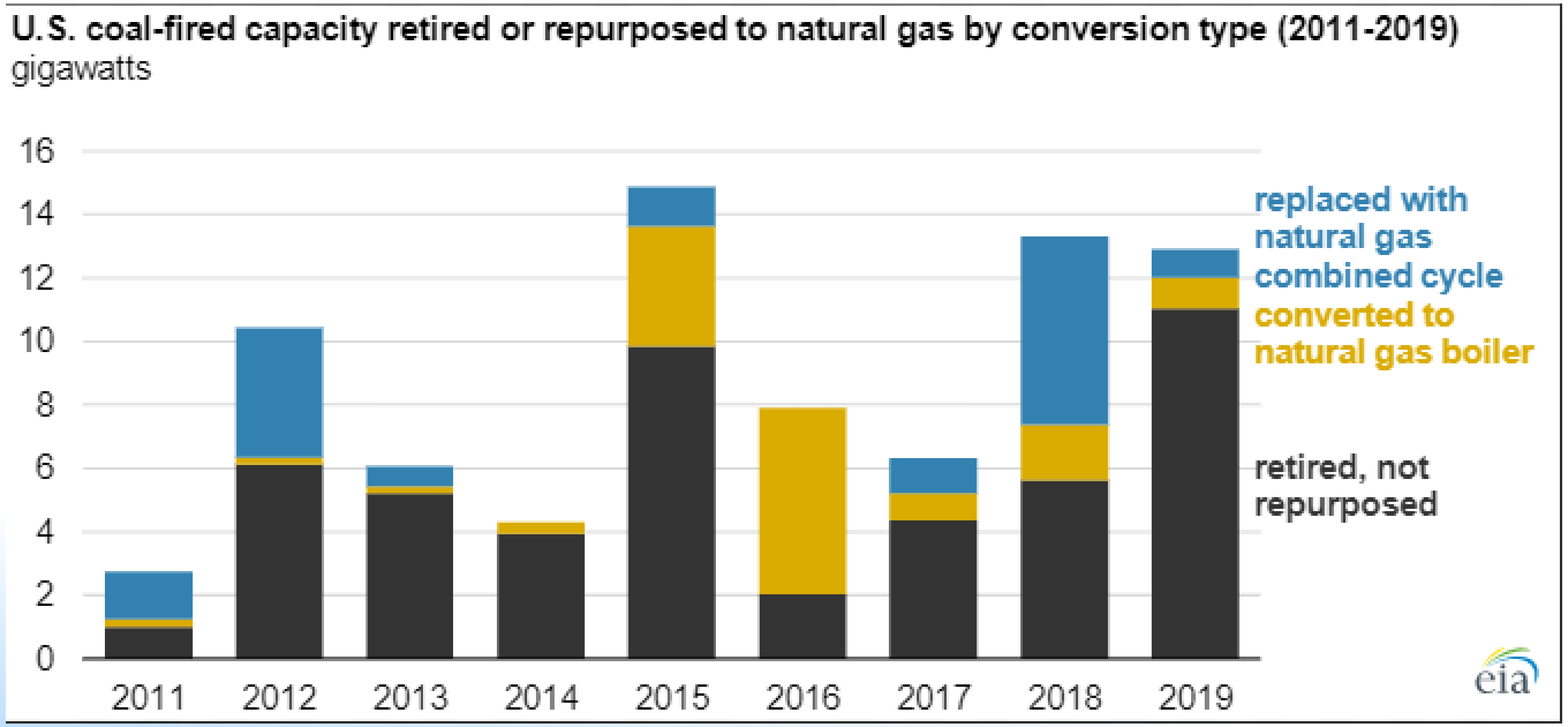
Figure 5. Ramping capabilities of nuclear, coal fired and gas fired generation [28].

- Flexibility requirements may increase with large %shares of variable renewables
- Both large scale nuclear and LWR-based SMRs can be operated flexibly, with higher flexibility characteristics than coal
- Enhanced flexibility from multi-unit SMR plants
- Advanced reactors can have higher flexibility characteristics

Nuclear Energy for a Net Zero World (IAEA, 2021)

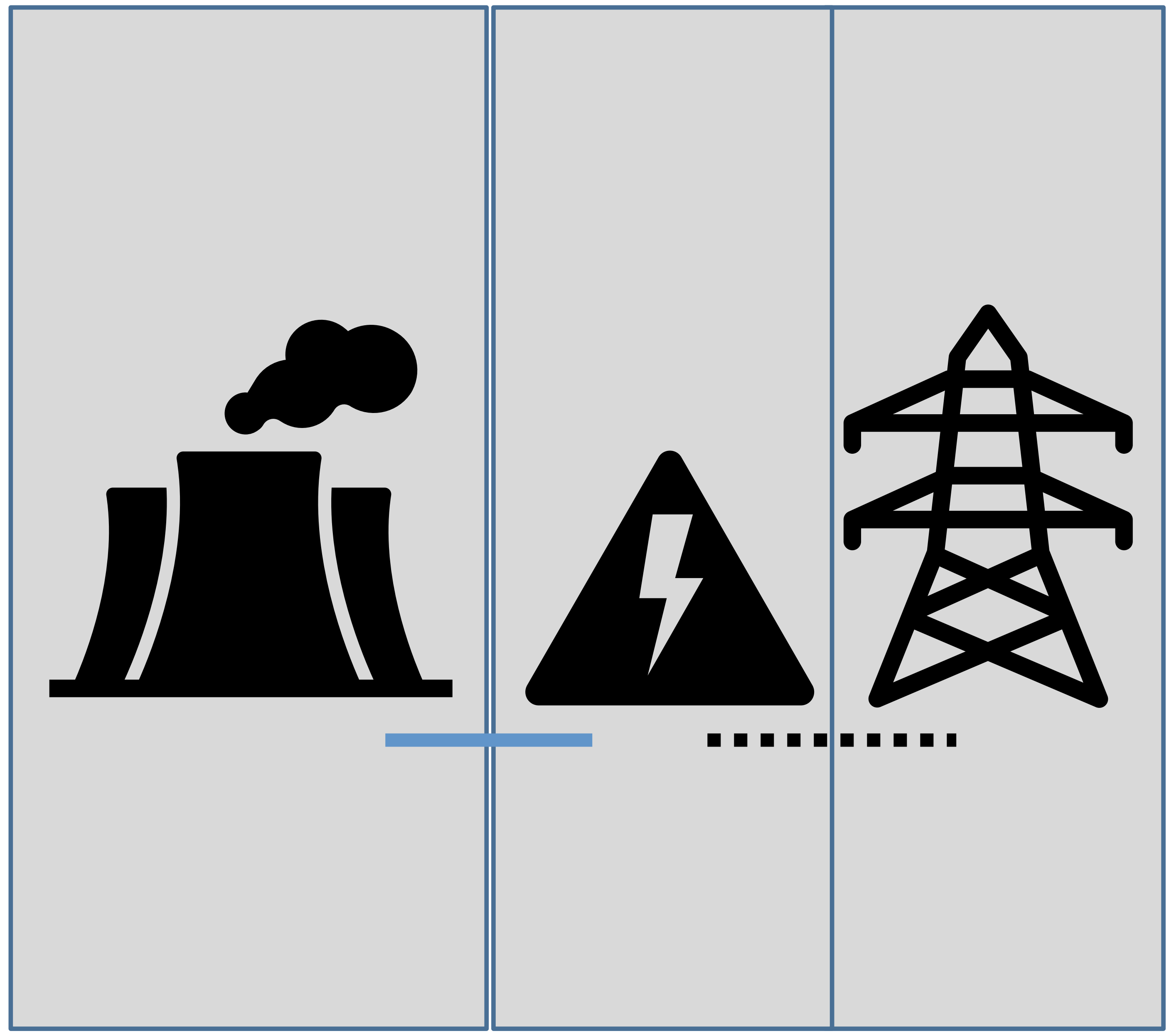
Repowering coal plants: *Coal to Gas*

- Most common form of repowering — i.e. re-utilization of coal power plant components typically steam generation and heat rejection systems — is converting from coal to NG
- According to EIA, in the U.S., between 2011 and 2019, 17 converted to new NGCC and 104 converted the coal boiler to gas boiler
- Repowering coal plants with nuclear power may also enable other elements of the existing infrastructure to be retained — such as transmission and cooling systems — resulting in significant savings and faster deployment

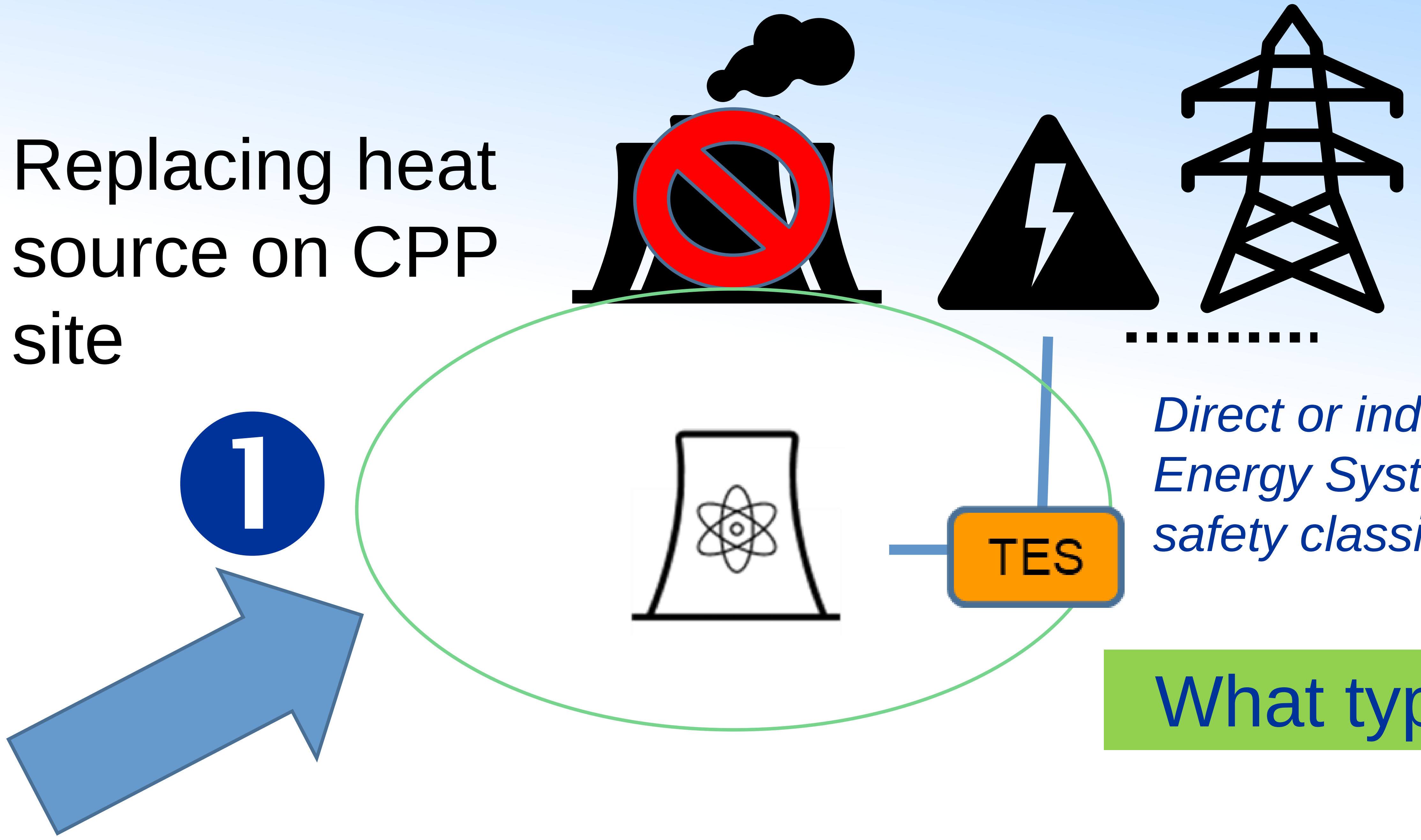


U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Coal to Nuclear:
Different options:

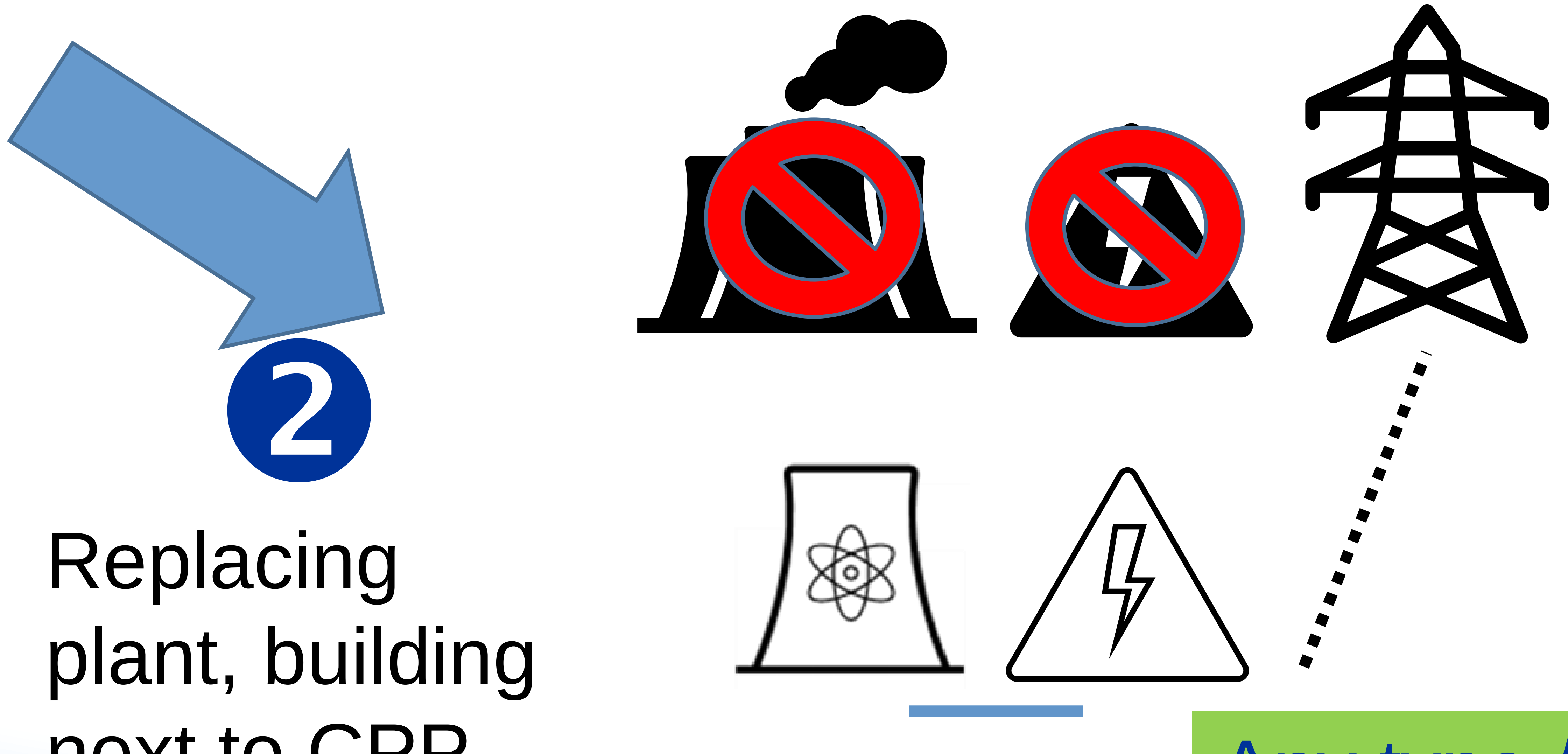


Replacing heat source on CPP site



Direct or indirect coupling (through a Thermal Energy System) / direct coupling may require safety classification of turbine hall

What type of nuclear reactor?



Replacing plant, building next to CPP,
reusing grid, water access

Any type / size depends on site and grid characteristics

Example of Natrium SMR plant in Wyoming

https://www.energy.gov/ne/articles/next-gen-nuclear-plant-and-jobs-are-coming-wyoming

TerraPower will build its Natrium demonstration reactor at a retiring coal plant in Wyoming.

TerraPower

NATRIUM

a TerraPower & GE-Hitachi technology

IAEA / Fossil Fuel Repurpose
5/31/2022

Decision to go from a "Coal site" to "near a Coal site"

- Timing and spatial logistics
- Soil, ground water, surface water contamination
- FOAK/Demonstration reactor project has construction/execution risk on its own
- Natrium Demo Site is 3-4 miles south of Naughton Plant

Technical considerations (1)

- Nuclear replacement designs can have a lower capacity size because they operate at higher capacity factors than coal power plants:
  - 1200 MW coal plant ⇔ 900 MW nuclear
- Coal vs. nuclear turbines

Table 4-3. Typical CPP and NPP steam-cycle characteristics.

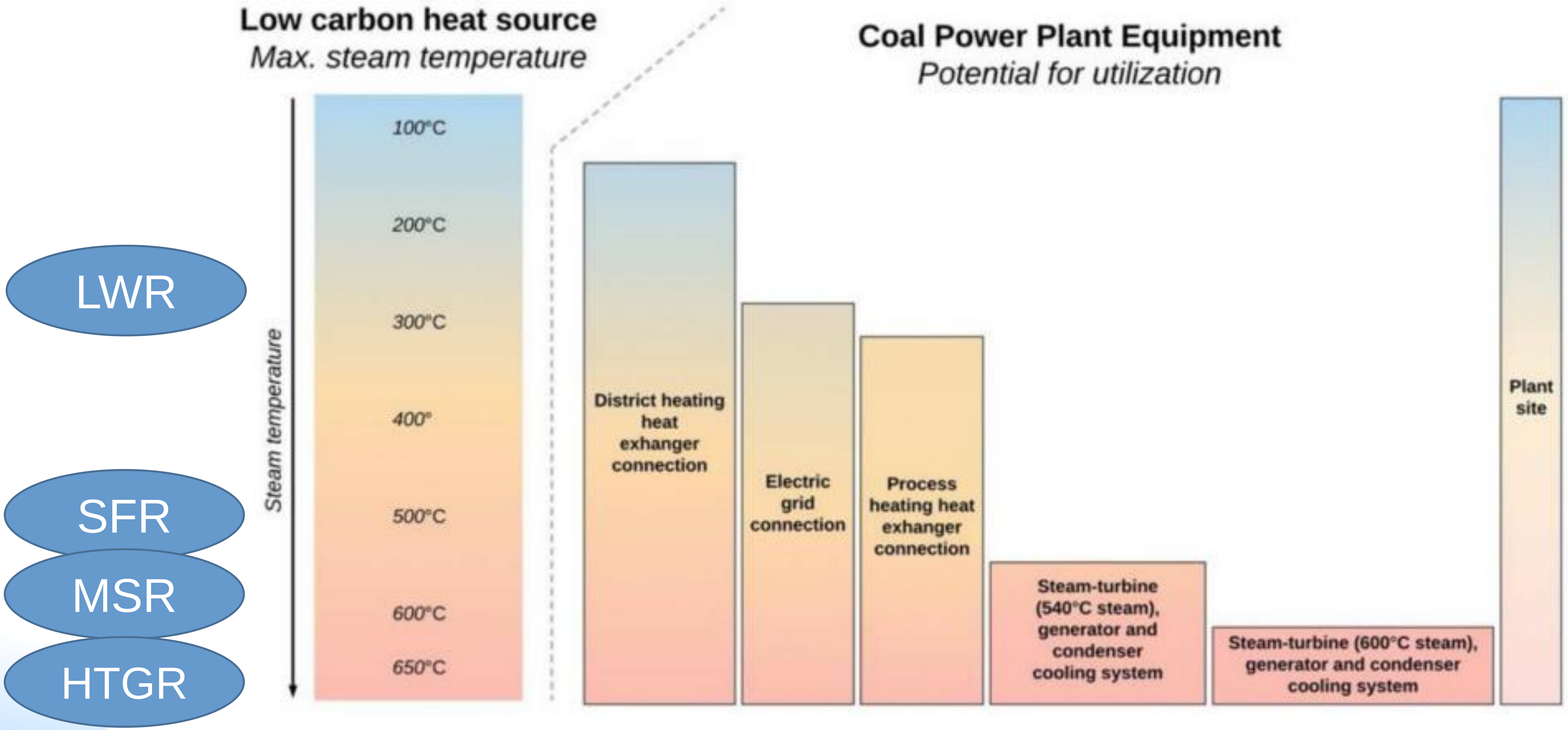
Power plant	Steam-cycle type	Pressure (MPa)	Temperature (°C)
CPP	Subcritical (Sub)	16.5	538
CPP	Supercritical (SC)	22	600
CPP	Ultra-supercritical (USC)	32	610
NPP – PWR	Subcritical (Sub)	8	290
NPP – SFR	Subcritical (Sub)	15	500
NPP – VHTR	SC to USC	15-20	650

Source: DOE-INL/RPT-22-67964

- Which reactor technology:
  - Advanced reactors (with higher temperatures than LWR)
  - LWRs with multi-stage compressor (Holtec https://www.world-nuclear-news.org/Articles/Holtec-claims-SMR-160-can-repurpose-any-coal-fired)

Technical considerations (2)

IAEA



Source: (Qvist, 2021)

Figure 8. Re-utilization potential of coal plant assets based on maximum live steam temperature available from a low-carbon heat source.

Economic considerations (1)

- Some coal plant sites that have been retired too long (more than 10y) – not suitable (deterioration of infrastructure) / not attractive to investors
- Remaining useful life of the equipment (given that new nuclear targets at least 60y lifetime)
- Reusing equipment / facilities vs. value of stranded assets
- Cost of liabilities for contaminated land, water, etc
- Size of coal plant / large NPP – SMR - AR
- Emergency Planning Zones of nuclear / advanced nuclear and population density around sites
- Availability / characteristics of cooling sources – permitting

Economic considerations (2)

- Revenue gaps: between the moment the CPP stops producing and the moment the (repowered/new) NPP starts producing
- Costs of different processes:
  - Pre-application
  - Decommissioning of CPP
  - Regulatory activities for the Coal to Nuclear
  - Specific safety-related licensing
  - Construction of nuclear components/plant etc
- Detailed analysis from external sources:
  - DOE/INL report (2022)
  - TerraPraxis work (2022)
  - Bipartisan Research Center report (2023)
  - Qvist et al. (2021)

- showing potential savings between 15% and 35% in Overnight Capital Costs (option 1)
- Up to 10% (option 2)

Just transition: example of EU countries

- A large proportion of coal power plants and mines are located in **lower income regions**, i.e. regions with a GDP per capita below the national average.
- → importance of maintaining jobs, economic activity

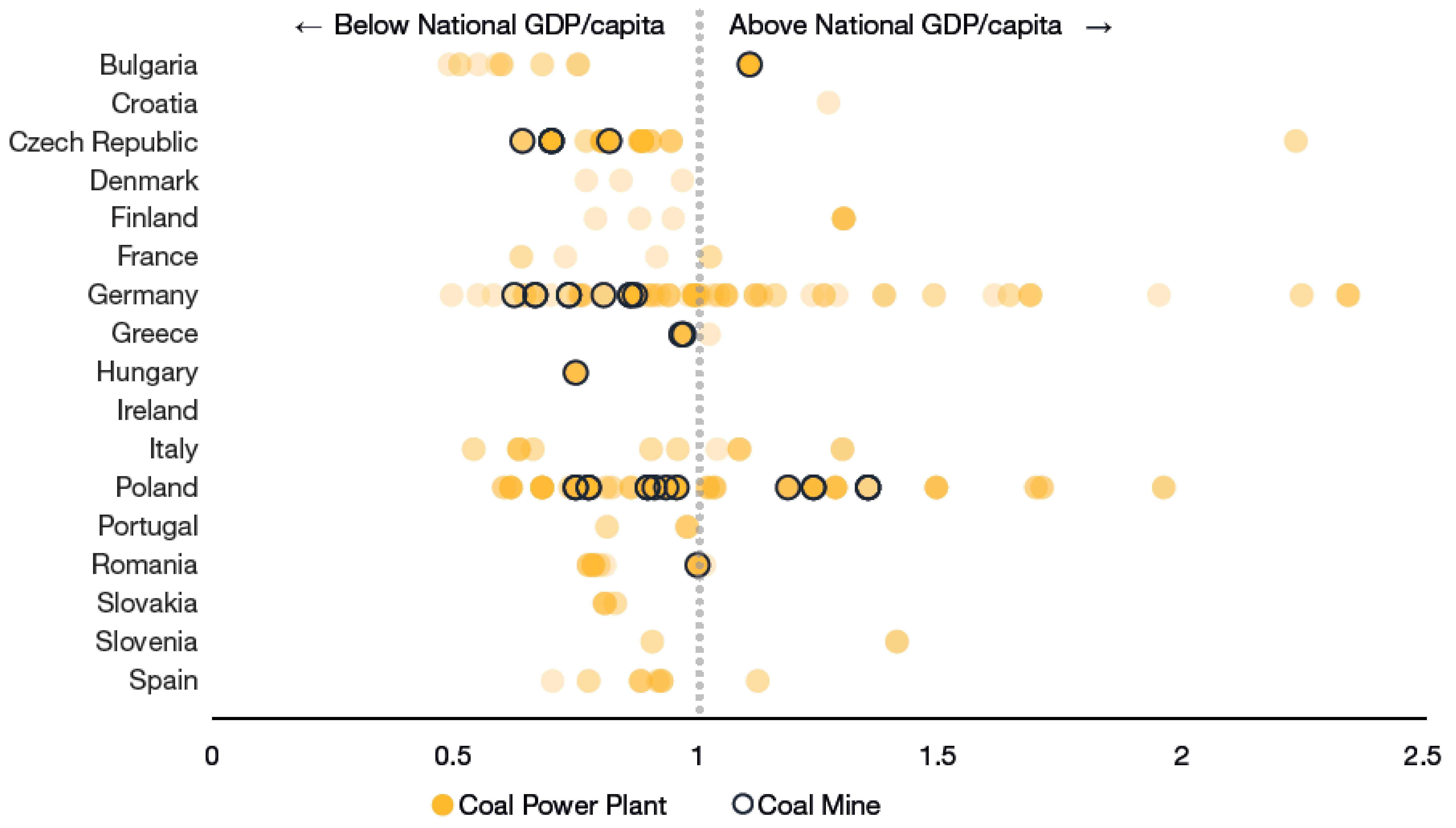
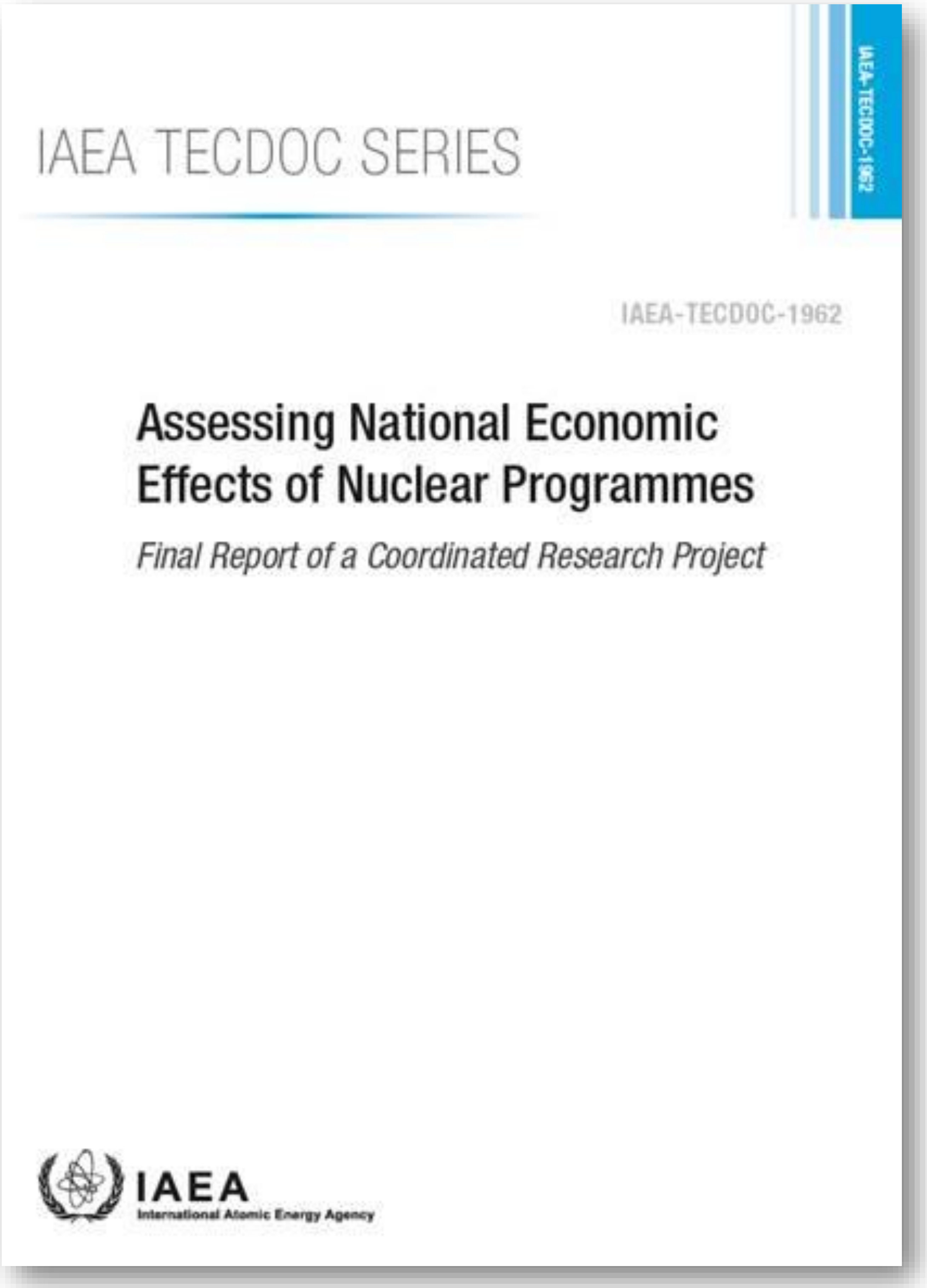


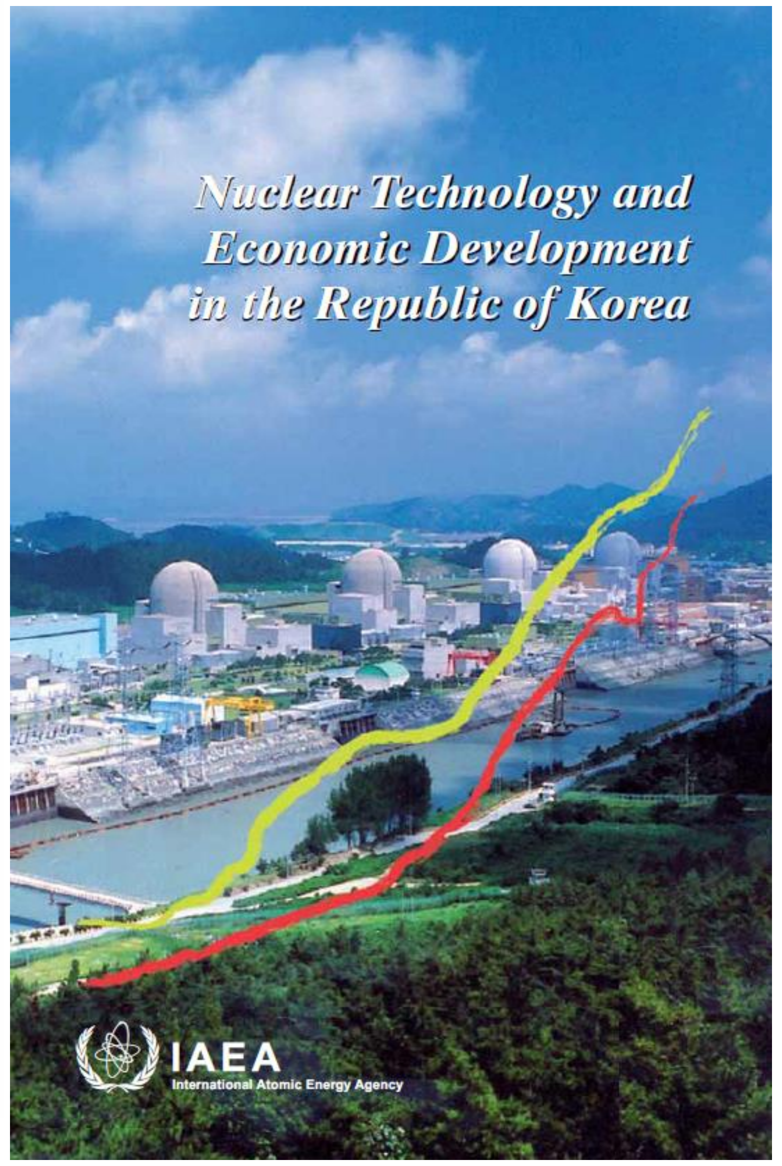
Figure 6. Relative GDP/capita in regions with coal fired generating plants and coal mines, compared to the average national GDP/capita for selected countries in 2018. Refs [34–36]. Note: Dark shades of yellow indicate a larger number of units at coal plants.

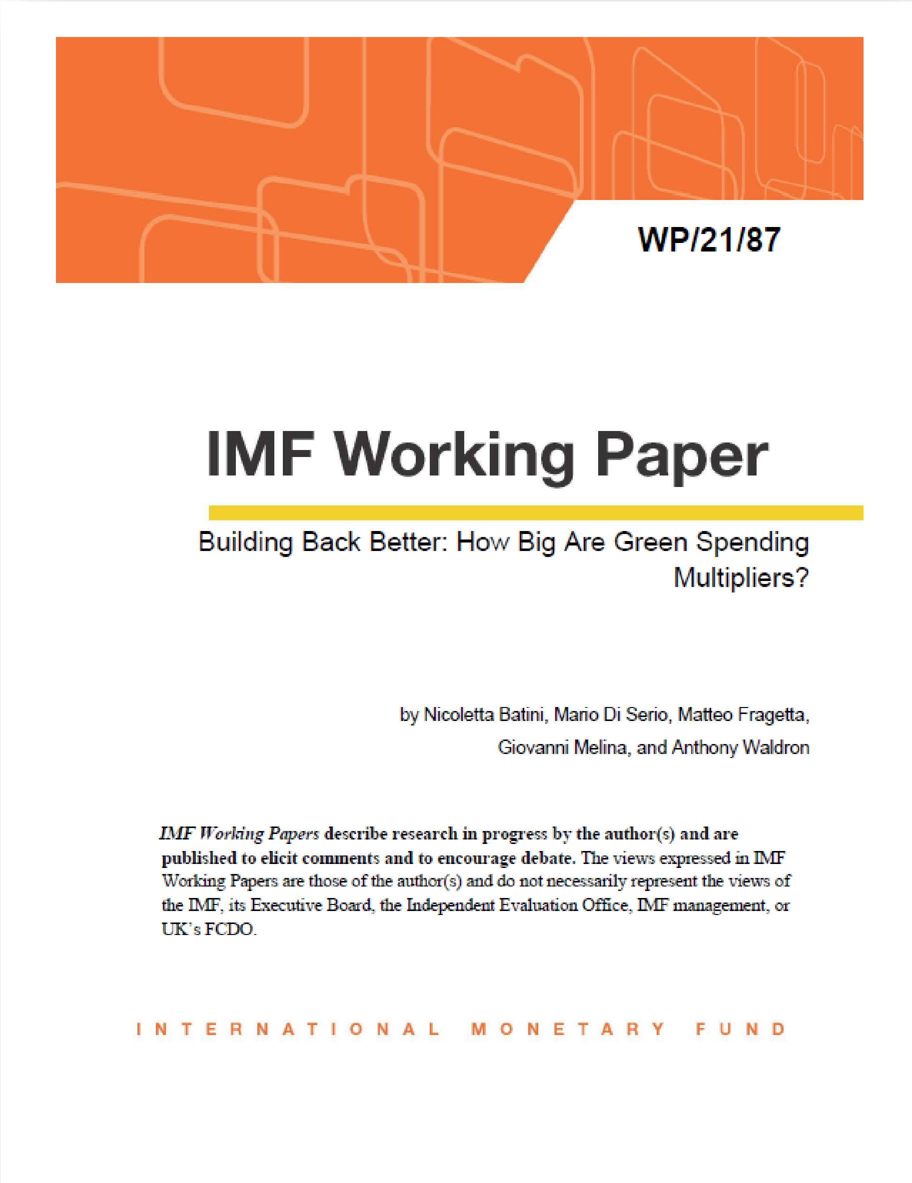
Nuclear Energy for a Net Zero World (IAEA, 2021)

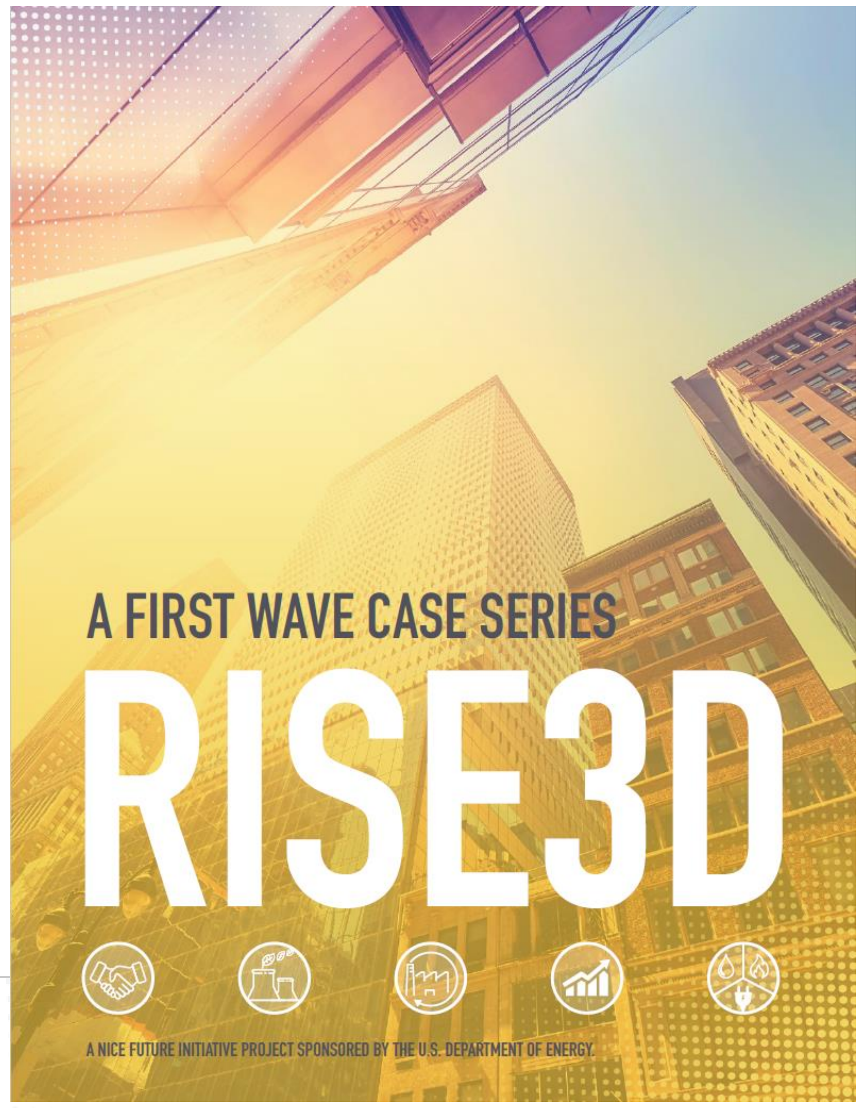
Macroeconomic impacts of nuclear investments / Just Transition

- Can clean energy investments compensate for the economic losses associated with the transition away from fossil fuel activities?
- Analyses (including from IMF) suggests that **“green investments” can have positive impacts – and nuclear investments can have the highest GDP multipliers**
- Level of supply chain localization is an important consideration.







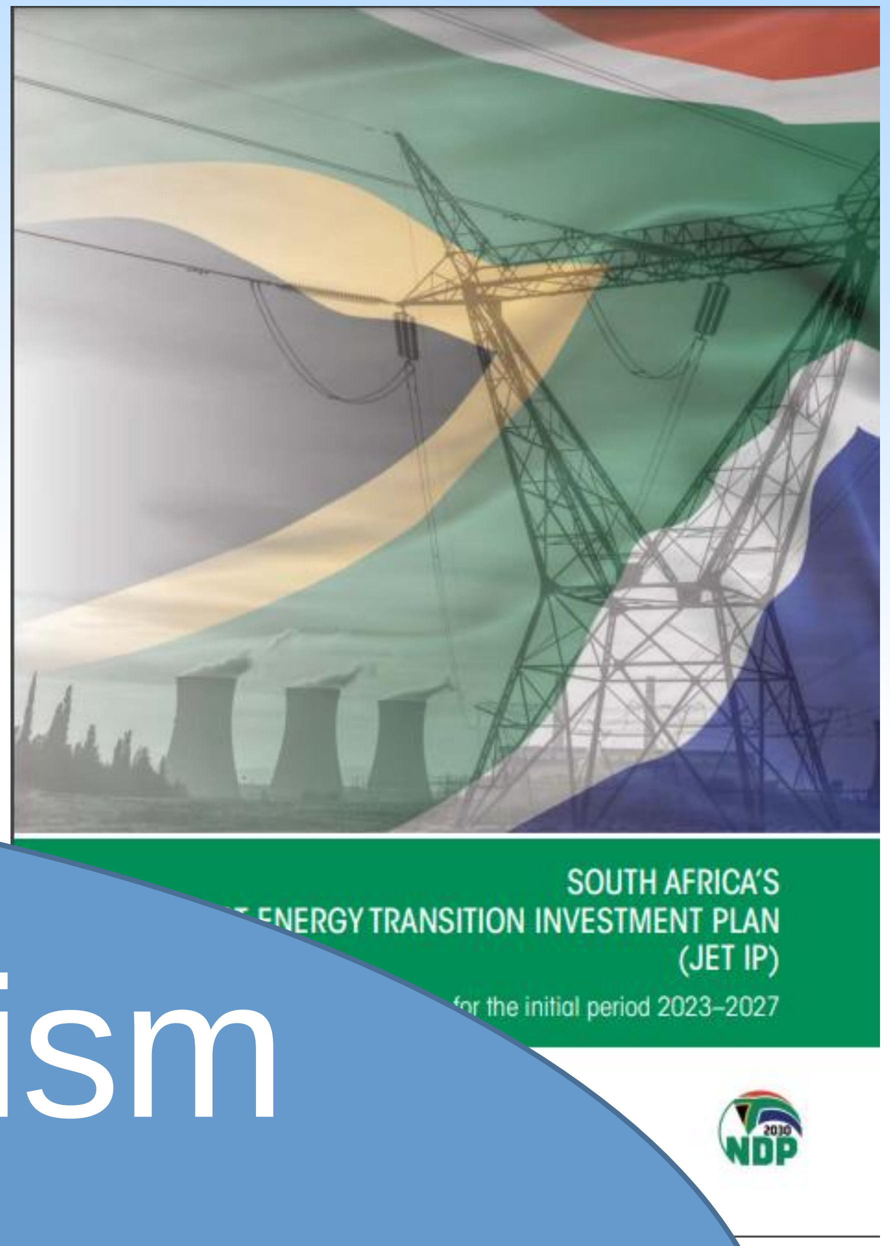


Research teams from 10 IAEA MSs (Croatia, Indonesia, Korea, Malaysia, Poland, RF, South Africa, Tunisia, Uruguay, Viet Nam) applied the new macroeconomic model (EMPOWER) to estimate economy-wide effects from construction and operation of a nuclear plant

Just Energy Transition Partnerships (JETP)

- **South Africa: (2021)**
  - Includes repowering (with clean technologies – wind and solar) and re
- **Indonesia: (202**
  - funding will
    phasing ou
    down coal-
    account for t
    mix
- **Viet Nam: (2022)**
  - Reduce the number of coal-fired power plant
    in Vietnam

Will a similar mechanism be developed for repurposing coal plants with nuclear ?



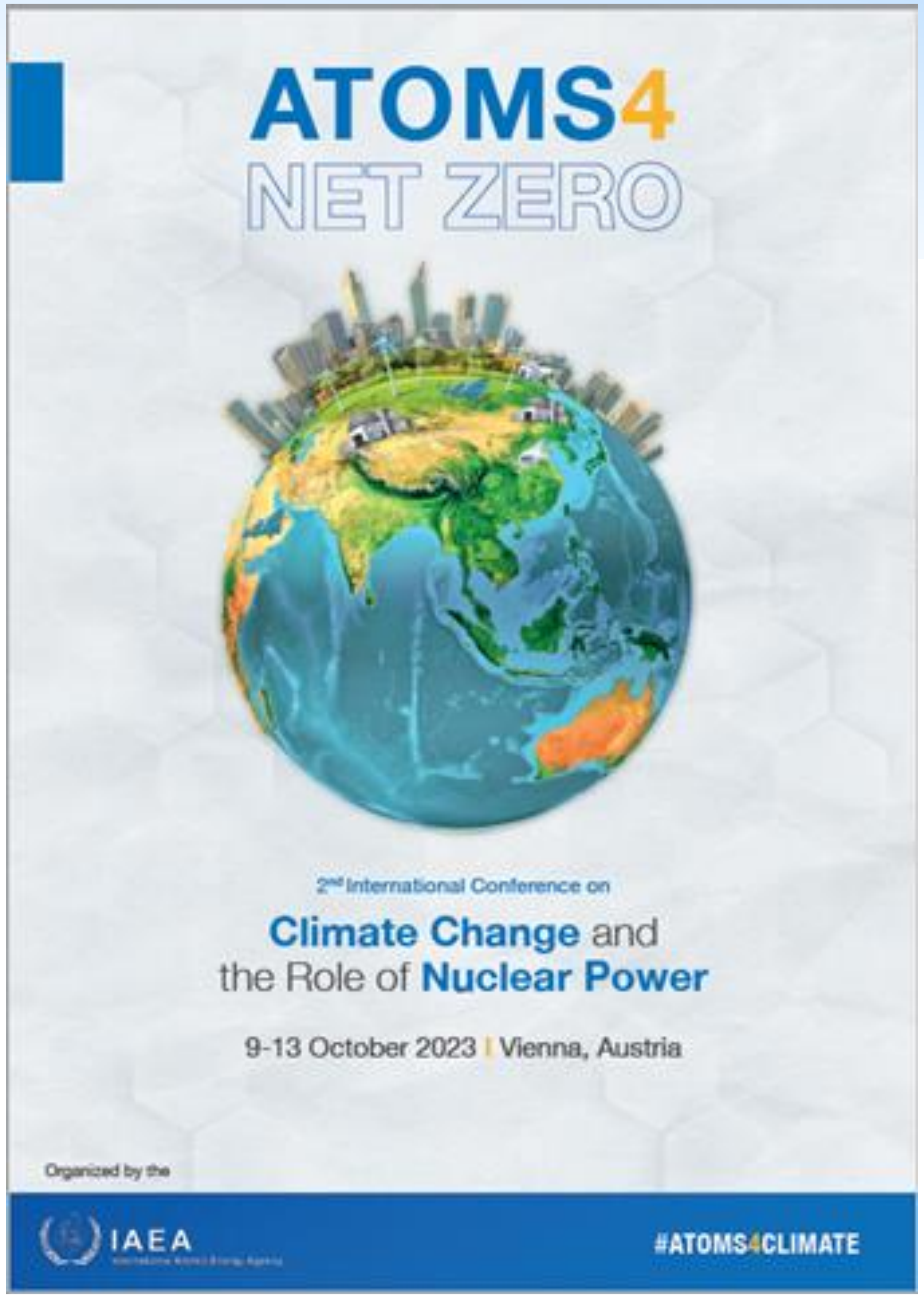
Fossil to Nuclear: beyond power

- Heat markets:
  - District Heating:
    - Decrease CO2 emissions + Pollution
    - China:
      - AP1000 DH in Haiyang
      - Dedicated nuclear “heating” reactors under development
    - Poland: - largest DH system in Europe, 72% heat from coal / gas n an option → nuclear
    - Czech Republic
  - Process Heat:
    - Poland looking at HTGR technology to replace coal-boilers
    - Dow and X-energy announcement to develop first grid-scale next-generation nuclear reactor for an industrial site in North America
- Hydrogen:
  - Need for large amounts of low-carbon hydrogen to decarbonize hard to abate sectors

2nd International Conference on Climate Change and the Role of Nuclear Power: Atoms4NetZero

Includes Topic “Releasing the full potential of nuclear energy”:

- What are the latest innovation breakthroughs and advancements in nuclear energy
- What are the keys to fast development of advanced reactors including SMRs
- How to enable safe and economical Long-Term Operation of Nuclear Power Plants
- How to accelerate the demonstration and commercialization of non-electric applications of nuclear energy (heating, hydrogen, desalination.)
- Call for Abstracts: **deadline 28 April 2023**



References

IAEA:

- Nuclear Energy for a Net Zero World, IAEA (2021)
- Climate Change and Nuclear Power, IAEA (2022)
- Other resources from IAEA CRP on Economic Appraisal of SMRs (TECDOC under preparation)
- IAEA webinar 2022 repurposing fossil plant sites with advanced reactors

Others

- Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants, DOE-INL/RPT-22-67964 (2022)
- Repowering the global coal fleet by 2050, TerraPraxis (2022)
- Can Advanced Nuclear Repower Coal Country? – Bipartisan Policy Center report (2023)
- Retrofit Decarbonization of Coal Power Plants—A Case Study for Poland, S. Qvist et al., Energies 2021, 14

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Thank you!

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Webinar Series: Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Ms Kirsty Gogan

- Founding Director and Co-CEO of TerraPraxis from the UK
- Expert in the design and deployment of scalable strategies to address global climate and energy needs
- Member of the UK Government's Nuclear Innovation Research and Advisory Board (NIRAB)
- UK representative on the IAEA Director General's Special Advisory Group on Nuclear Applications
- Member of the Board of Nuclear Innovation Alliance, and Voices for Nuclear

DESIGNING FOR FAST, LOW-COST AND REPEATABLE COAL FLEET REPOWERING

From project economics to product economics

LOW COST
FAST
REPEATABALE

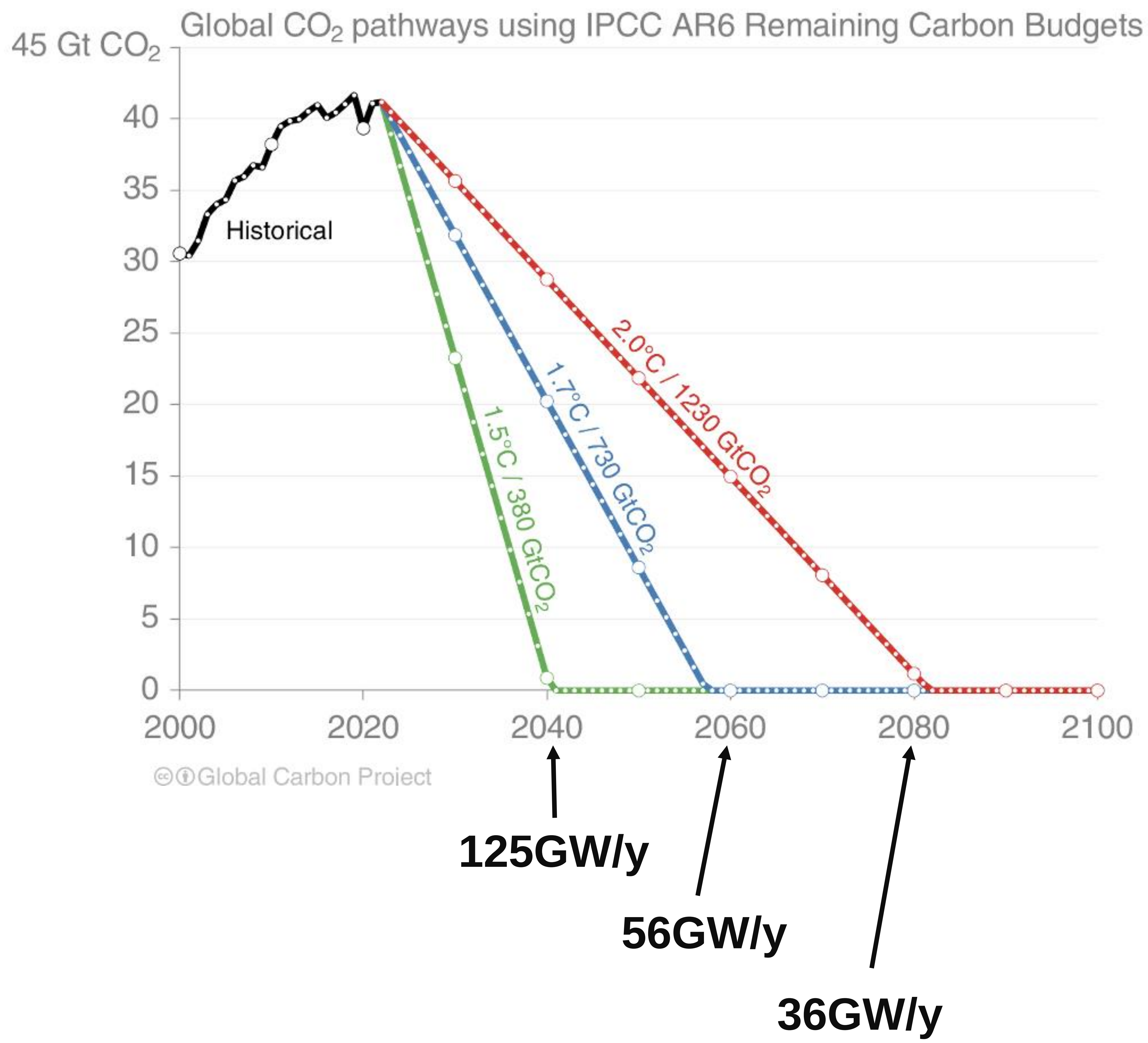
TERRA PRAXIS

April 2023

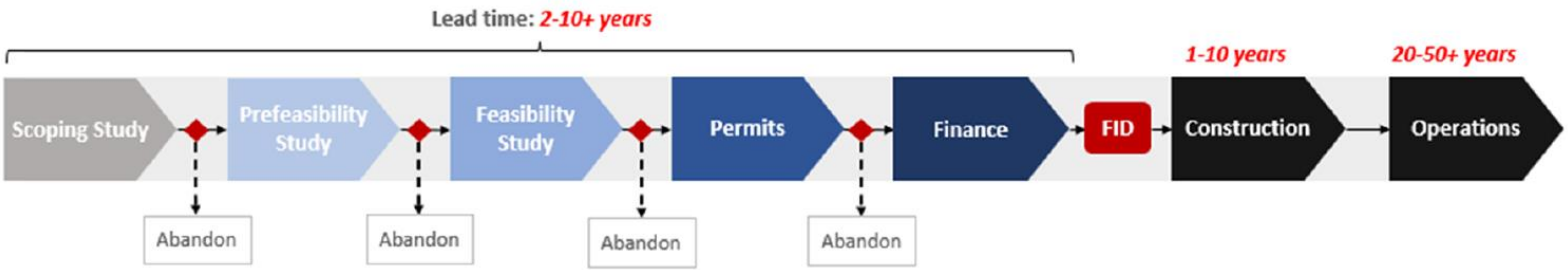
The ambition gap

- Approximately 15GW per year to 'maintain 10%' (~400GW by 2050)
- ~100 GW per year to repower all coal power plants
- (600 GW per year to replace oil and gas)

Annual deployment of Repowering to reduce coal plant emissions on pro rata basis



Pre-development time and cost represents a huge risk to Net Zero

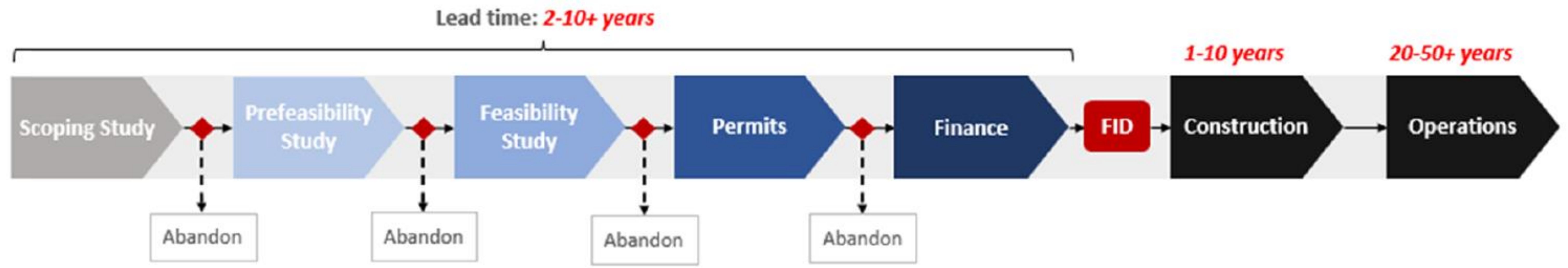


Source: Energy Environ. Sci.,2022, 15, 3114

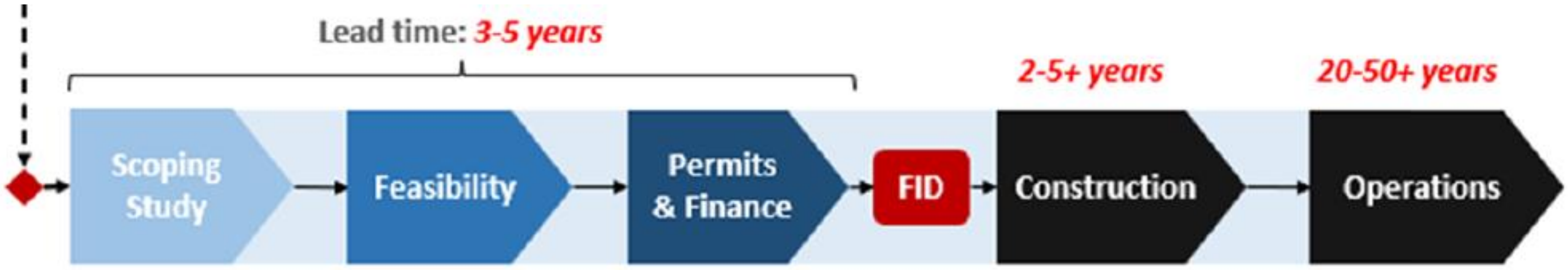
TERRA PRAXIS

We need a simplified scoping, siting, permitting, licensing, financing, procurement, installation, and operation process – more like a product than a project.

From this:



To this:

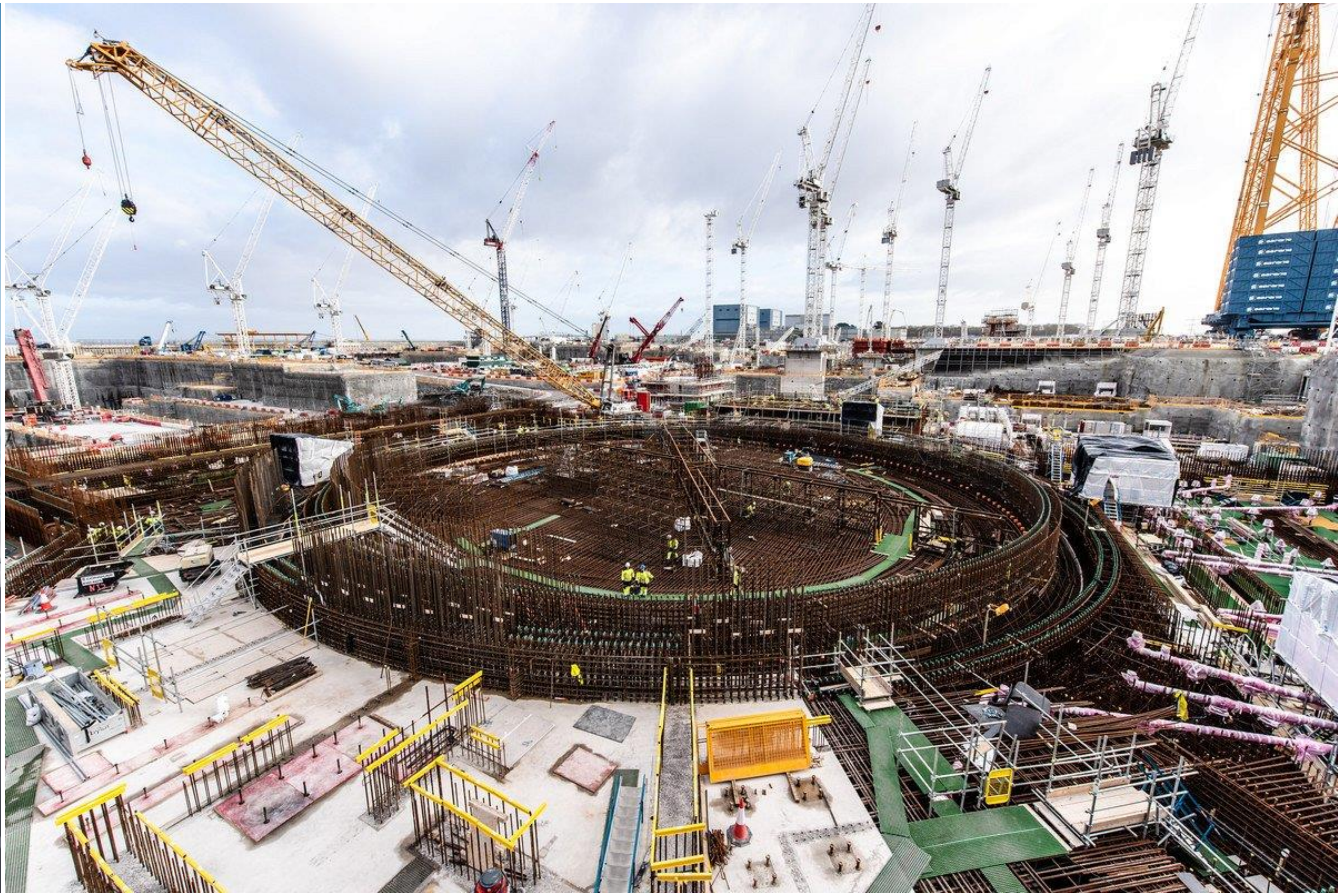


Source: Energy Environ. Sci.,2022, 15, 3114

TERRA PRAXIS

WHAT IS A PRODUCT?

What is a product?



Product

Construction Project
(Not a Product)

Products are engineered for factories

Basic Gigafactory Stats

- 5 years: from construction start to full production
- 500,000 vehicles per year
- 20,000 employees
- ~$30B in annual revenue per factory
- ~250kW per car
- 125,000MWe per year
- 5,000kW per worker per year
- **$240/kW**

Projects are engineered for each site

Basic Project Stats

- 5,600MWe
- ~10 years, excluding comisssionsing
- $24B construction
- ~5,000 workers
- 560MWe per year
- 112kW per worker per year
- **$4,285/kW**

The kind of difference we need for x50 - x100 scale up

Basic Gigafactory Stats

- 5 years: from construction start to full production
- 500,000 vehicles per year
- 20,000 employees
- ~$30B in annual revenue per factory
- ~250kW per car
- 125,000MWe per year
- 5,000kW per worker per year
- $240/kW

X 223 more

X 45 more

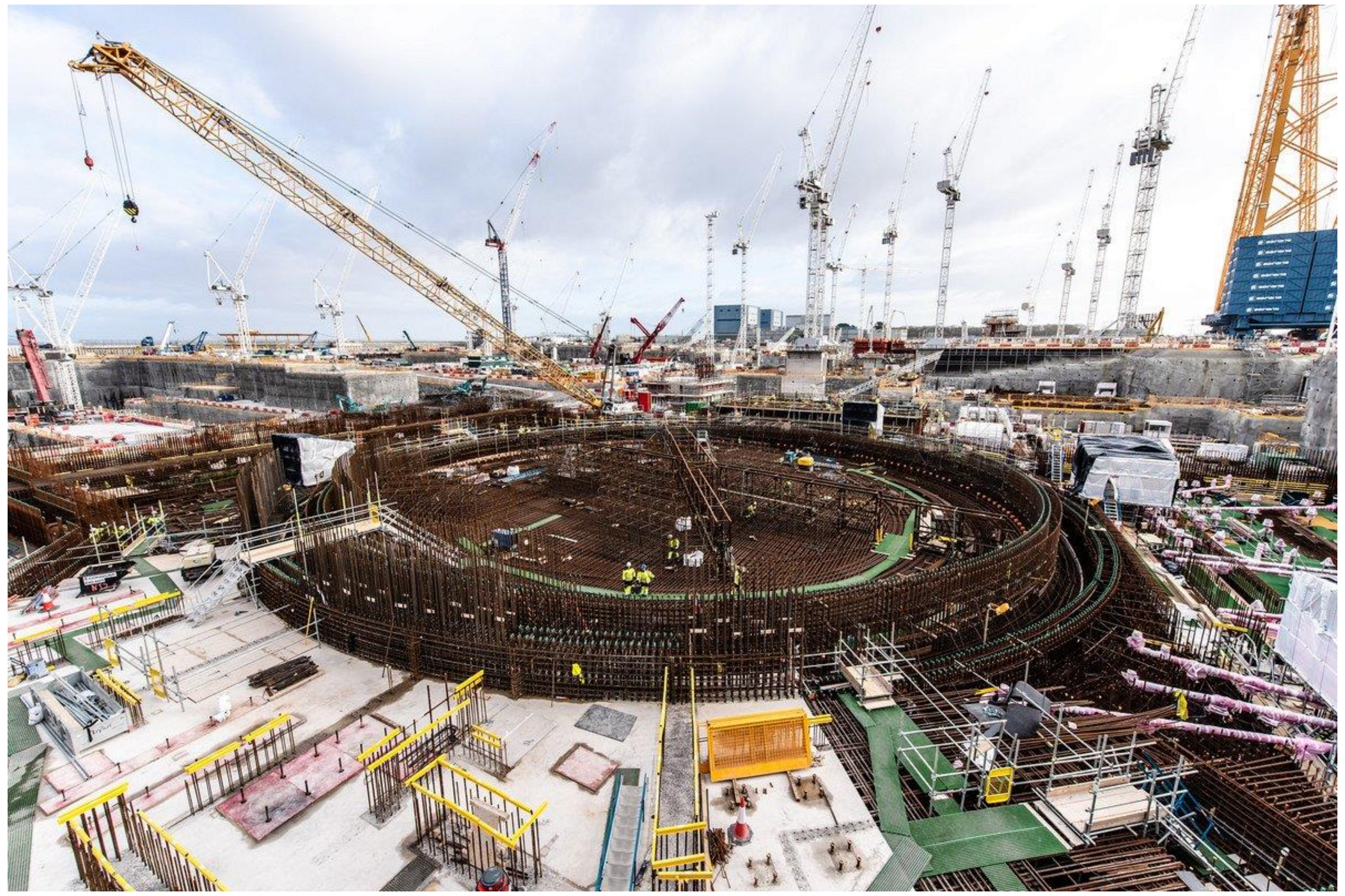
X 18 less

Basic Project Stats

- 5,600MWe
- ~10 years, excluding commissioning
- $24B construction
- ~5,000 workers
- 560MWe per year
- 112kW per worker per year
- $4,285/kW

FROM PROJECTS TO PRODUCTS

How do we get from project-based construction projects to high volume manufactured product-based licensing for nuclear energy?



Project-based design: Long, complex, expensive, high-risk site-specific engineering for each site, each time

Closing the gap between projects and products

Product-based design: license once, build many

Reducing or eliminating site specific design enables product deployment

Design project each time

Product

- **More ‘new engineering’**
- **Large engineering cost**
- **More chance for errors**
- **Longer licensing review**
- **Less certainty on cost**
- **More schedule risk**

- **No ‘new engineering’**
- **Shorter, lower cost, less risky pre-development**
- **Minimal engineering cost**
- **Errors previously eliminated**
- **Shorter licensing review**
- **Certainty on cost**
- **Minimal schedule risk**

These business models have very different incentives

Design project each time

Incentives:
Design hours are revenue
Licensing hours are revenue
Construction oversight is revenue
Goal is to maximize revenue per project

- **More 'new engineering'**
- **Large engineering cost**
- **More chance for errors**
- **Longer licensing review**
- **Less certainty on cost**
- **More schedule risk**

Product

Incentives:
Design to reduce marginal cost
Invest to reduce marginal cost
Eliminate non-scalable processes
Increase profit/unit * # of units

- **No 'new engineering'**
- **Minimal engineering cost**
- **Errors previously eliminated**
- **Shorter licensing review**
- **Certainty on cost**
- **Minimal schedule risk**

THEORY INTO PRACTICE (PRAXIS)

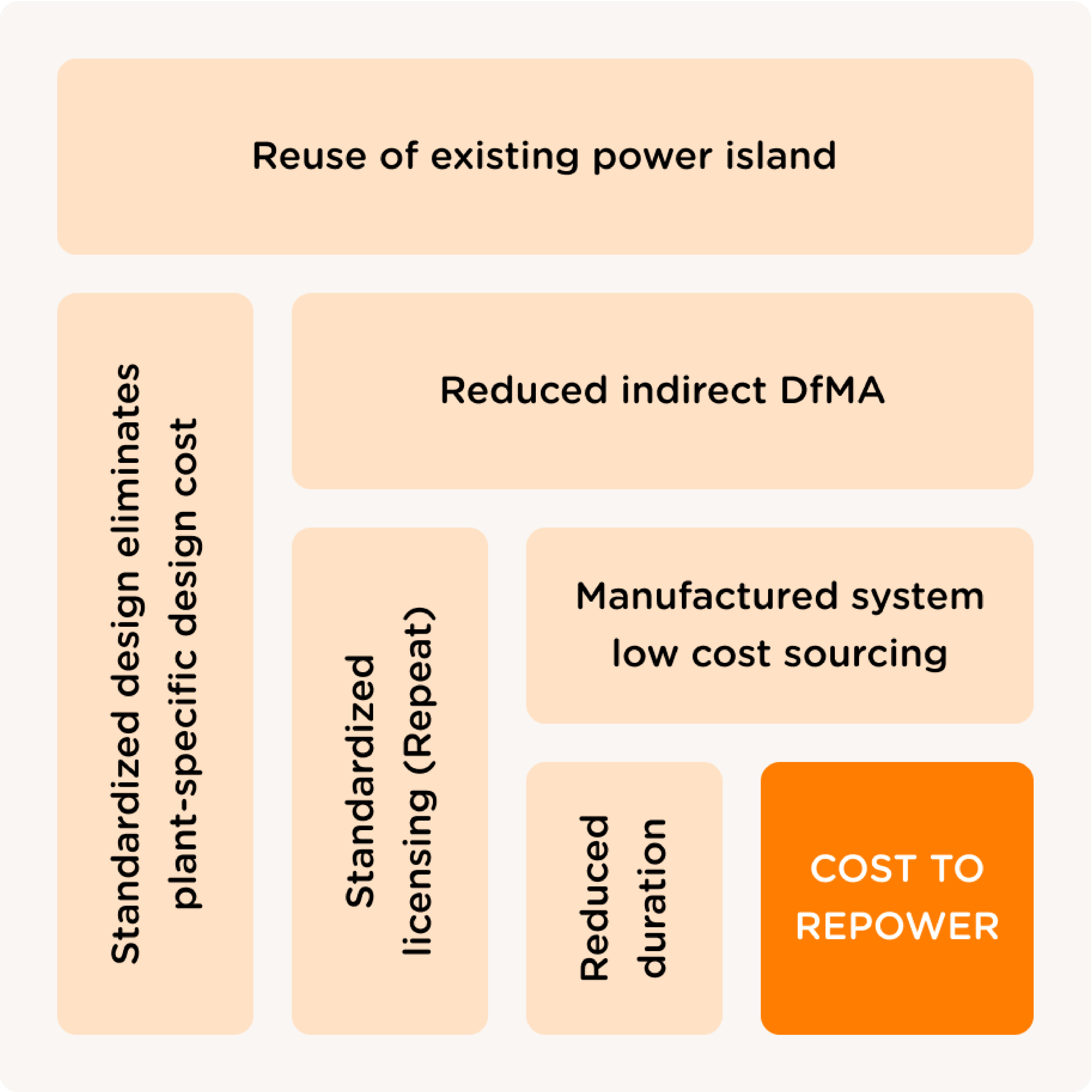
Strategies for moving from projects to products

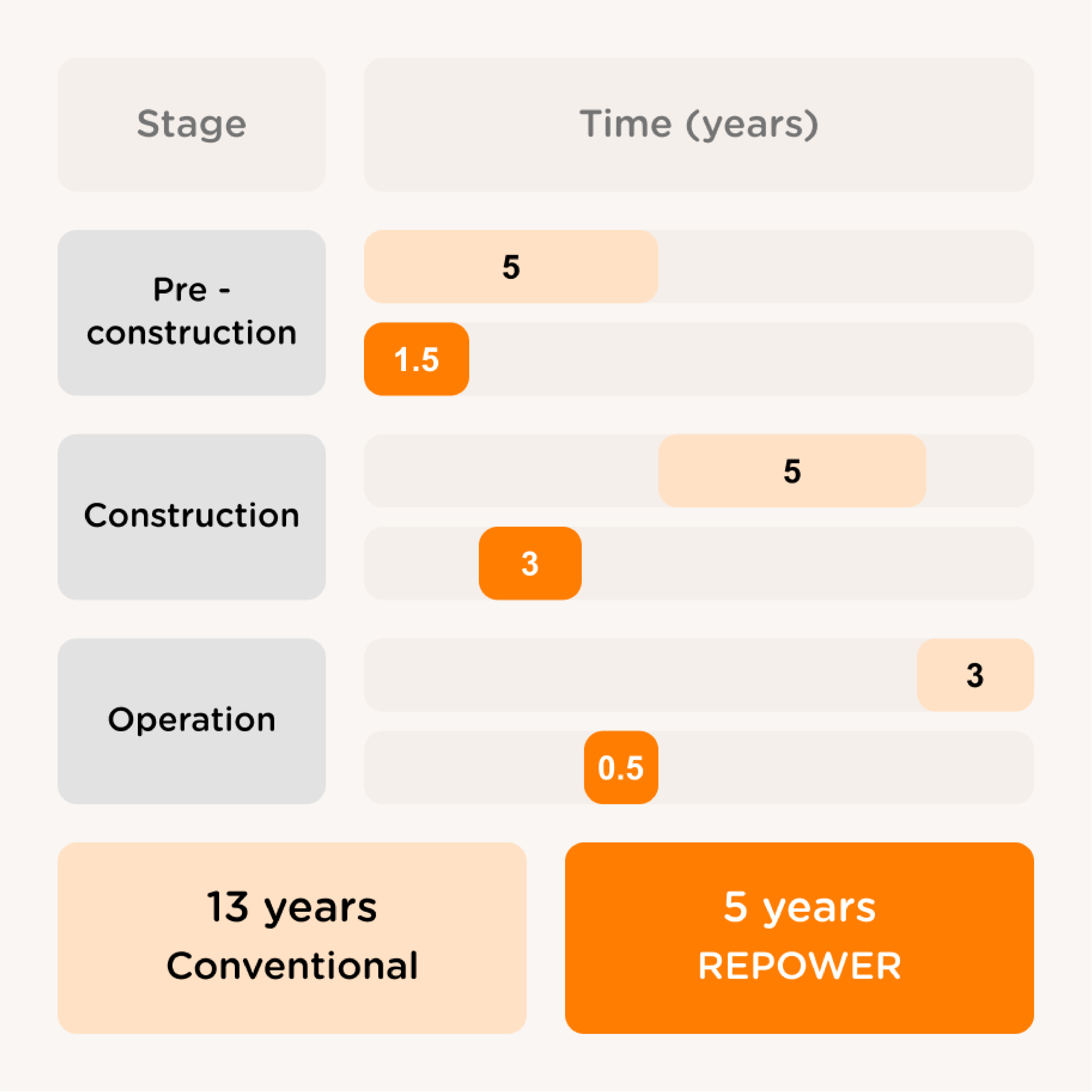
- Design for a large enough set of sites but with sufficiently common characteristics to enable highly standardized design
- Design special features to isolate the plant from the variation in the set of chosen sites
- Design to be repeatable with no safety relevant variation
- Design for manufacture and assembly

REPOWER COAL PLANT FOR $2,000/KWE IN JUST FIVE YEARS WITH LOWER RISK

The emissions-free repowered plants will be more profitable to operate than before and help to ensure continuity for communities reliant these plants for energy, jobs and continued economic development.

TARGET COST IS $2,000/KWE AND 5 YEAR SCHEDULE



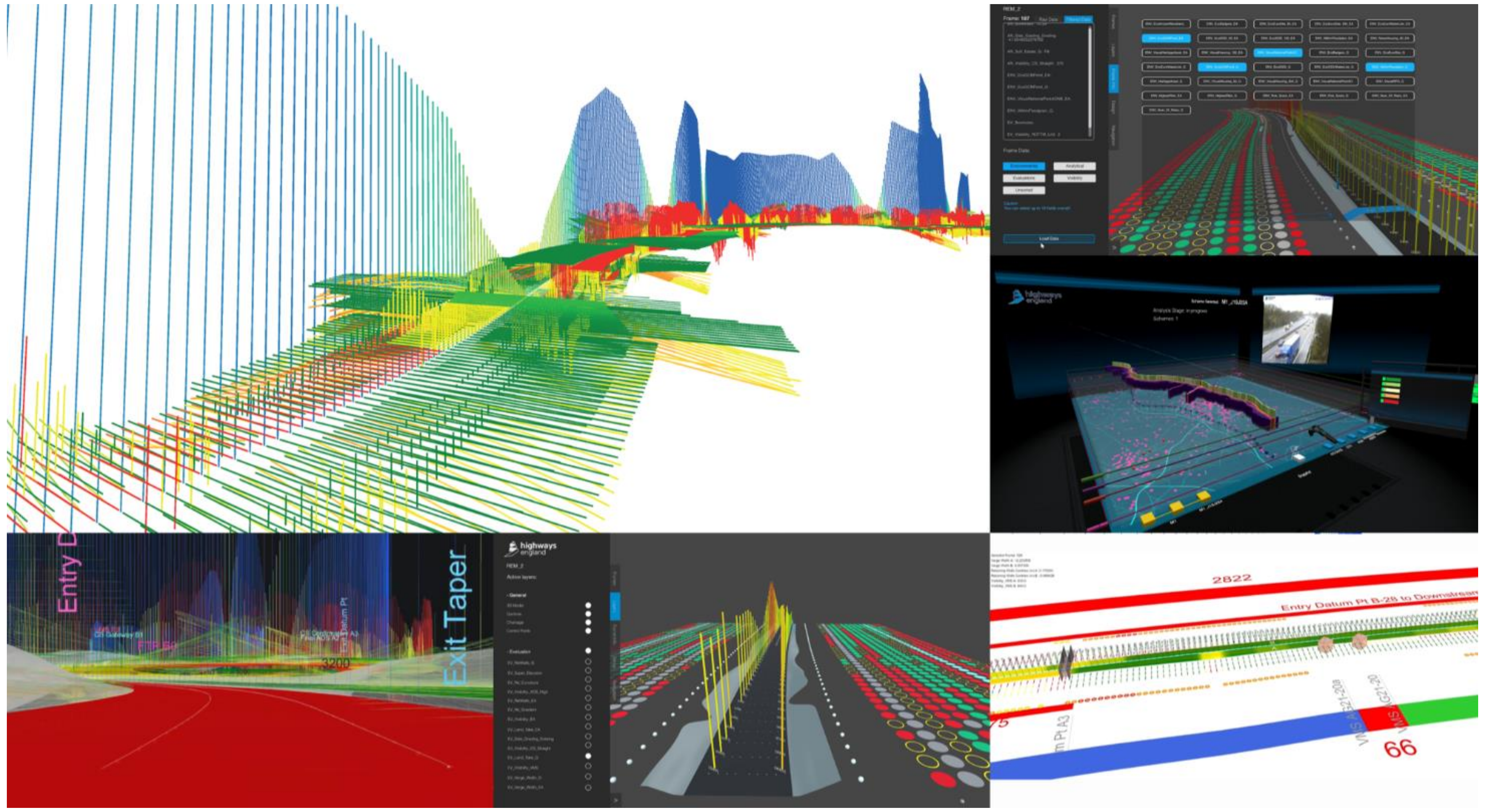


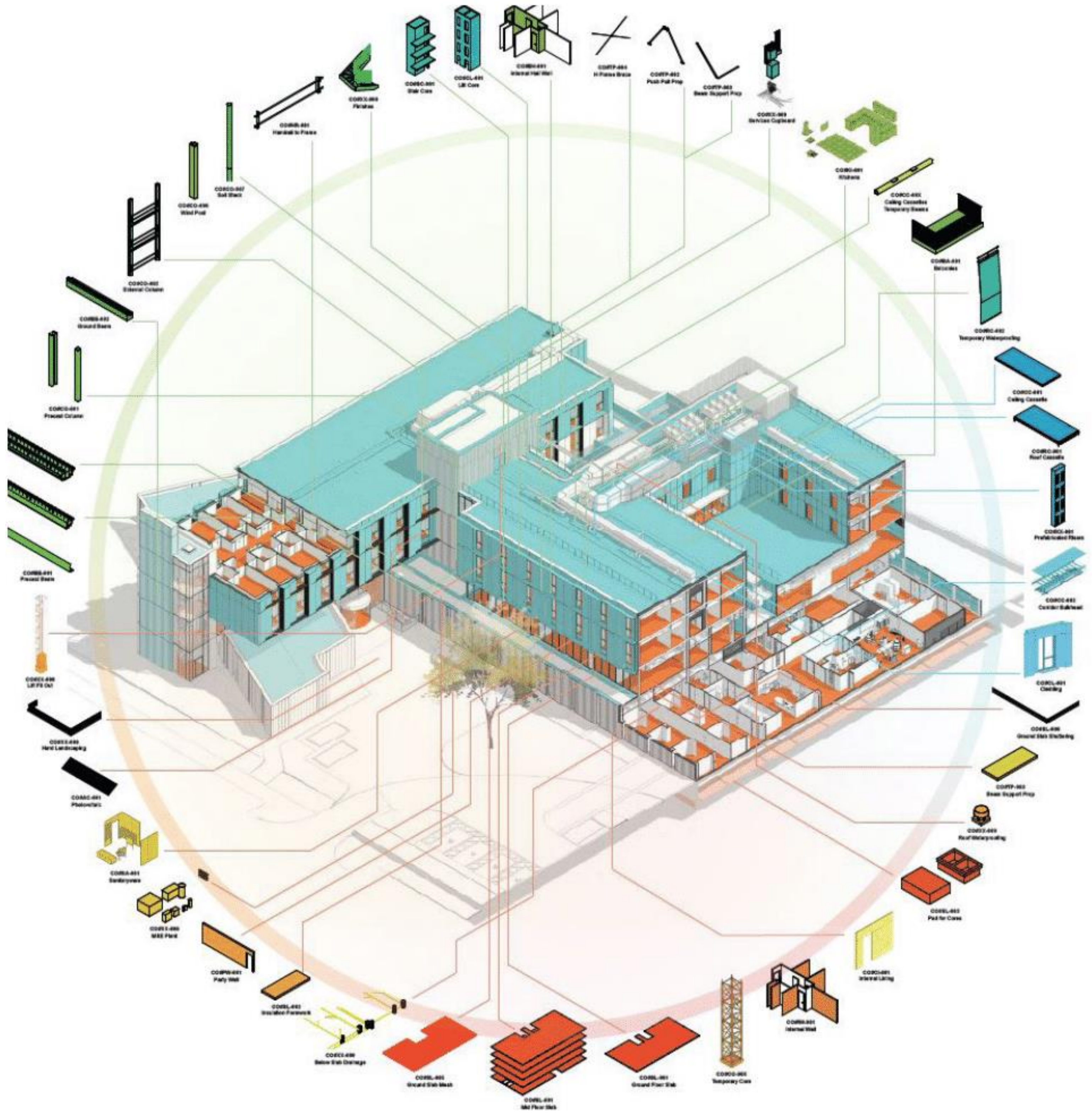
Proven Approach

40%
Reduced cost

40%
Reduced programme

Design time:
~~Years~~
Weeks



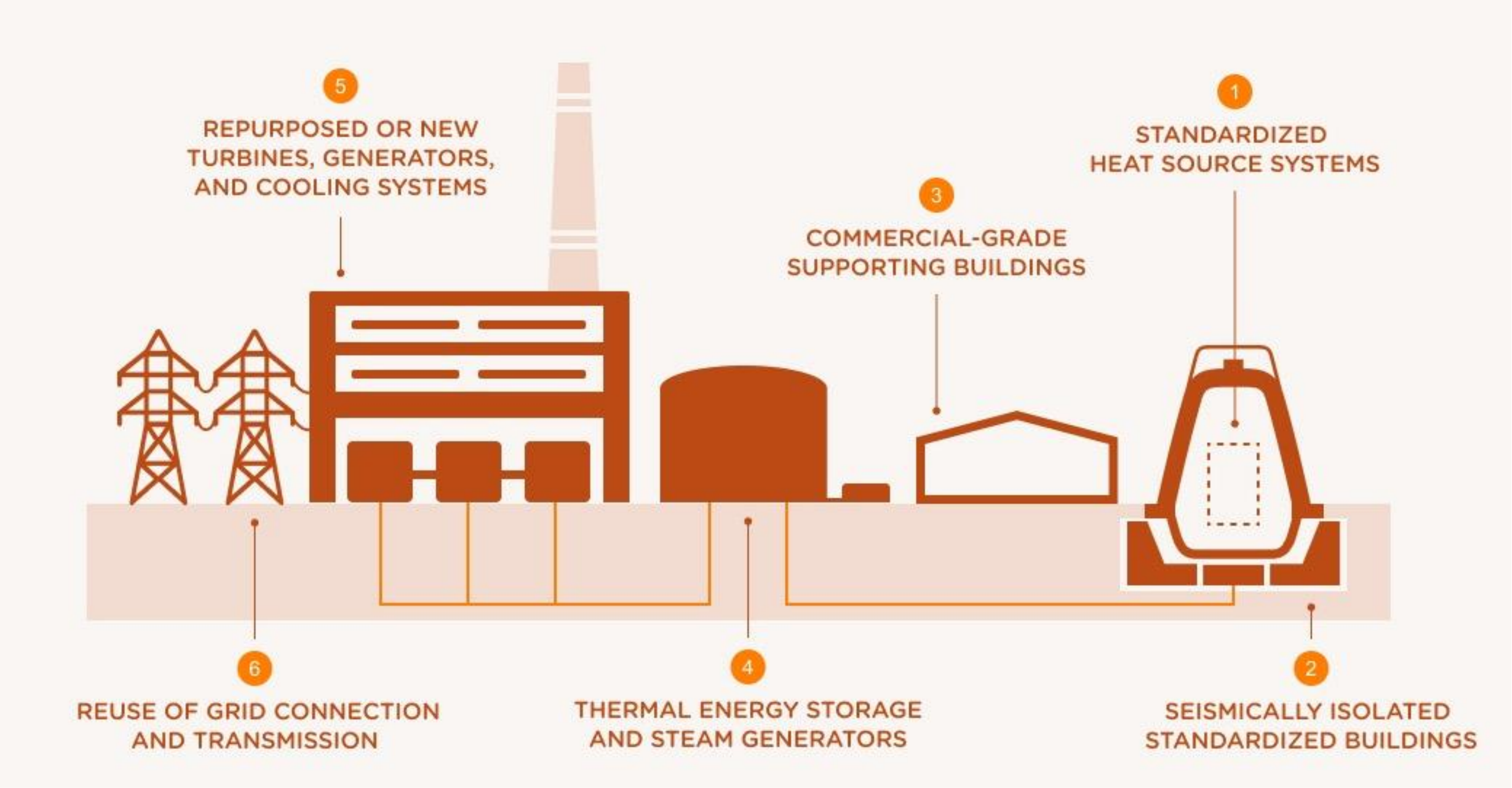



Infrastructure and Projects Authority
Reporting to Cabinet Office and HM Treasury
Transforming Infrastructure Performance: Roadmap to 2030

TERRA PRAXIS

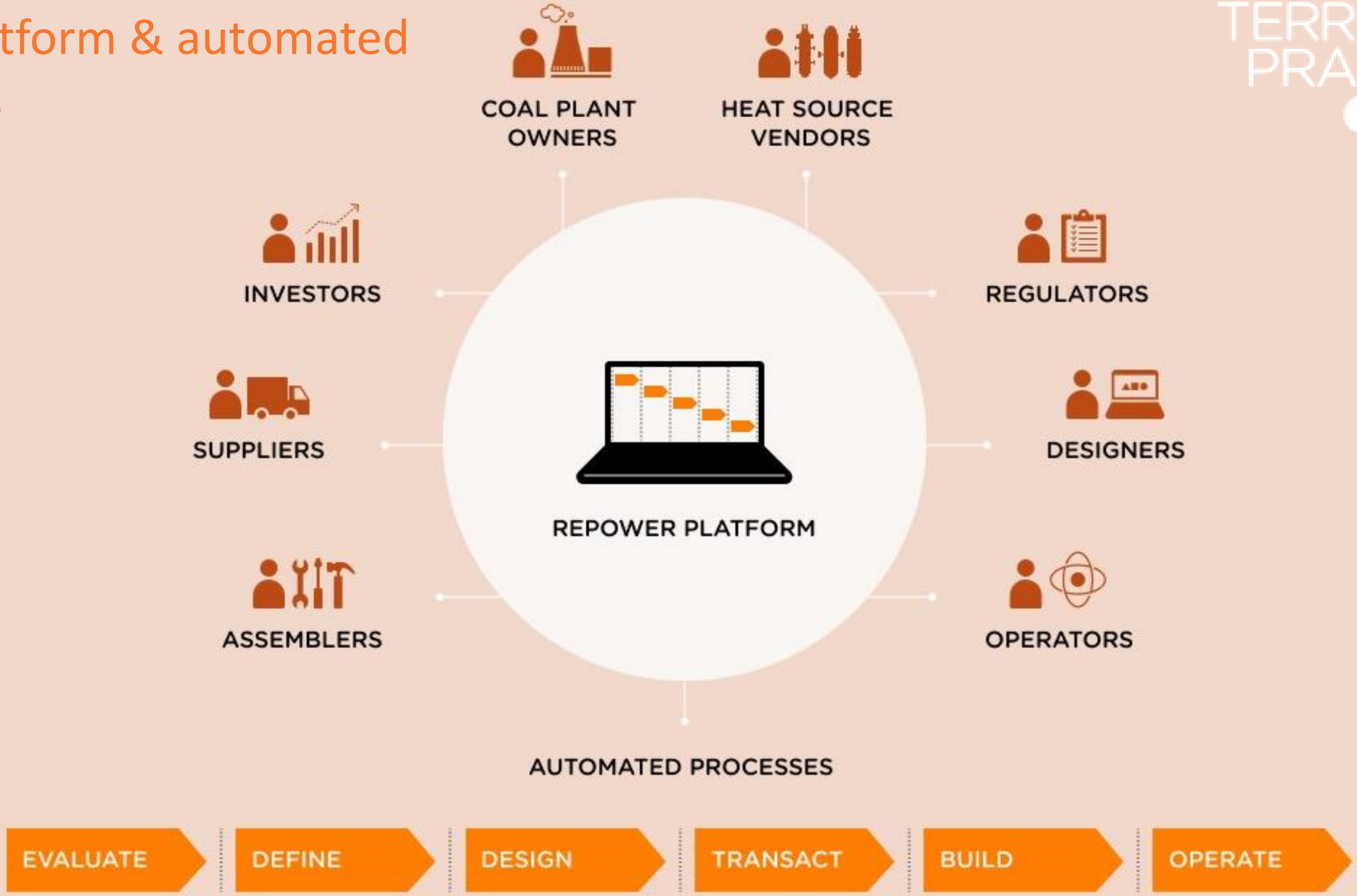
Bryden Wood

Built Systems Must Enable Scale and Speed



2TWe
2050

Digital platform & automated processes



TERRA PRAXIS REPOWER

EVALUATE

OUR APPLICATION 'EVALUATE' IS DESIGNED TO ESTIMATE THE FEASIBILITY, COST AND TIME TO REPOWER COAL-FIRED POWER PLANTS.

TerraPraxis has partnered with Microsoft to make this pilot version of our site assessment and business viability application. Coal plant owners and institutional investors can see estimates of project feasibility and costs that benefit from a standardized component and production strategy. We make this pilot available so you can help us make its features meet your business needs.

THE POWER OF EVALUATE

EVALUATE will reduce study costs and duration from millions of dollars and years to a matter of hours.

EVALUATE will enable you to assess your business case for repowering, including cost, potential for increased revenues after repowering, jobs and socio-economic benefits, and carbon emissions reduction.

EVALUATE will also, in the future, provide you with a conceptual plant layout, hazard analysis (e.g. earthquake, wind, flood), high-level plant economics and expected schedule, and other information needed to move to a conceptual design.

ENERGY INNOVATION FOR A PROSPEROUS PLANET

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Webinar # 2

The Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Webinar Series: Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Mr Łukasz Bartela

- Associate Professor of Silesian University of Technology (Poland)
- Researcher on Coal- and Gas-fired Units issues
- Interests in Clean Production and Large-scale Storage of Electricity
- Expert on Thermodynamic Analyses, Economic Analyses and Optimization of Energy Systems
- Coordinator of the project on Coal-to-Nuclear Decarbonization Pathway

Silesian University of Technology

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE
Ministry of Science and Higher Education

Coal-to-Nuclear as decarbonization pathway for Poland - first assessment of the potential

Łukasz Bartela
Paweł Gładysz
Staffan Qvist

Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

online webinar, 5 April, 2023

DEsire Team:

DEsire

NCBR
Narodowe Centrum Badań i Rozwoju
Rzeczpospolita Polska

Silesian University of Technology

Ministerstwo Klimatu i Środowiska

EPK

ichtj

INSTYTUT SOBIESKIEGO

Genesis of the DEsire project

- works done by the Qvist-Gładysz-Bartela team

C2N

C2N#0 Greenfield

- *NPP is being built near the decommissioned CPP,*
- *no material links between the liquidation and the investment,*
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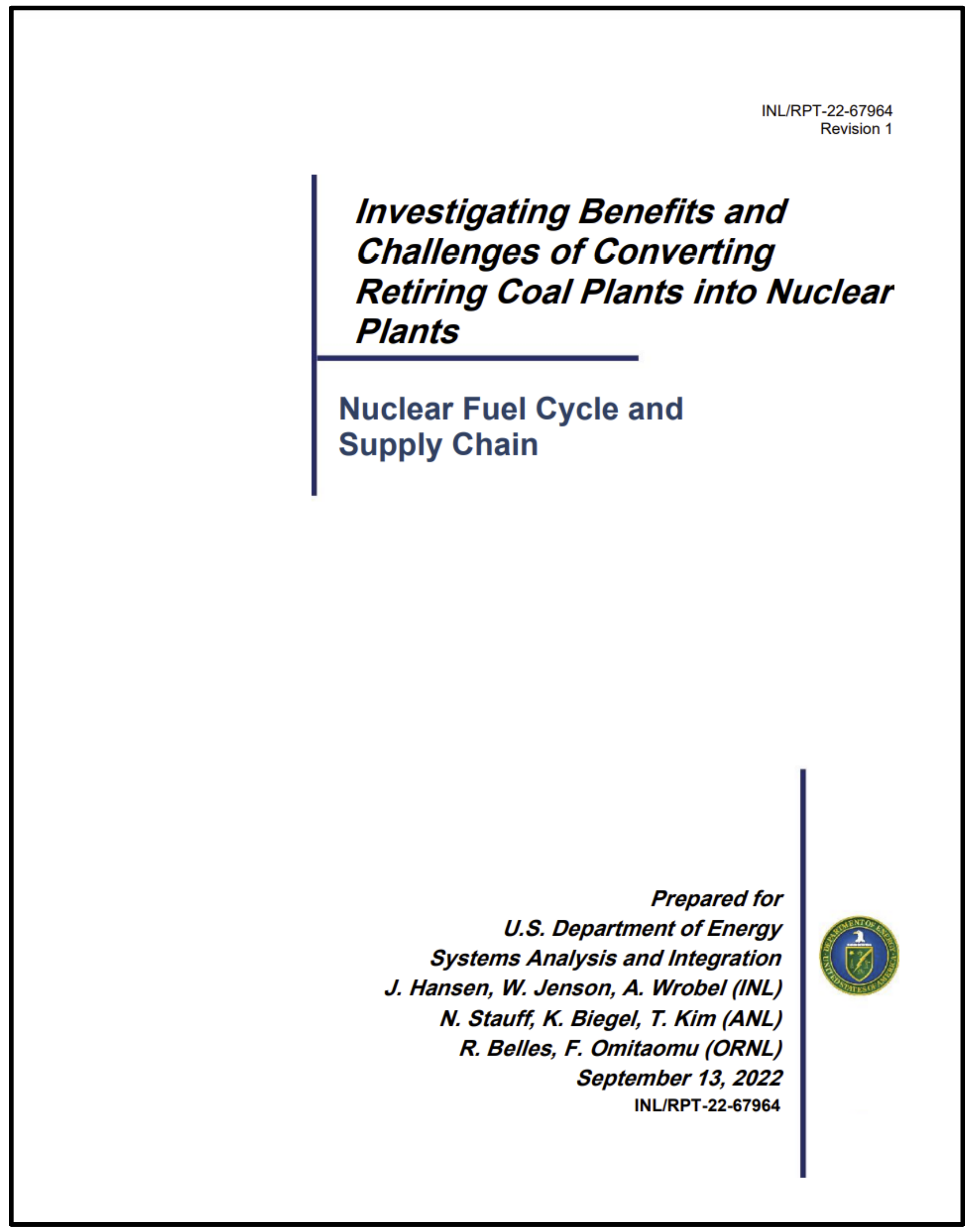
INL/RPT-22-67964
Revision 1

Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis and Integration
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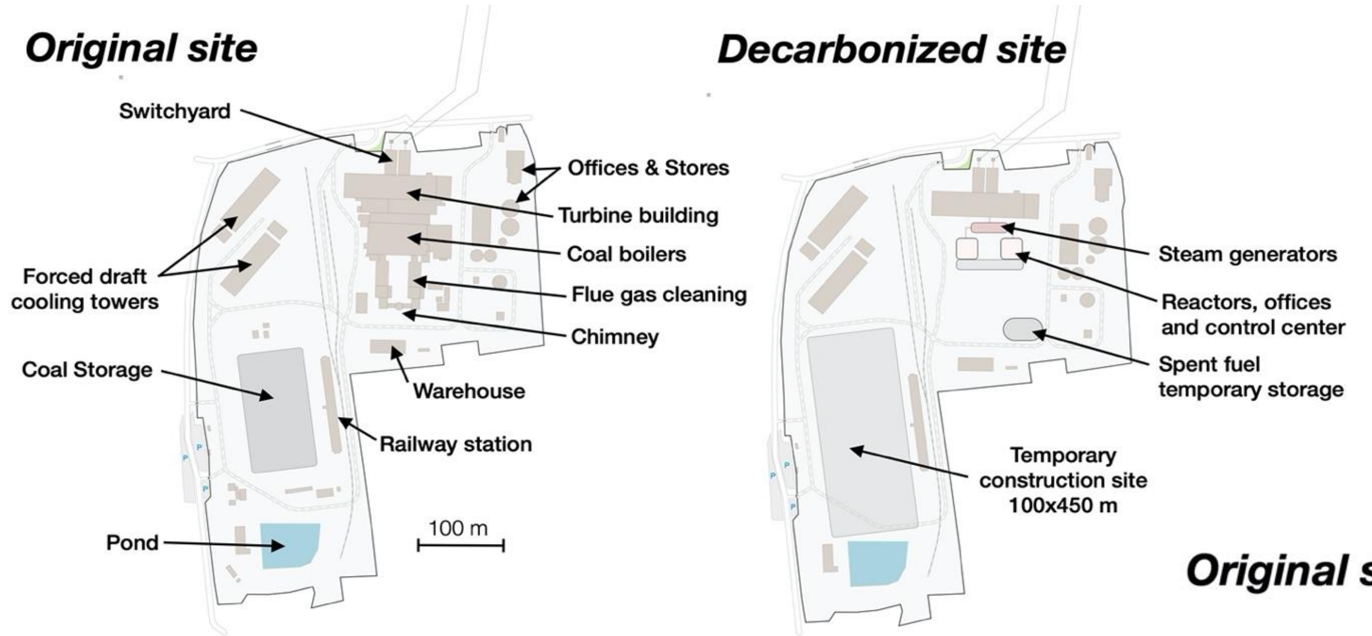
R. Belles, F. Omitaomu (ORNL)
September 13, 2022
INL/RPT-22-67964

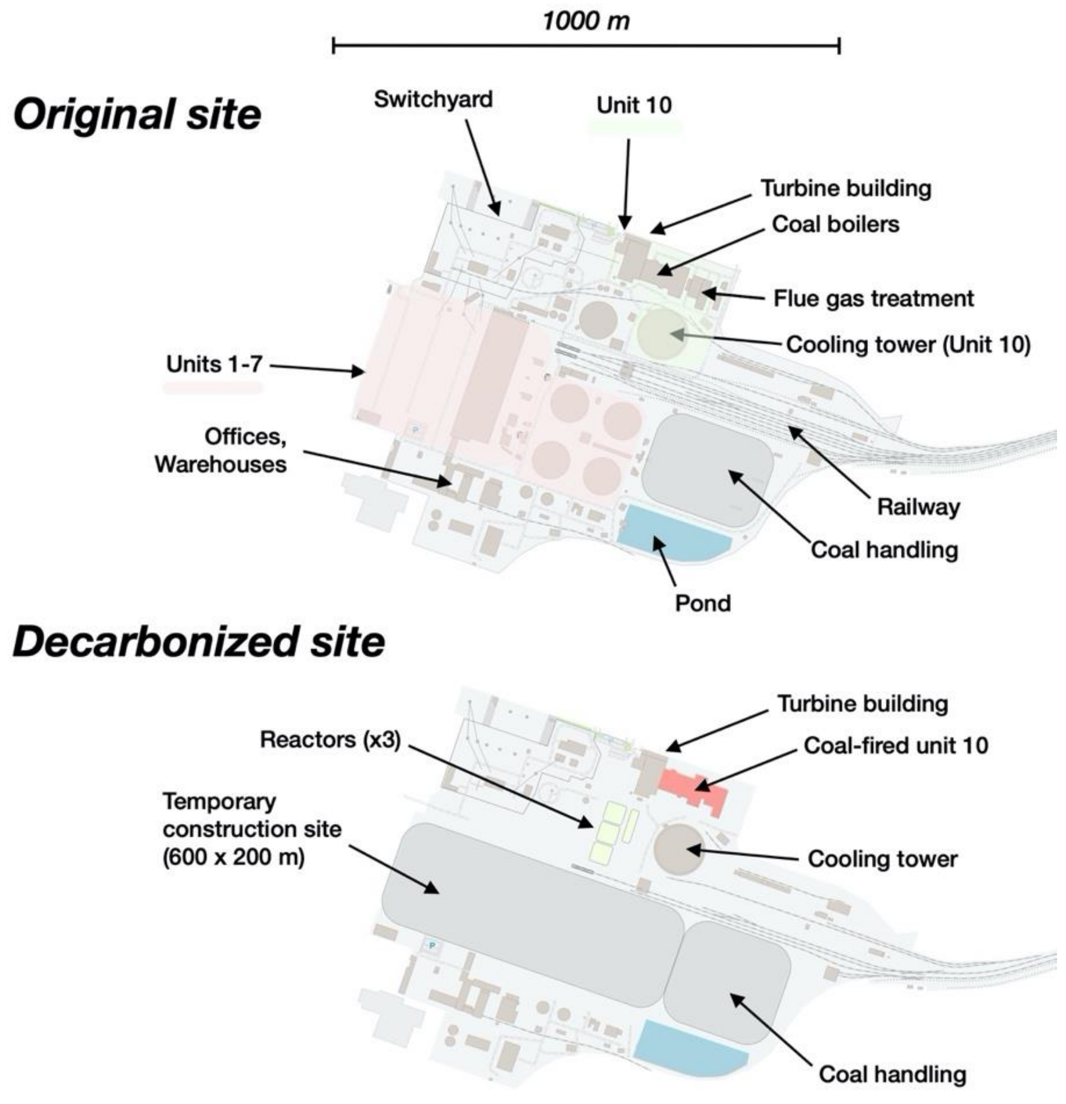
Repurposing

Full Repowering & Partial Repowering

Genesis of the DEsire project

- works done by the Qvist-Gładysz-Bartela team





2019 – 2020

Scope:

- **General assessment of Polish energy sector** and options for decarbonization within retrofit of existing units
- Small modular reactors reftrofit **case studies** for three different coal-fired plants in Poland (**Coal-to-Nuclear option**)

2021 – 2022

Scope:

- **Coal-to-Nuclear** with **Thermal Energy Storage (TES)** option – case study for Łagisza Power Plant and Kairos KP-FHR
- Gas-to-Nuclear option – case studies for (i) reference state-of-the-art NGCC and (ii) specific CHP NGCC located in Poland

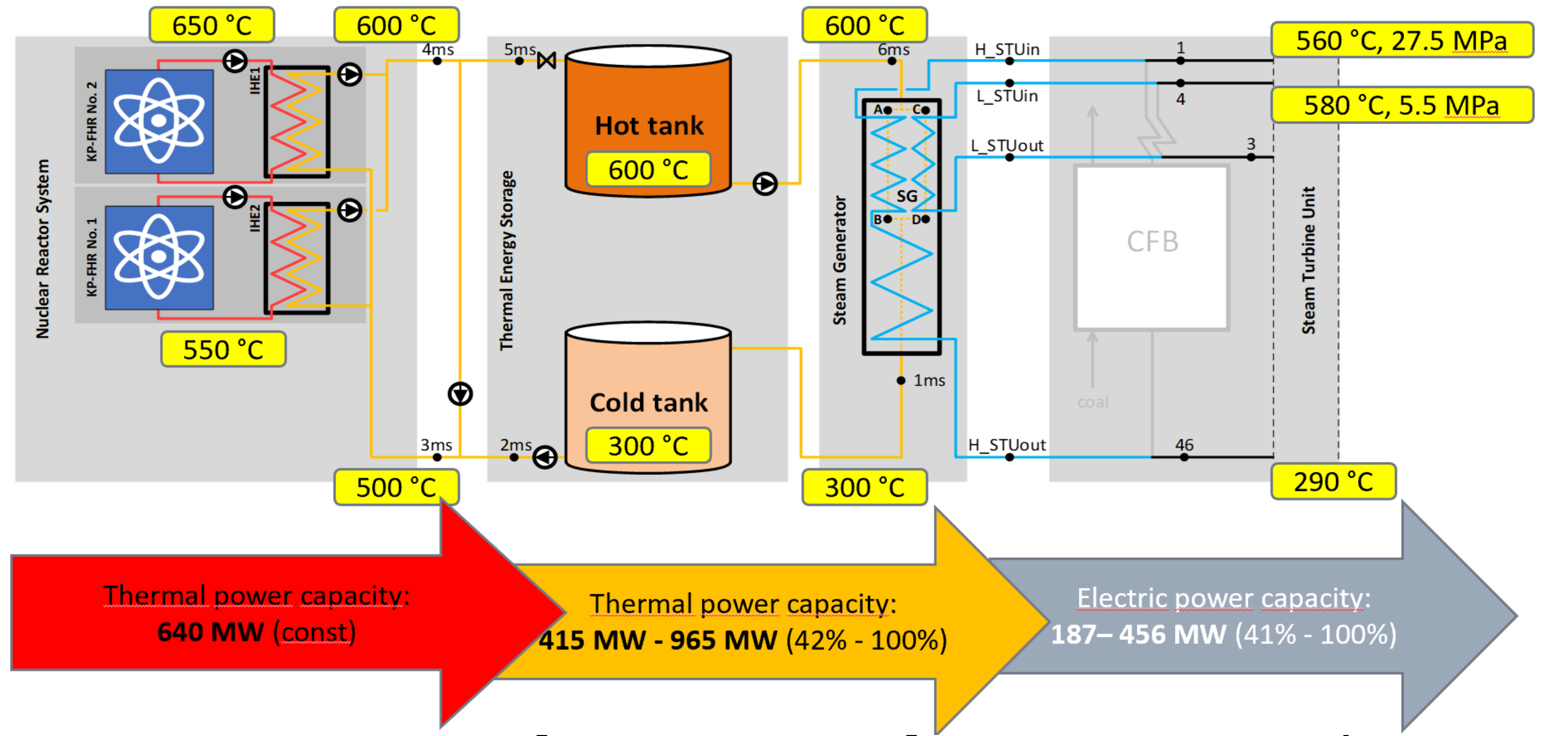


Fig. Diagram of integration of SMR system with TES at Łagisza unit

Silesian University of Technology

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DEsire

Genesis of the DEsire project

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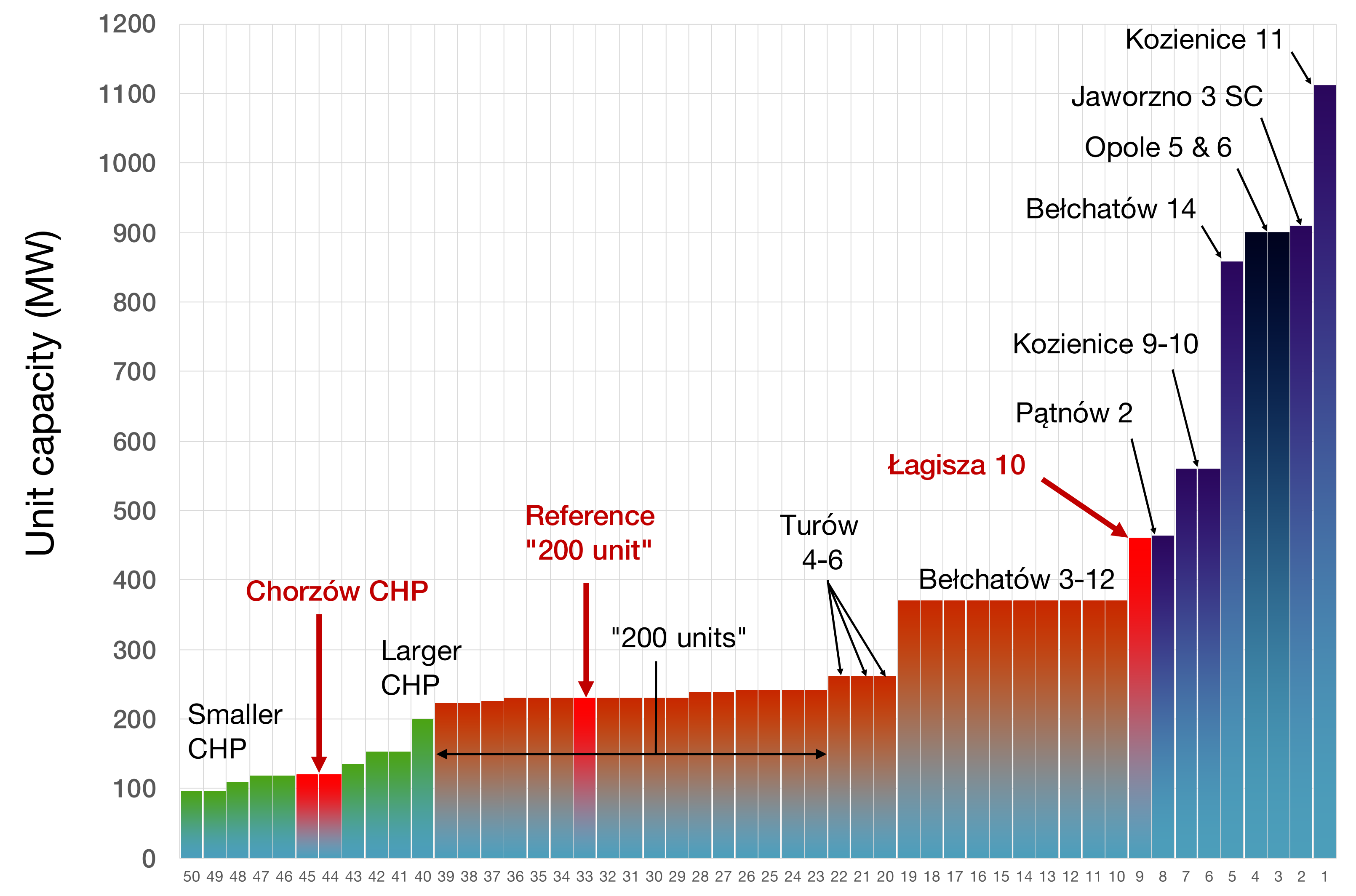


Fig. Unit-by-unit retrofit decarbonization recommendation

- **Łagisza Power Plant – 460 MW Unit:**
  - integration with HTR-PM (China)
  - integration with Kairos KP-FHR (US)
- **Reference 200 MW Class Unit:**
  - integration with Kairos KP-FHR (US)
  - integration with generic MSR
- **CEZ Chorzów Combined Heat and Power Plant:**
  - integration with Kairos KP-FHR (US)
  - integration with generic MSR

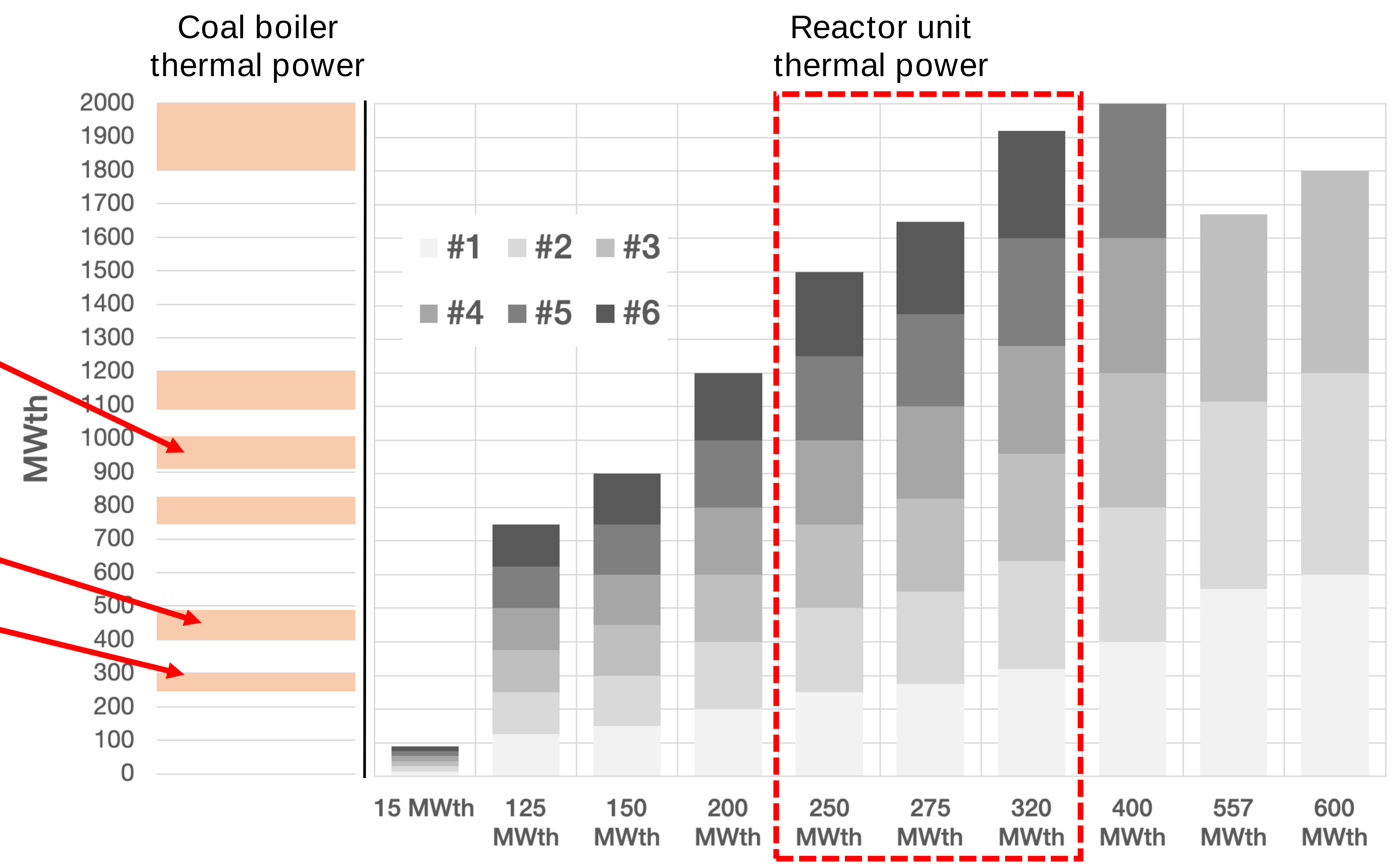
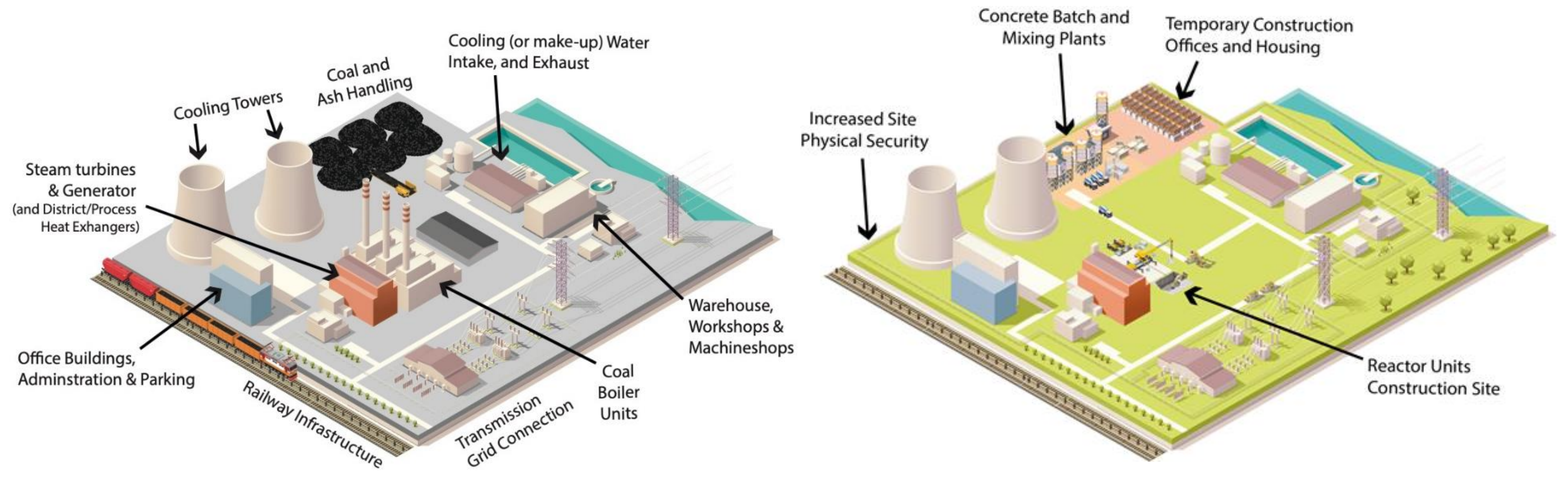


Fig. Matching the thermal power output of coal boilers with SMRs



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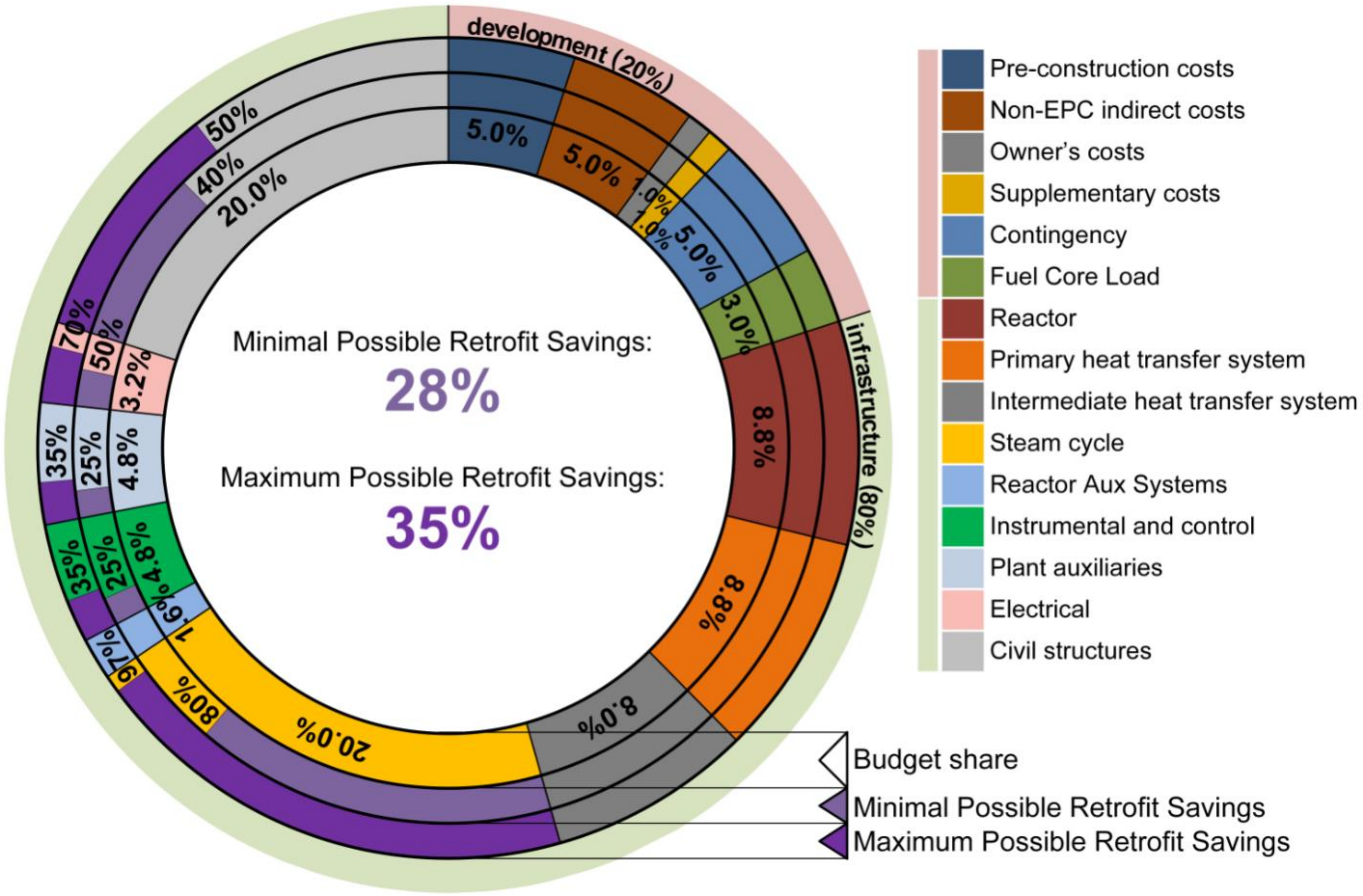

Fig. Possible investment savings due to the use of the existing infrastructure of the coal-fired power unit

Total capital investment cost (*TCIC*) = overnight capital cost (*OCC*) + interests during construction (*IDC*)

$$TCIC_{RET} = OCC_{GF}(1 - RS) + IDC_{RET}$$

RS – **retrofit savings in direct retrofit (C2N#2)** option for Łagisza power plant were estimated to be **up to**:

- **97% for steam cycle**,
- 35% for instrumental, controls and other plant auxiliaries,
- 70% for electrical side,
- 50% for civil structures.

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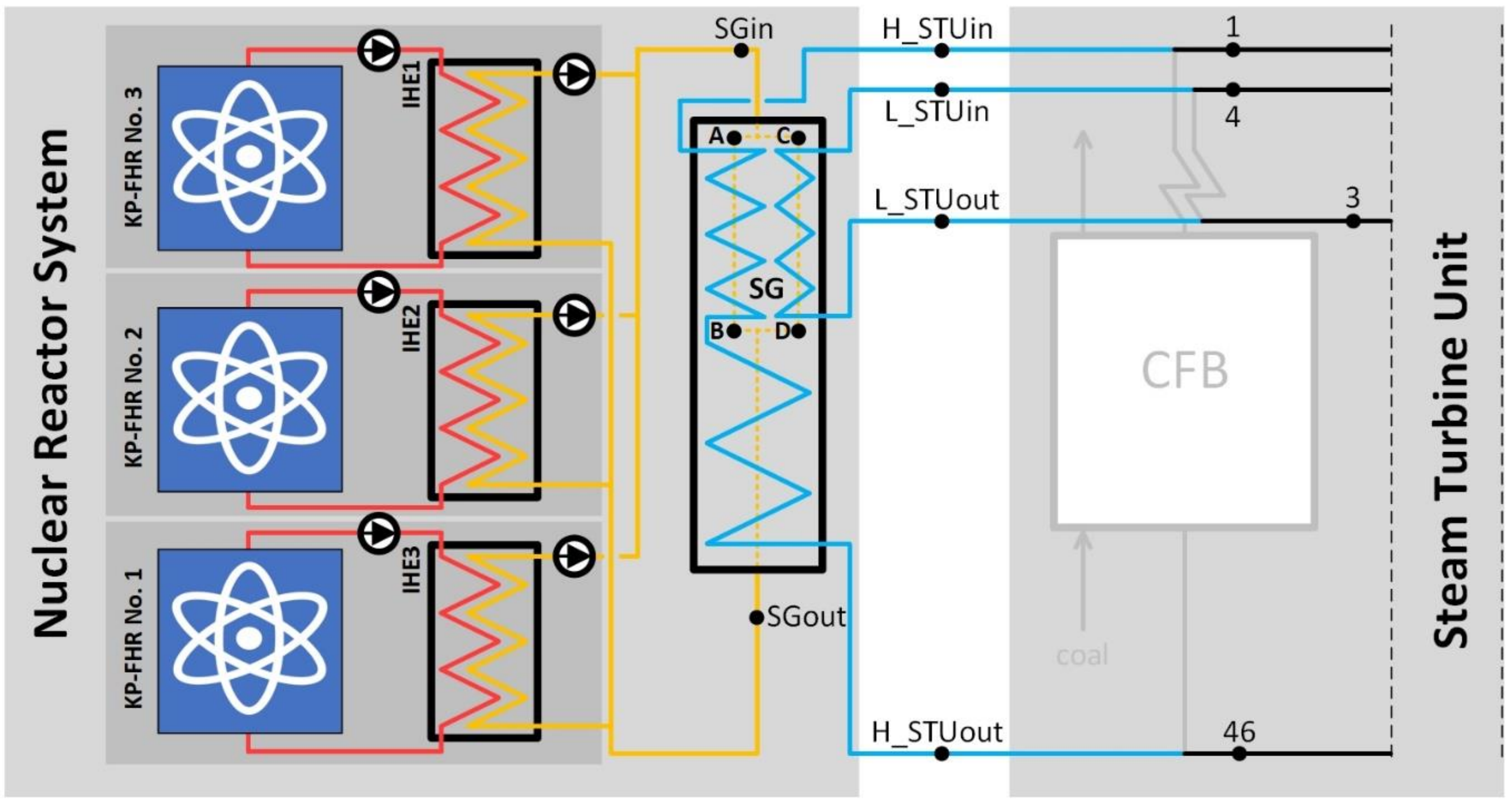

Fig. Diagram of integrations of SMR systems with a 460 MW Łagisza unit

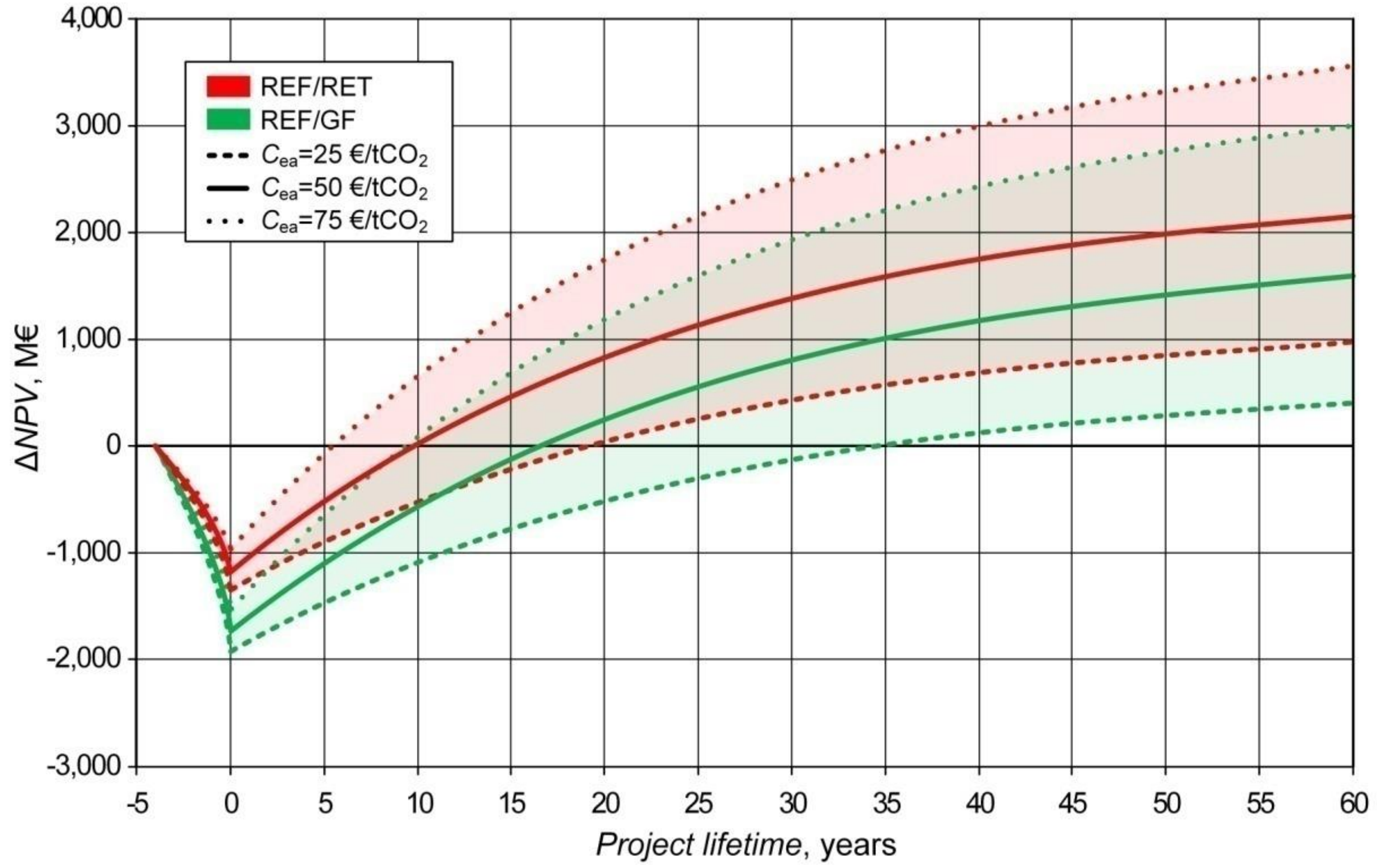

Fig. ΔNPV as a function of project lifetime for the GF and RET investment pathways for Łagisza unit

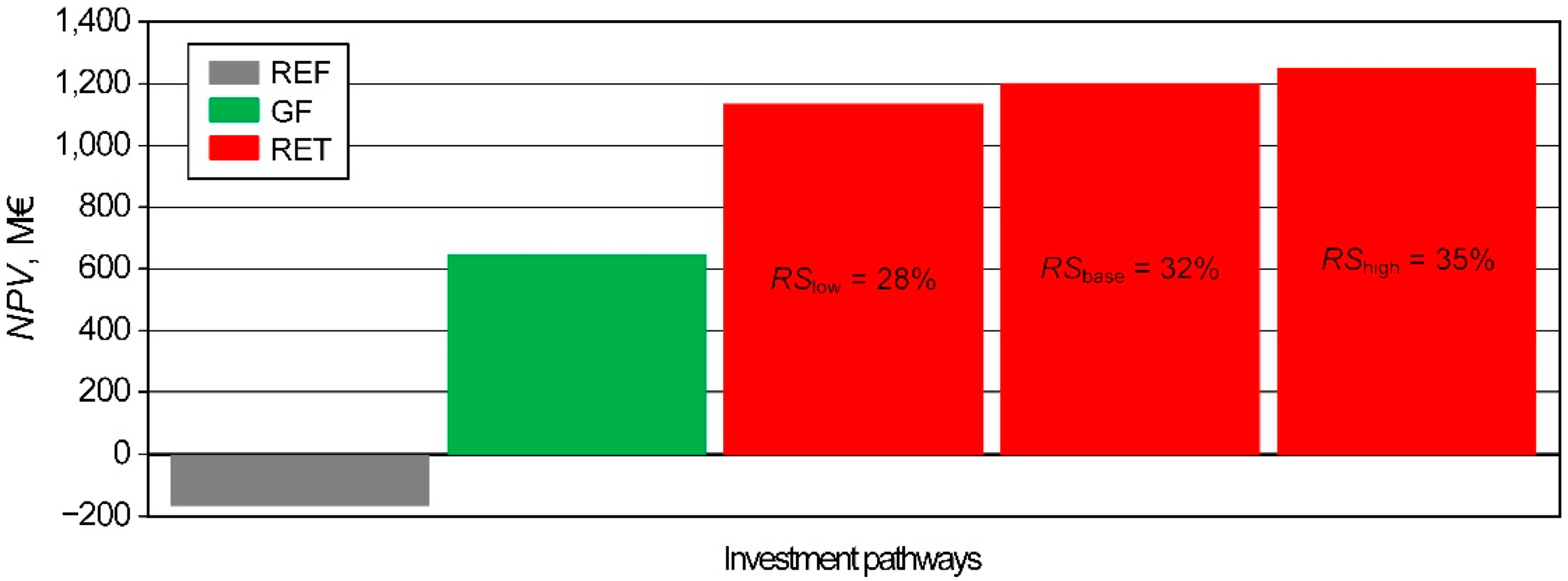

Fig. NPV for base assumptions for three investment pathways (retrofit investment pathway for three different values of retrofit savings) for Łagisza 460 MW unit

Genesis of the DEsire project

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Table. Discount payback period for different electricity (el), coal and CO_2 emission allowance (ea) prices for two investment pathways

		Pathway of investment					
		GF			**RET**		
		C_{ea}, €/tCO2			C_{ea}, €/tCO2		
		25	**50**	75	25	**50**	75
C_{el}, €/MWh	50	33	14	8	18	8	4
	75	35	**17**	10	19	**10**	6
	100	33	17	12	19	11	8
C_{coal}, €/GJ	1.6	>60	26	9	41	15	14
	3.2	35	**17**	10	19	**10**	6
	6.4	13	8	6	8	5	3

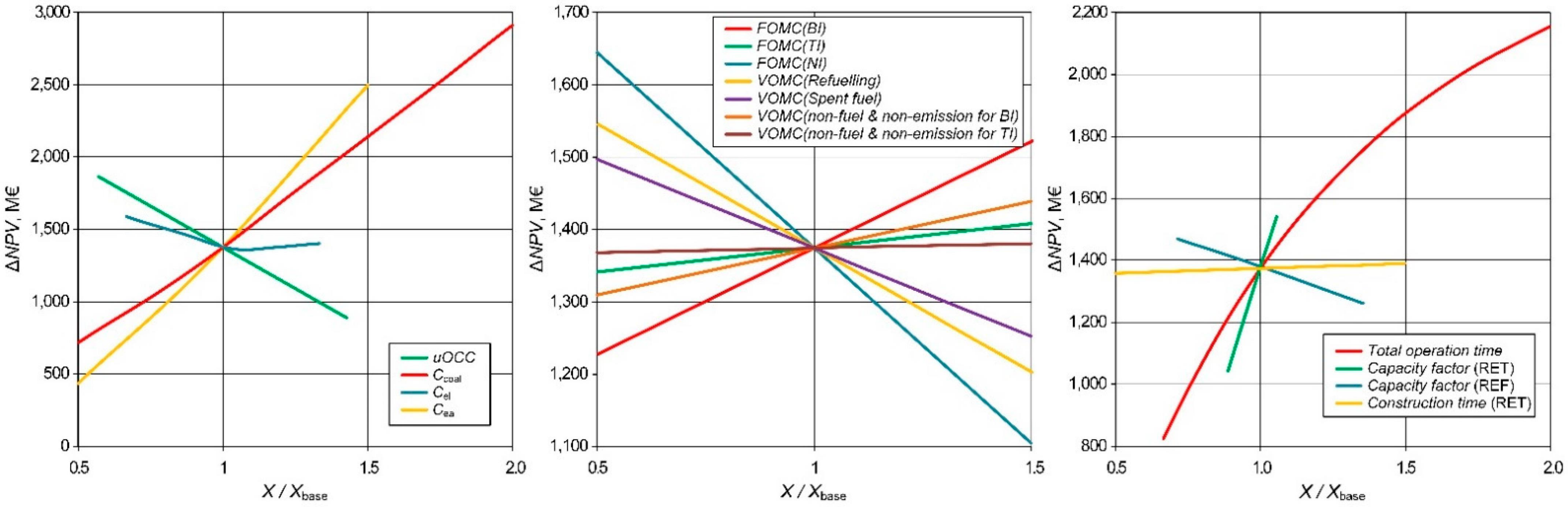

Fig. The results of the ΔNPV sensitivity analysis to changes in the main parameters determining the investment environment for the RET investment pathway for Łagisza 460 MW unit

CtN projects are highly sensitive to:

- the price of coal and CO_2 emission allowance,
- GF overnight capital costs,
- total operational time.

Coal-to-Nuclear classification – DEsire project

C2N

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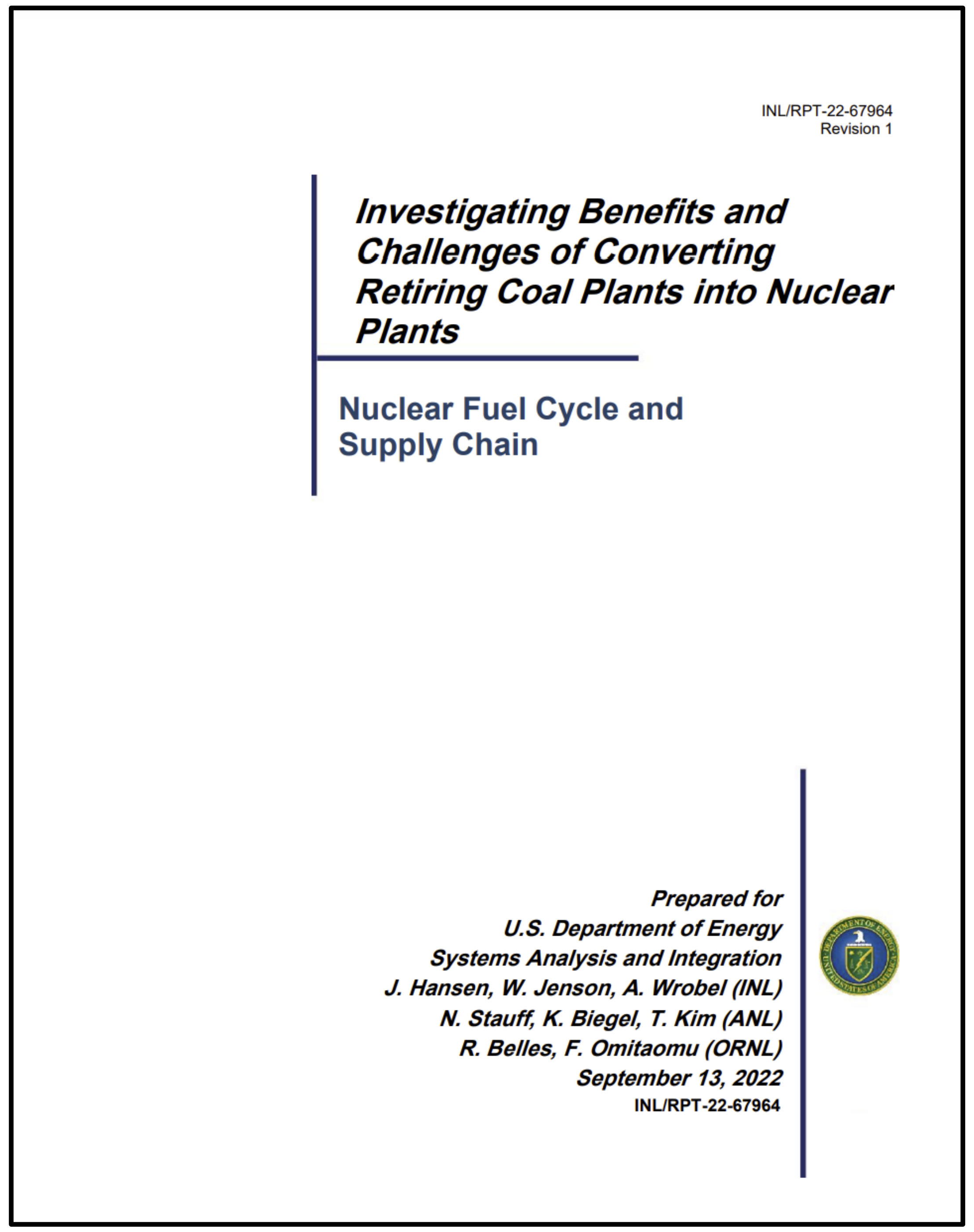
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Nuclear Fuel Cycle and Supply Chain

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Main goals of the DEsire project

A plan of decarbonization of the power industry through modernization with the use of III+ and IV generation nuclear reactors

which will be a roadmap for the organization of investment processes aimed at transforming centralized generation systems, considering the criteria of sustainable development

Pilot of the national Cluster of Power Industry Transformation (CPIT)

which will provide organizational support for activities aimed at increasing the effectiveness of various stakeholder groups in the process of transformation of domestic power plants and combined heat and power plants.

Structure of project

PHASE A - on going
Industrial research and development works

- Identification and analysis of the national energy and accompanying infrastructure
- Development of an integrated model for assessing energy and economic aspects
- Organization and security of the process of modernization and operation

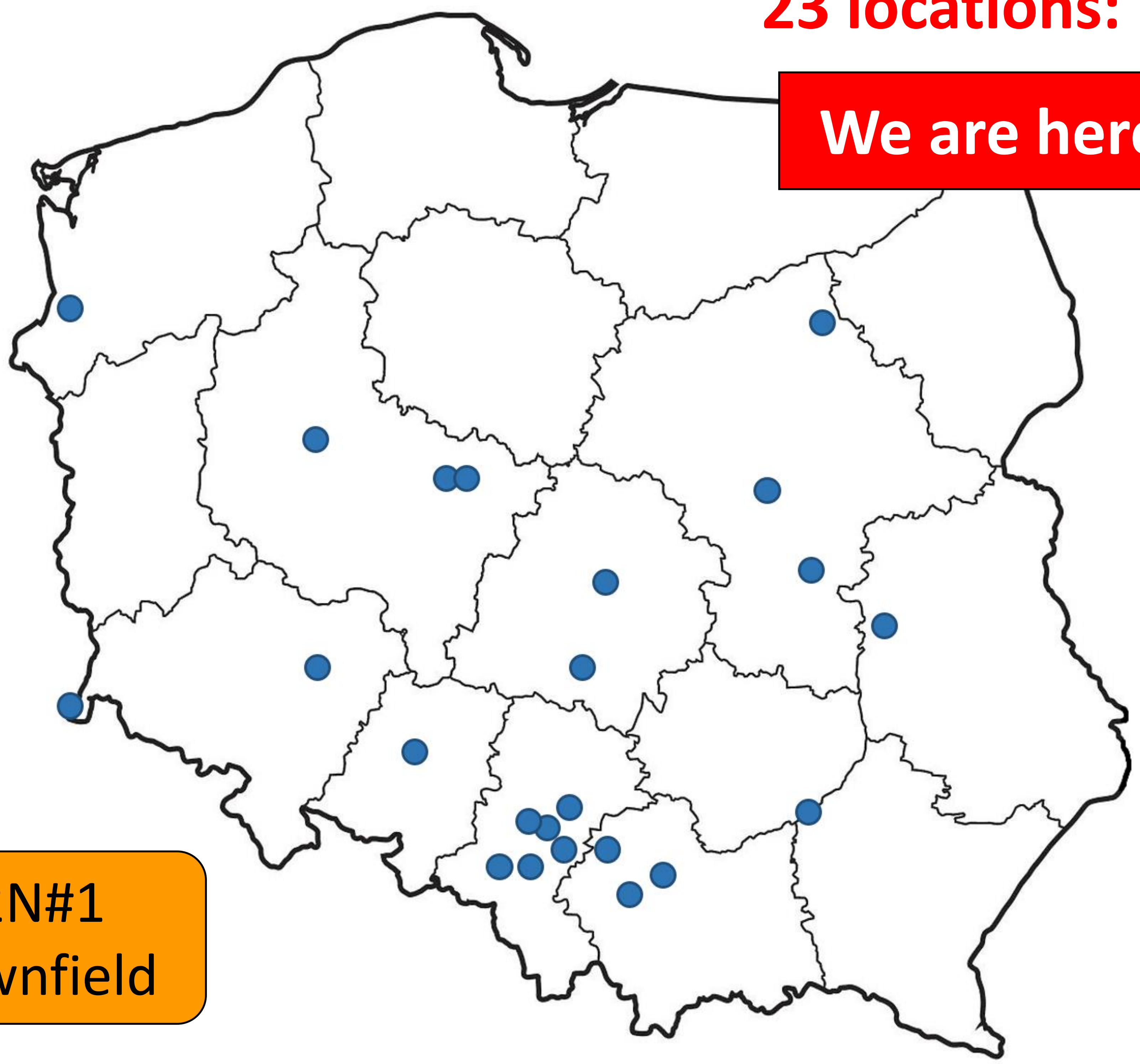
PHASE B
Pre-implementation works

- Procedures for modernization and two feasiblity studies
- Social diagnosis and preparation of analytical materials supporting the implementation of the modernization plan
- Preparation for the practical application of the project results
- Preparation of the modernization plan

Locations

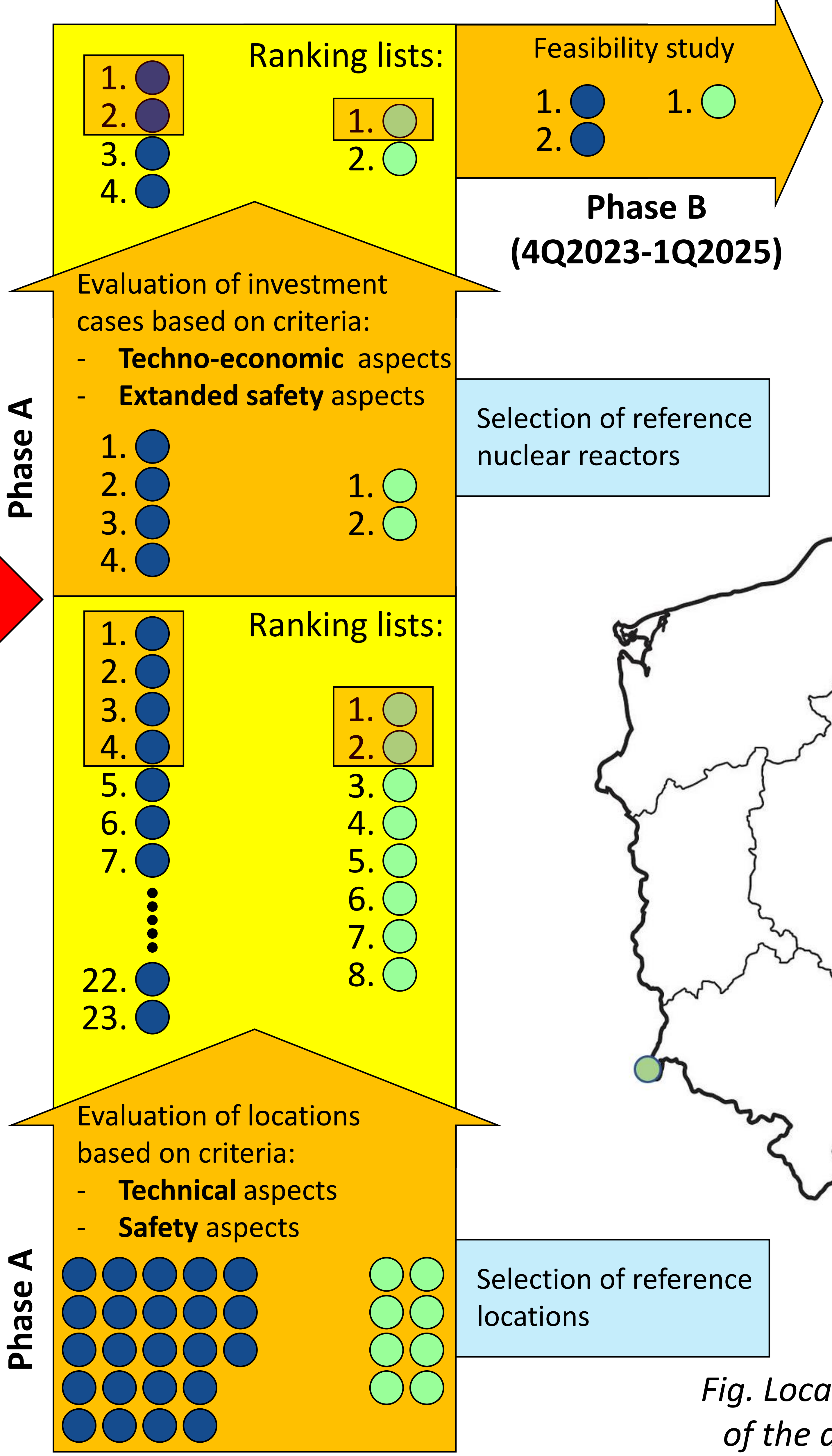
23 locations:

We are here



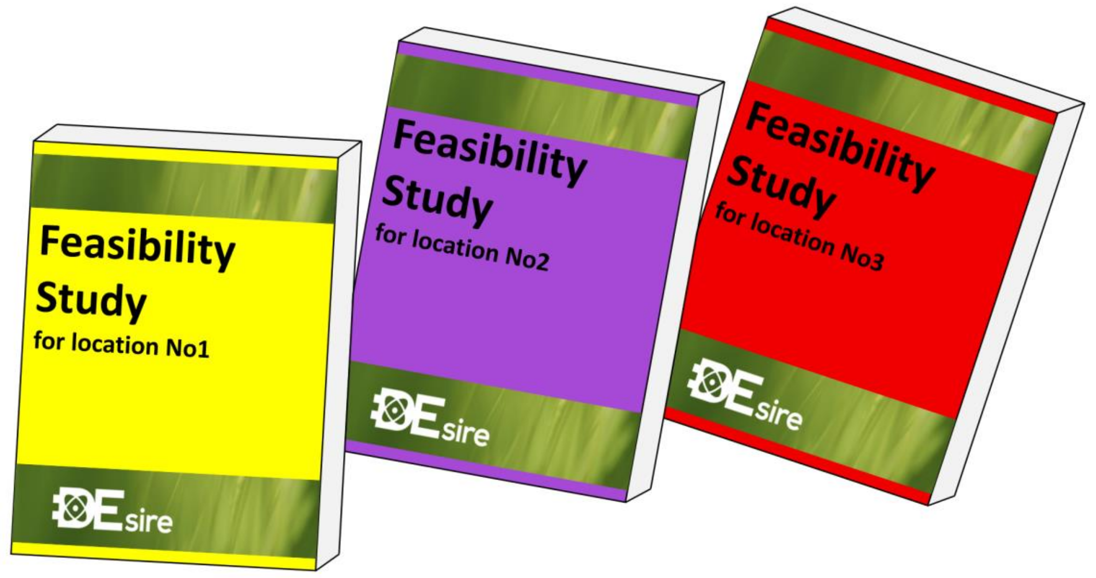
C2N#1
Brownfield

Fig. Locations of CPPs selected for the assessment of the brownfield C2N conversion pathway potential

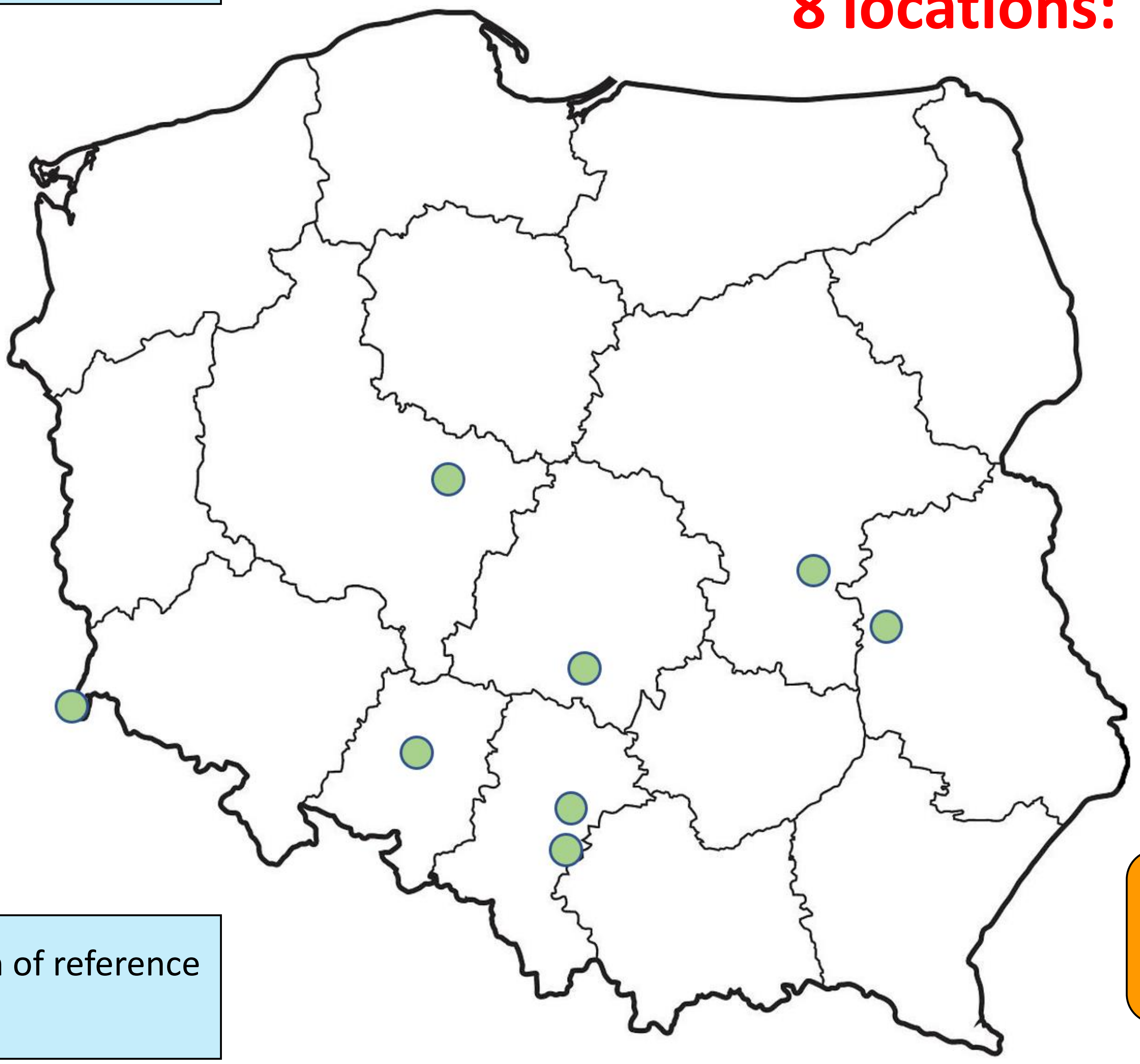


Selection of reference nuclear reactors

Selection of reference locations



8 locations:



C2N#2
Direct

Fig. Locations of CPUs selected for the assessment of the direct C2N conversion pathway potential

Locations

- locations indicated in the **Polish Nuclear Power Programme** (strategic government document)
- locations analyzed in the **DEsire project**
- cluster of conventional coal-fired power plants in **Silesia-Malopolska region** (ca. 8.5 GW_{el})

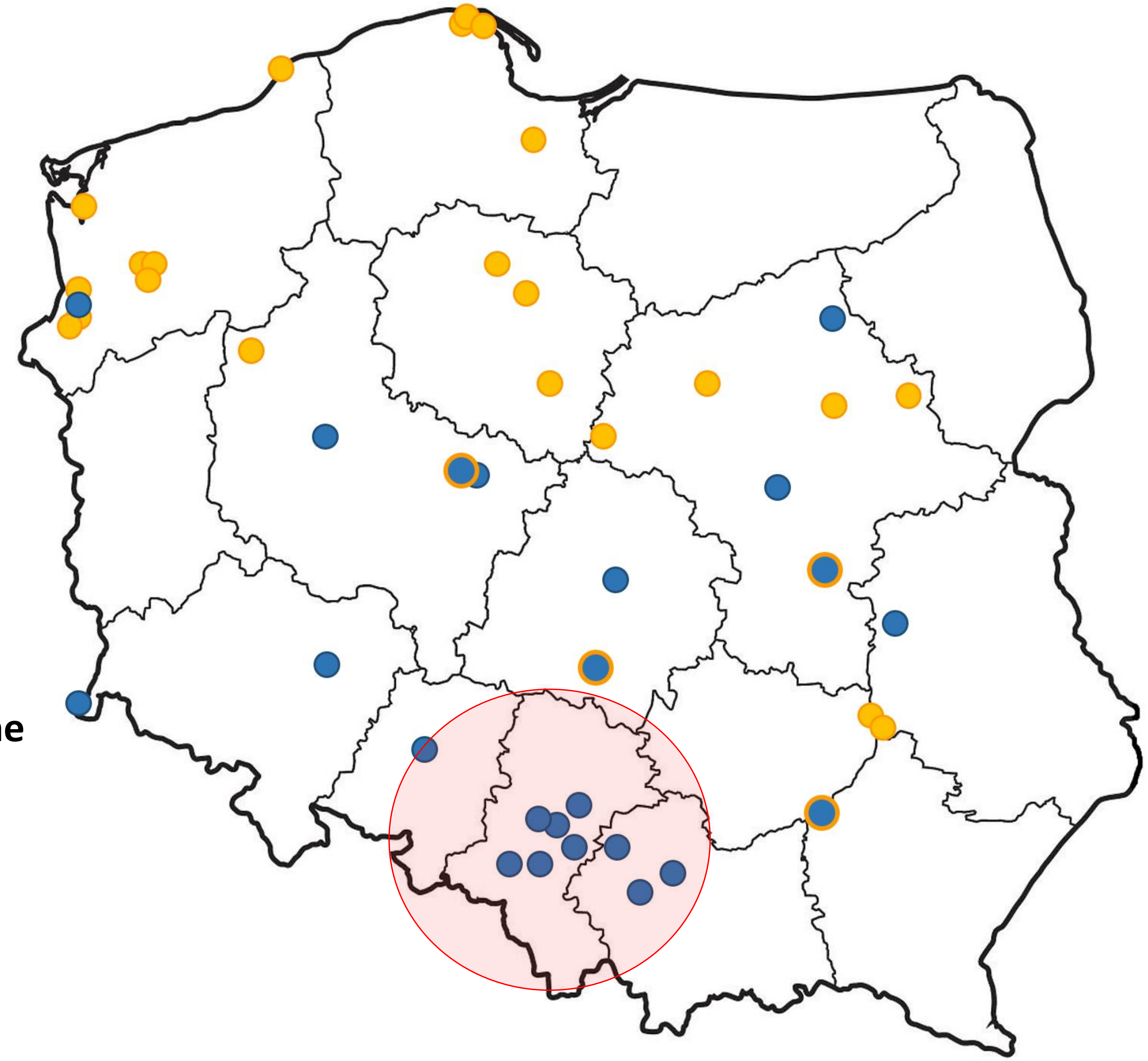
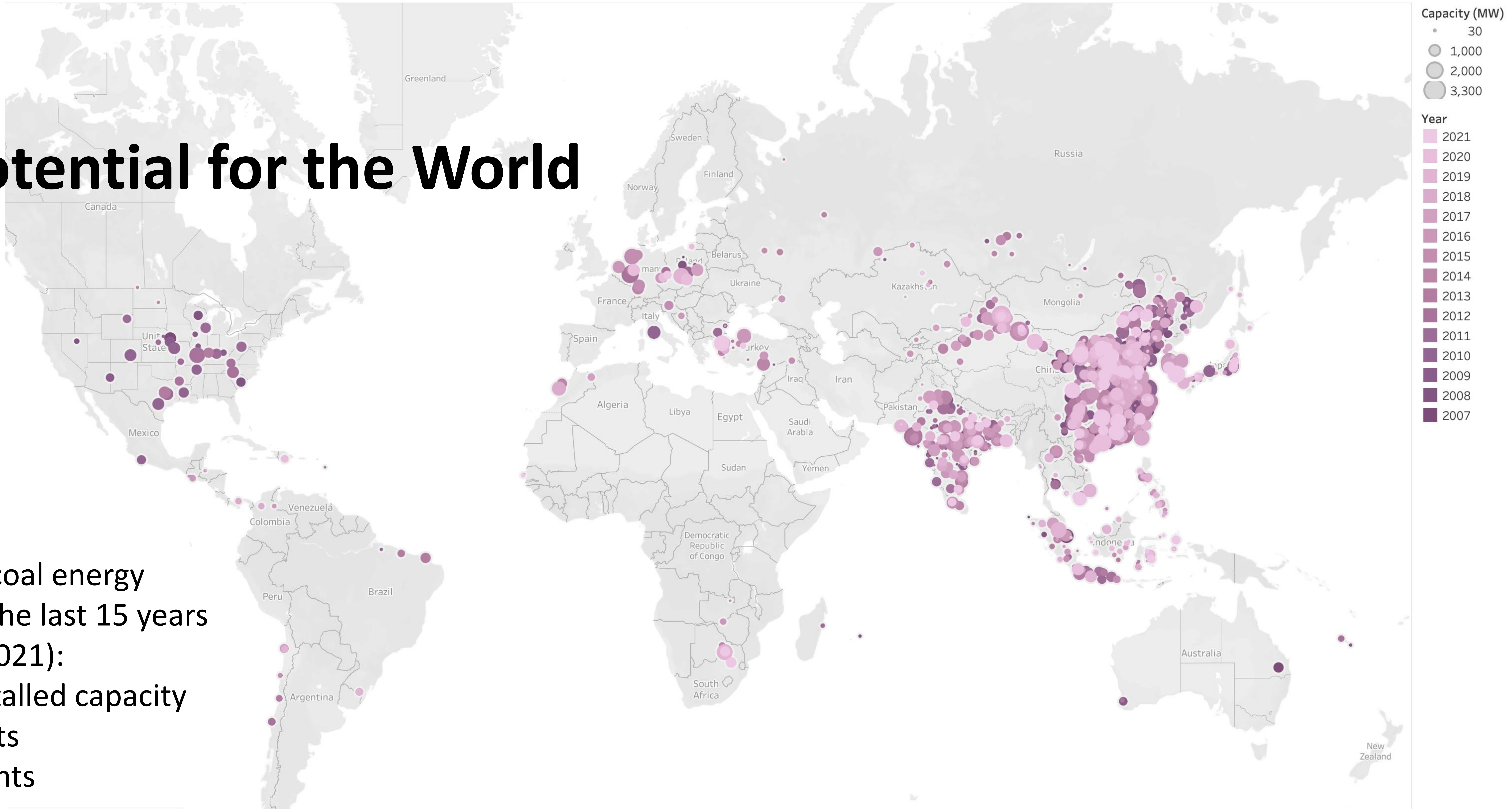


Fig. Locations indicated in the Polish Nuclear Power Programme and analyzed in the DEsire project

Potential for the World



Investments in coal energy
in the world in the last 15 years
(from 2007 to 2021):
1350 GW of installed capacity
3400 power units
1300 power plants

Nuclear Ready status

NR

1. **Assessment** of the feasibility of conversion in accordance with the **Coal-to-Nuclear** pathway.
2. Determining the **coal-to-nuclear-readiness level (CtNRL)** can indicate the adequateness of the discussed option.
3. Entities responsible for the coal energy sources in question should make efforts to assess the CtNRL (different classes) and to obtain **Nuclear-Ready** status if it is possible.
4. **Planned coal units**, should be designed and build as **Nuclear-Ready** units, i.e., meeting all formal and technical requirements for the use of nuclear reactors in the future (most preferable using direct or indirect conversion pathway).

concept proposed by the Bartela-Gladysz-Haneklaus-Qvist team

Potential for the World

Investments in coal energy in the world in the last 15 years (from 2007 to 2021):
1350 GW of installed capacity
3400 power units
1300 power plants

Capacity (MW)
30
1,000
2,000
3,300

Potential for the World

Coal-to-Nuclear Readiness Level

NR

	Coal-to-*Nuclear-Readiness*		
	Class C	*Class B*	*Class A*
Coal Plant Specific Factors			
Rated Capacity	<100 MWth	100-250 MWth	>250 MWth
Relevant Equipment Age	>20 years	10-20 years	<10 years
Investment Type	Brownfield	Brownfield to Repowering	Repowering to Retrofit
Potential Cost Savings	<15%	15-25%	>25%
↓	...	...	...
Site Specific Factors			
Heat Sink Availability	Low	Medium	High
Population Density	High	Medium	Low
Seismic Activity	High	Medium	Low
↓	...	...	...

Exemplary coal-to-nuclear readiness evaluation sheet of a plant in three classes

Investments in coal energy in the world in the last 15 years (from 2007 to 2021):

1350 GW of installed capacity
3400 power units
1300 power plants

concept proposed by the Bartela-Gladysz-Haneklaus-Qvist team

DEsire Team:

Silesian University of Technology

Ministerstwo Klimatu i Środowiska

THANK YOU!

website:

https://projektdesire.pl/en

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Silesian University of Technology

RESEARCH UNIVERSITY EXCELLENCE INITIATIVE

The presentation was created as a result of the project: "Plan of decarbonisation of the domestic power industry through modernization with the use of nuclear reactors", financed by the National Center for Research and Development under the Program "Social and economic development of Poland in conditions of globalizing markets" GOSPOSTRATEG (Contract No.: Gospostrateg VI/0032/2021-00 dated 15.03.2022).

DEsire

Selected publications

- Qvist, S.; Gładysz, P.; Bartela, Ł.; Sowiżdżał, A. Retrofit Decarbonization of Coal Power Plants—A Case Study for Poland. *Energies* **2021**, *14*, 120. https://doi.org/10.3390/en14010120
- Bartela, Ł.; Gładysz, P.; Andreades, C.; Qvist, S.; Zdeb, J. Techno-Economic Assessment of Coal-Fired Power Unit Decarbonization Retrofit with KP-FHR Small Modular Reactors. *Energies* **2021**, *14*, 2557. https://doi.org/10.3390/en14092557
- Bartela, Ł.; Gładysz, P.; Ochmann, J.; Qvist, S.; Sancho, L.M. Repowering a Coal Power Unit with Small Modular Reactors and Thermal Energy Storage. *Energies* **2022**, *15*, 5830. https://doi.org/10.3390/en15165830
- Łukowicz, H.; Bartela, Ł.; Gładysz, P.; Qvist, S. Repowering a Coal Power Plant Steam Cycle Using Modular Light-Water Reactor Technology. *Energies* **2023**, *16*, 3083. https://doi.org/10.3390/en16073083

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Atoms for Peace and Development

Webinar # 2

The Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Webinar Series: Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Mr Yaoli ZHANG

- Associate Professor of College of Energy, Xiamen University (China)
- Areas of Research Interests: Coal-to-Nuclear, Nuclear Safety, supercritical carbon dioxide Brayton cycle, small modular reactors
- Ph.D., Institute of Nuclear and New Energy Technology, Tsinghua University
- Member of Nuclear Energy Committee of China Energy Research Society

Repowering Coal Power in China by Nuclear Energy

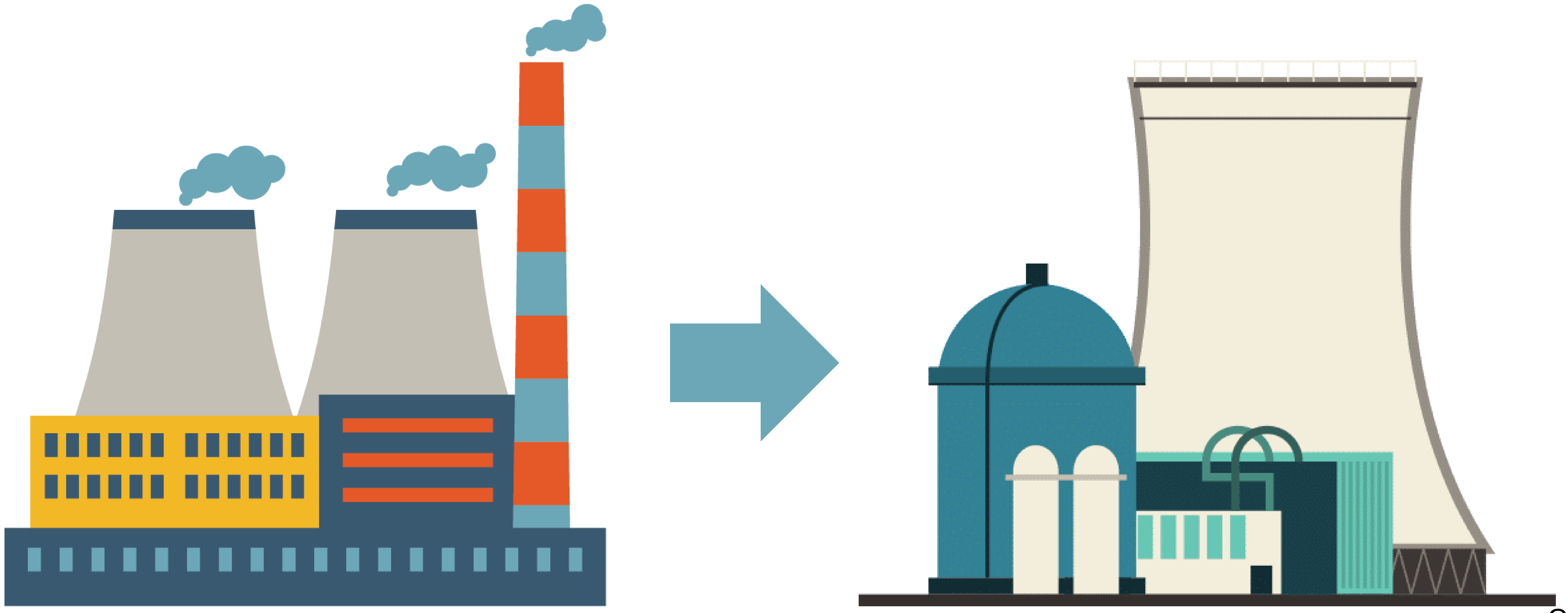
Dr. Yaoli ZHANG
Associate Professor
College of Energy, Xiamen University, China
zhangyl@xmu.edu.cn
5 April 2023

Introduction - Background

- The power consumption in China is based primarily on coal;
- Chinese government proposed “dual carbon goals”;
- However, there are some challenges in this process:
  - Ensure the reliable operation of the power system;
  - Consider the impact on the environment, health, etc.;
  - New technologies on the old power system.

Introduction - Concept

- Current decarbonization proposals:
  - Decommission coal-fired plants;
  - Implementing carbon capture systems.
- Repower of coal power units with nuclear energy – a third option.



Introduction - Scope of our work

- The scale of potential coal-fired power plants for repowering;
- The technical feasibility and constraints for repowering;
- The economic potential of repowering by nuclear power.

Methodology

- Develop a database describing the coal-fired units;
- Filter the database using the following criteria:
- Effective age of coal ≤ 15 years (in 2021);
- Thermal power of boiler: 250-2000 MW;
- Location: near river or the sea;
- Steam temperature ≤ 600 °C;
- A top-down method for economic analysis, G4-ECONS code was used to examine the cost of repowering;
- Energy Economic Data Base (EEDB) developed by DOE-NE was used.

Results – Location and size

China's power sector operates 1037 coal-fired power plants with a total installed capacity of 1131 GW.

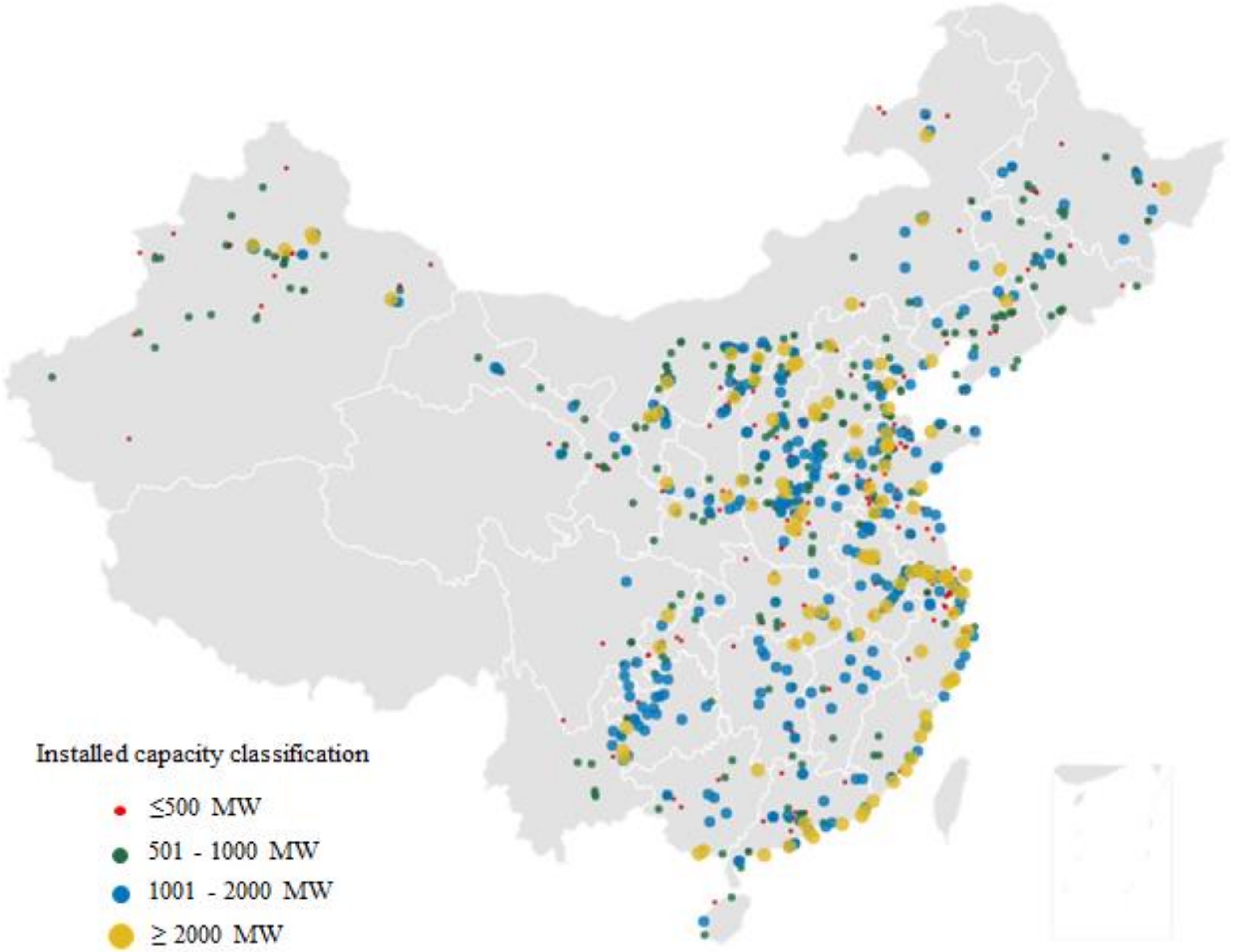


Fig. 1 Location and size of existing coal plants in China.

Table. 1 Threshold requirements for coal units inclusion in repowering analysis.

Parameter	Value	Motivation
Effective year	≤15 years	The main motivation for the repowering is to make full use of the remaining service life of existing equipment and avoid stranding of existing assets. Given the relatively young age of the Chinese coal power fleet, a value of 15 years is applied in the analysis.
Rated capacity	250–2000 MWth	The unit model selected for the retrofit project is HTR-PM, and the thermal power of a single unit is 250 MWth, so the transformation must meet the power requirements of the unit. Units with electric power less than 50 MWe are usually small-scale power stations or factory-owned power stations, which are difficult to repower.

- Total of 2264 coal units can be used for repowering;
- Total capacity of 906 GW;
- ≥ 80% of the coal-fired total capacity;
- About 80% were built after 2000.

Results – Three-step approach

Main reasons for three-step approach

1. There are no in-land nuclear power plants in China now;
2. Energy demand is greater in coastal areas.

1st step → 2nd step → 3rd step

Repower coal power plants located directly on the coast.

In coastal provinces which already have commercial nuclear power plants.

The repowering of coal power plants in inland provinces can be carried out.

In the first stage, there are 175 coal-fired power generating units with a total capacity of about 79 GW.

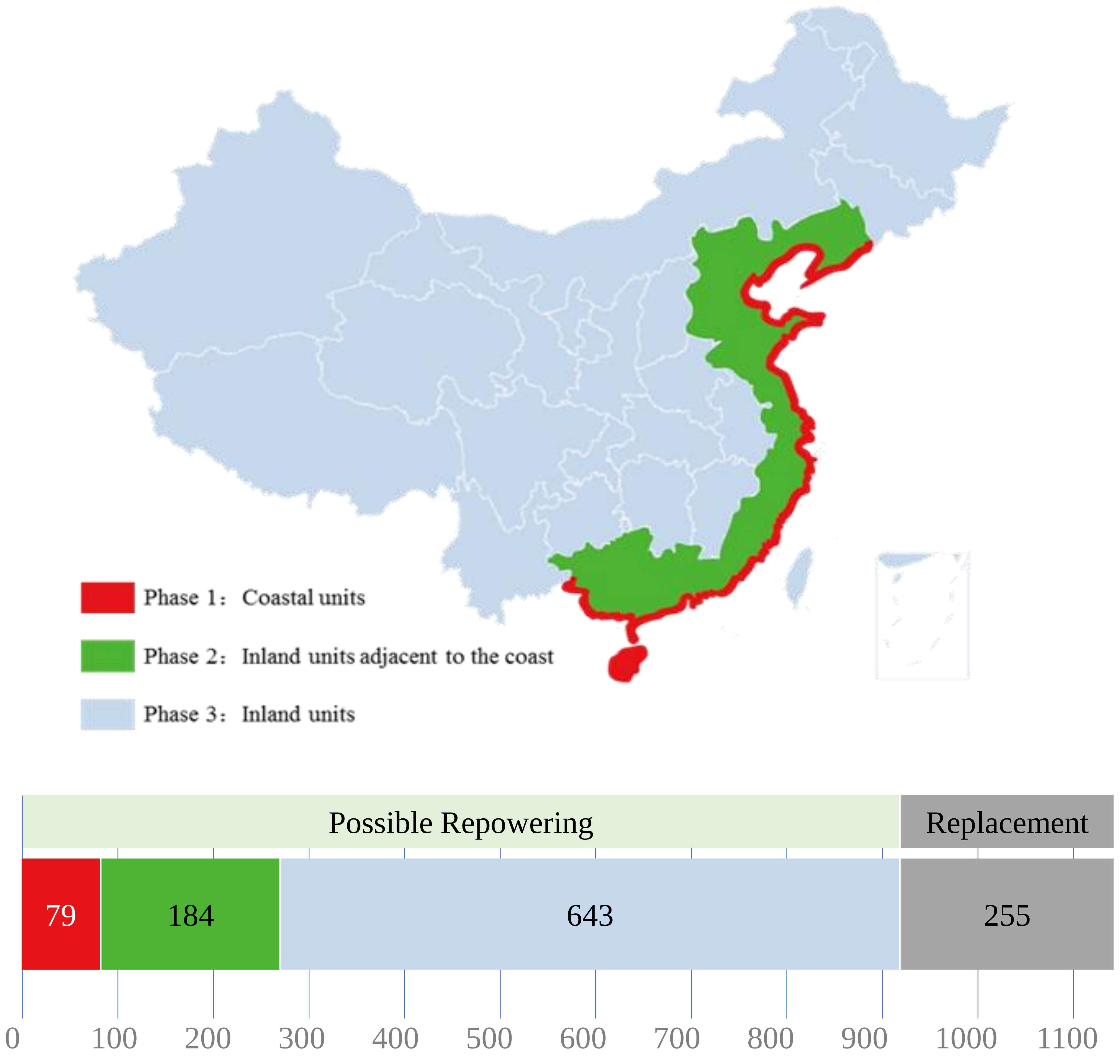


Fig. 2 Regional distribution of three-step approach

Results – Characteristics of coastal units

- 175 coal power units in coastal cities are subdivided into three categories according to the unit capacity.

Table 2. Categorization of coal power units.

Category	Description	Technical Details
1. Small units	Units with an individual electric capacity of less than 200 MW. Most individual unit capacity: 150 MW.	Capacity: 6,145 MW Number of units: 10 Subcritical steam cycles Live steam temperature: 535–549 °C
2. Medium units	In the 300–350 MW range. Individual unit capacity: 300 MW, 330 MW, 350 MW.	Capacity: 27,900 MW Number of units: 86 69% of units: subcritical steam cycles 31% of units: supercritical steam cycles Live steam temperature: 535–579 °C
3. Large units	Large units are defined as having a capacity larger than 600 MW. Individual unit capacity: 600 MW, 660 MW.	Capacity: 49,590 MW Number of units: 79 11% of units: Subcritical steam cycles 51% of units: supercritical steam cycles 38% of units: ultra-supercritical steam cycles Live steam temperature: 540–600 °C

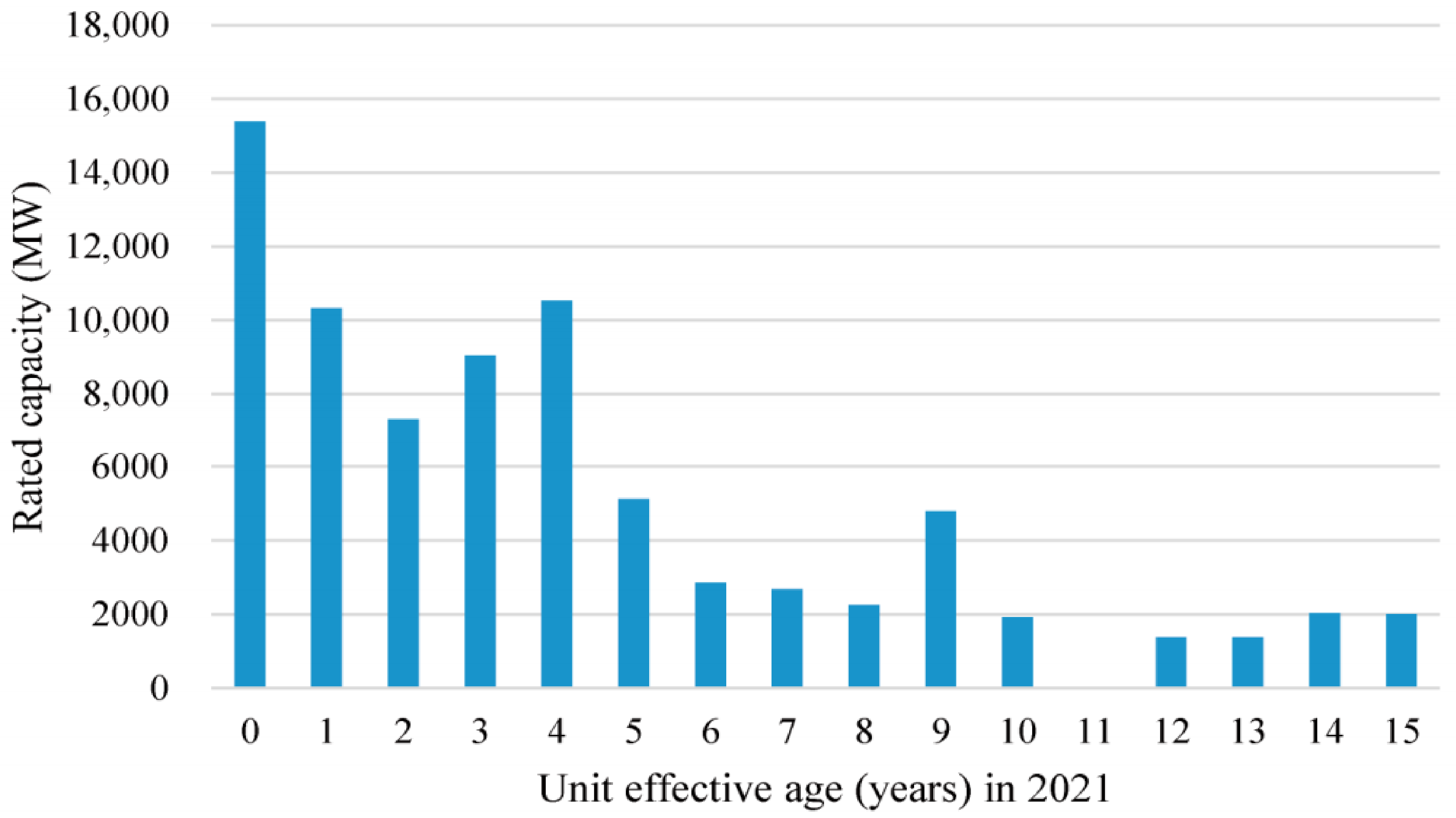


Fig. 3 Capacity age-distribution of first-stage coal units.

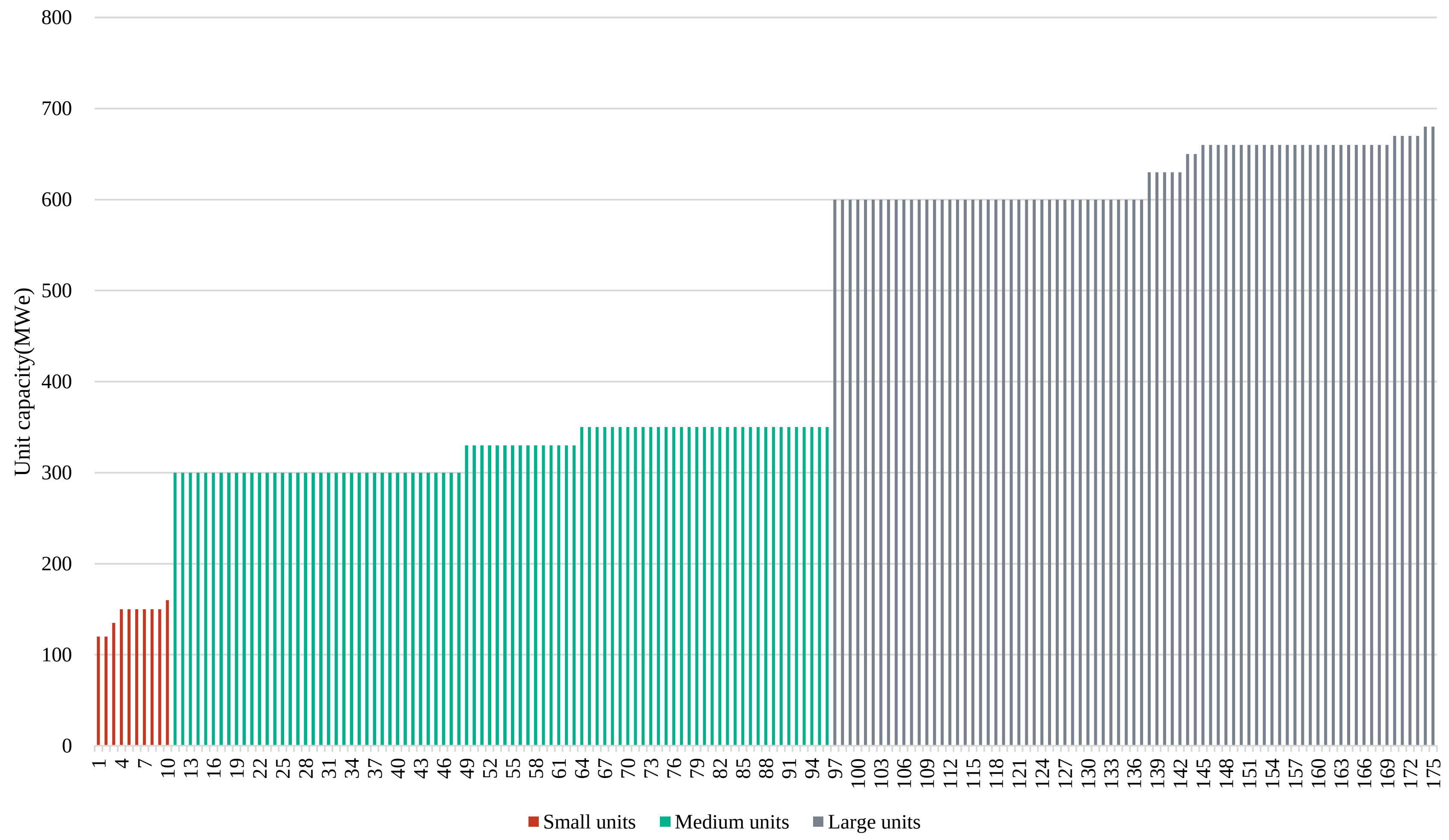


Fig. 4 Classification of coal power generating units in coastal cities.

Results – Steam temperature and usage

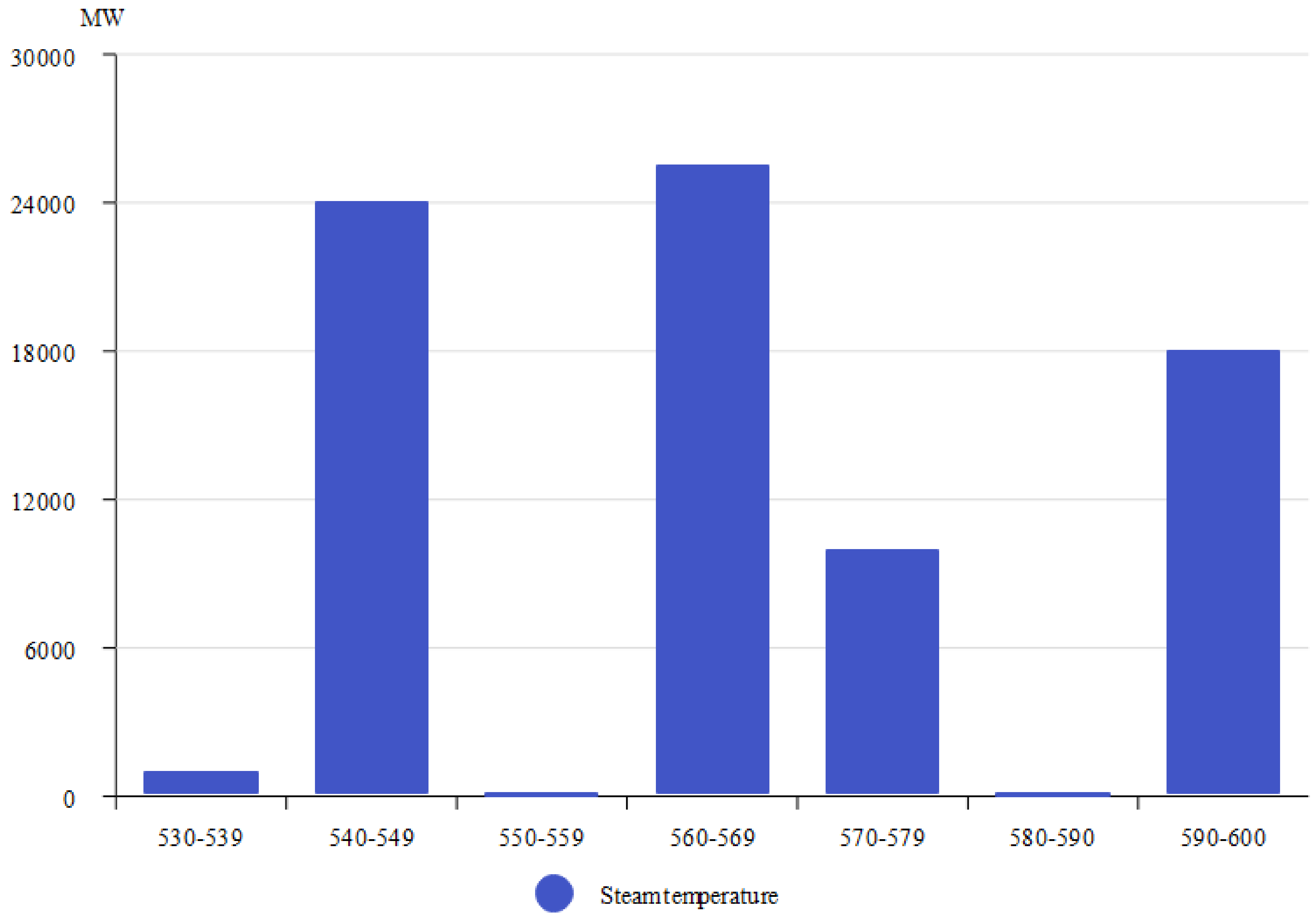


Fig. 5 Maximum steam temperature of modern large China coal units.

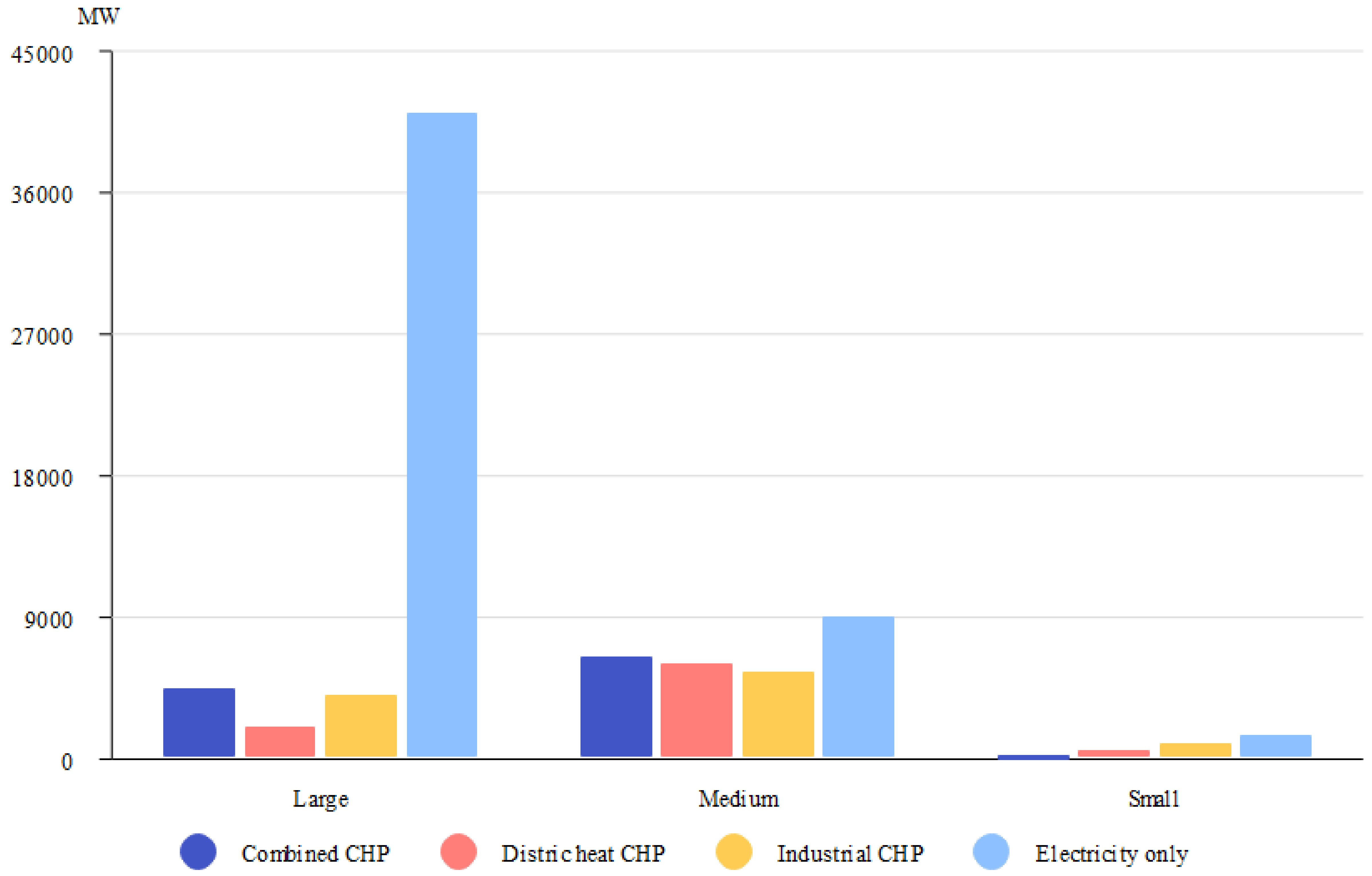


Fig. 6 Unit usage under different categories.

- Only 7 units with a total capacity less than 2000MW operate at steam temperature less than 539 °C (535 and 538 °C).

- Most large units provide only electricity;
- Medium units have diverse uses;
- Most small units are electricity-only or industrial CHP.

*Combined CHP: provides both district and industrial heat.

Results – Potential nuclear technology

Table 3. Advanced reactors under development in China.

Acronym	Design Org.	Coolant	Steam Temp (°C)	Type	Status
HTR-PM	Tsinghua University	Helium	540–600	GCR	In operation
CRF-600	CIAE	Sodium	500–550	SFR	In construction
CLEAR-I	INEST	Lead Bismuth Eutectic	480–570	LFR	Experimental
CSR1000	NPIC	Light Water	510–625	SCWR	Experimental
TMSR	SINAP	$LiF\text{-}BeF_2$	672–700	MSR	Experimental

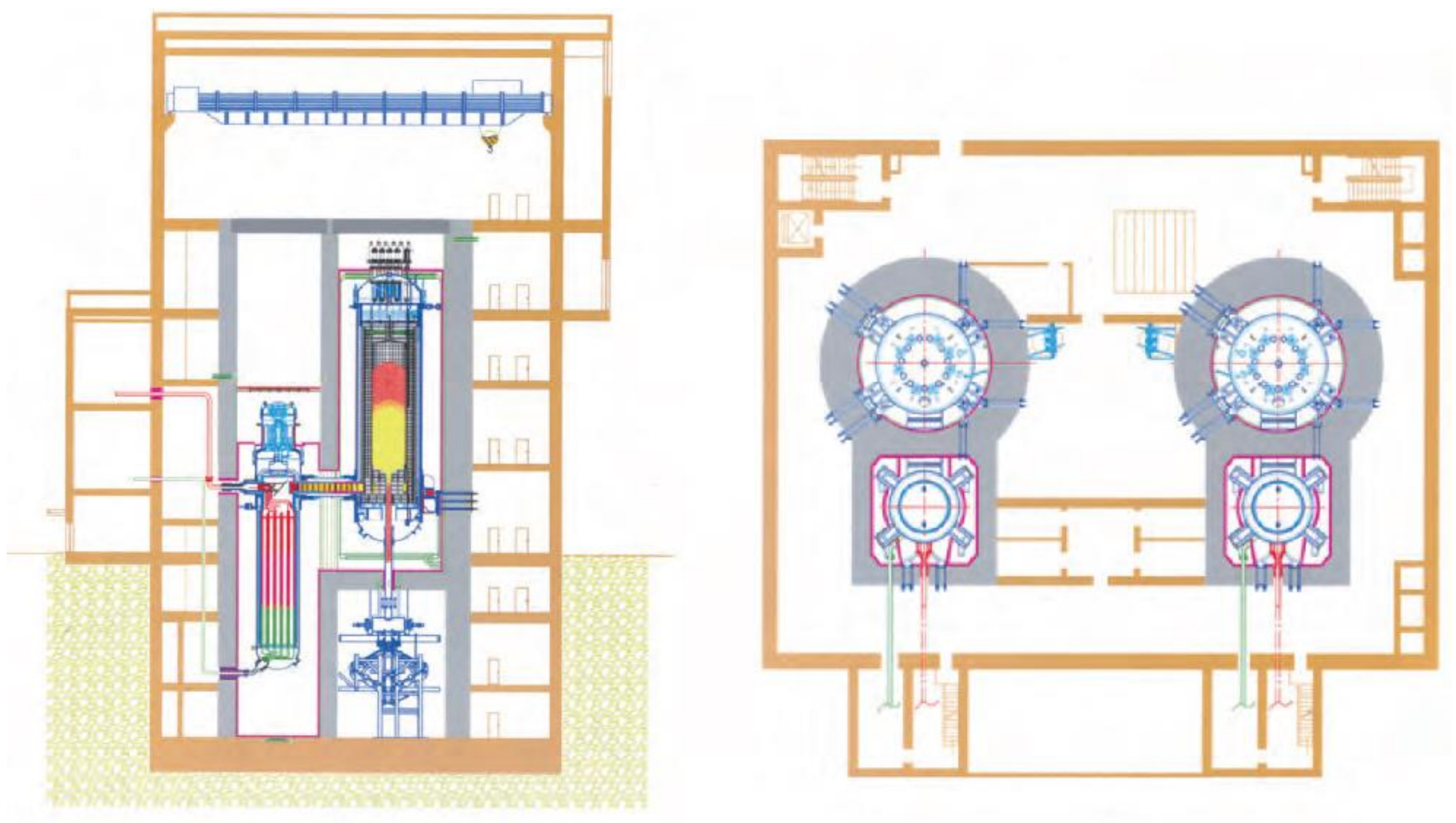


Fig. 7 A 200-MWe HTR-PM nuclear power plant.

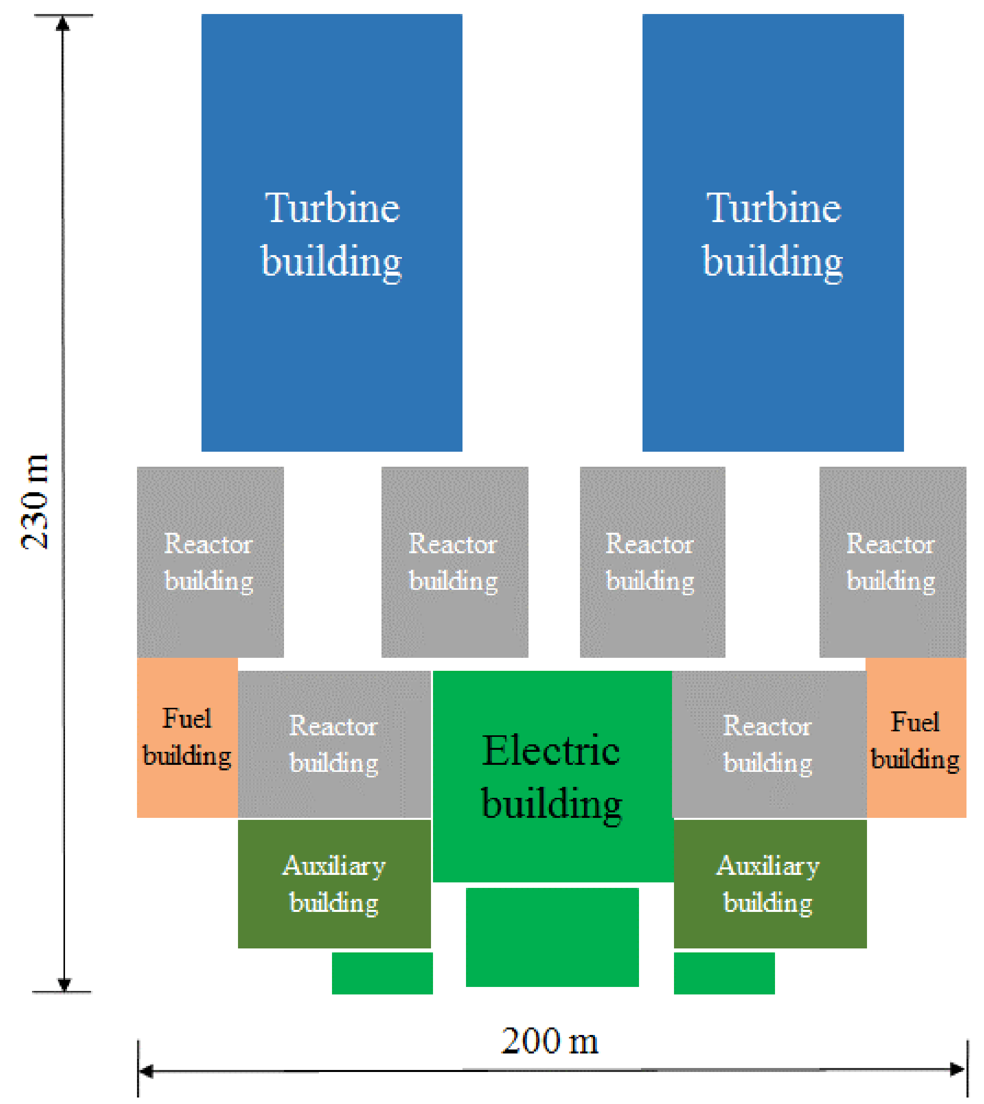


Fig. 8 A 2×600-MWe HTR-PM multi-modules plant.

- The key problem is to find a suitable type of reactor.
- A 200-MWe HTR-PM nuclear power plant has been built in Shandong Province, and now is in operation.
- The steam temperature of HTR-PM matches the coal-fired units well.
- Combining N into 1 concept of HTR-PM.

Results – Footprint of repowering

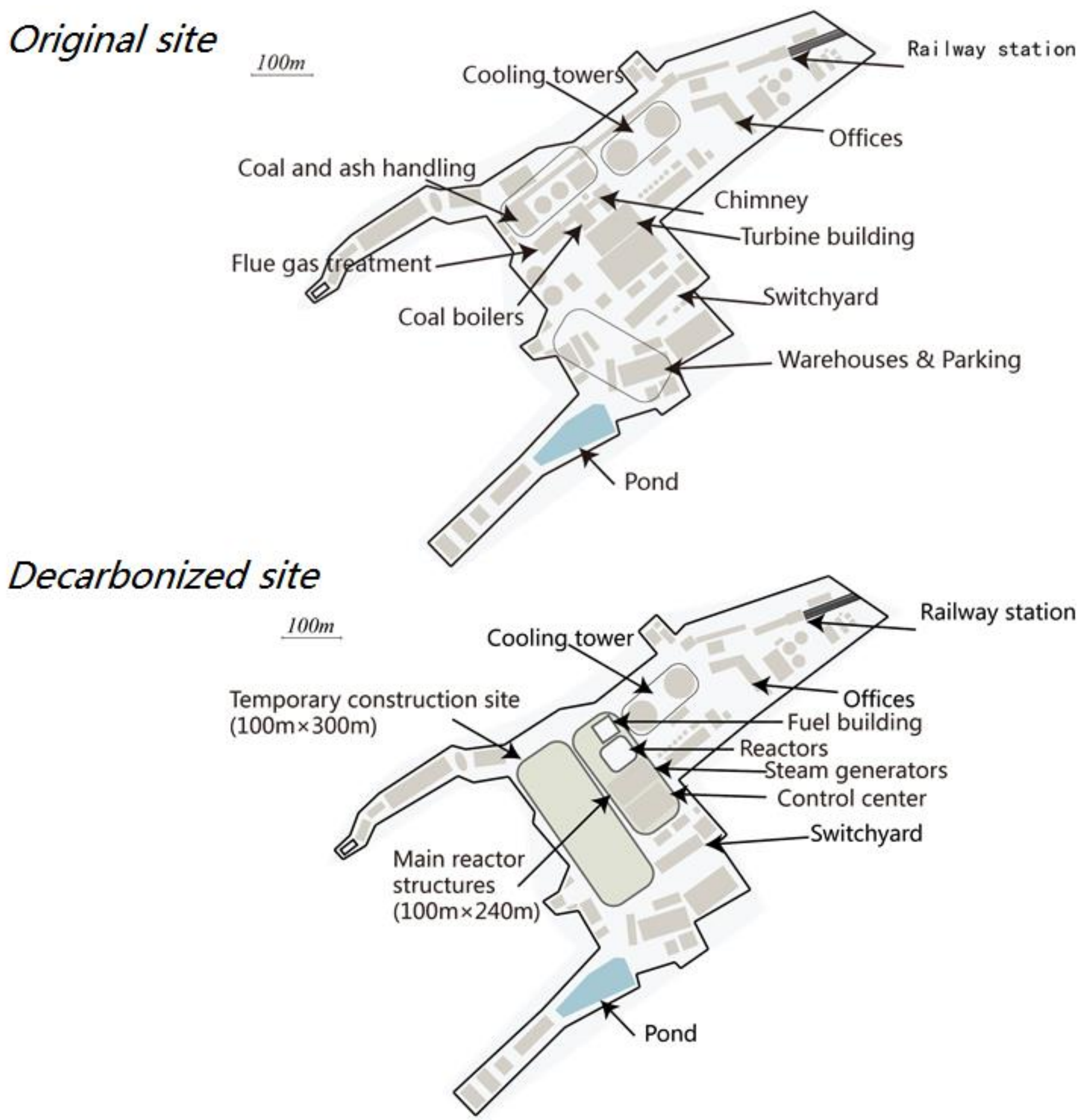


Fig. 9 Repowering a small coal-fired power plant with 200 MWe HTR-PM modules.

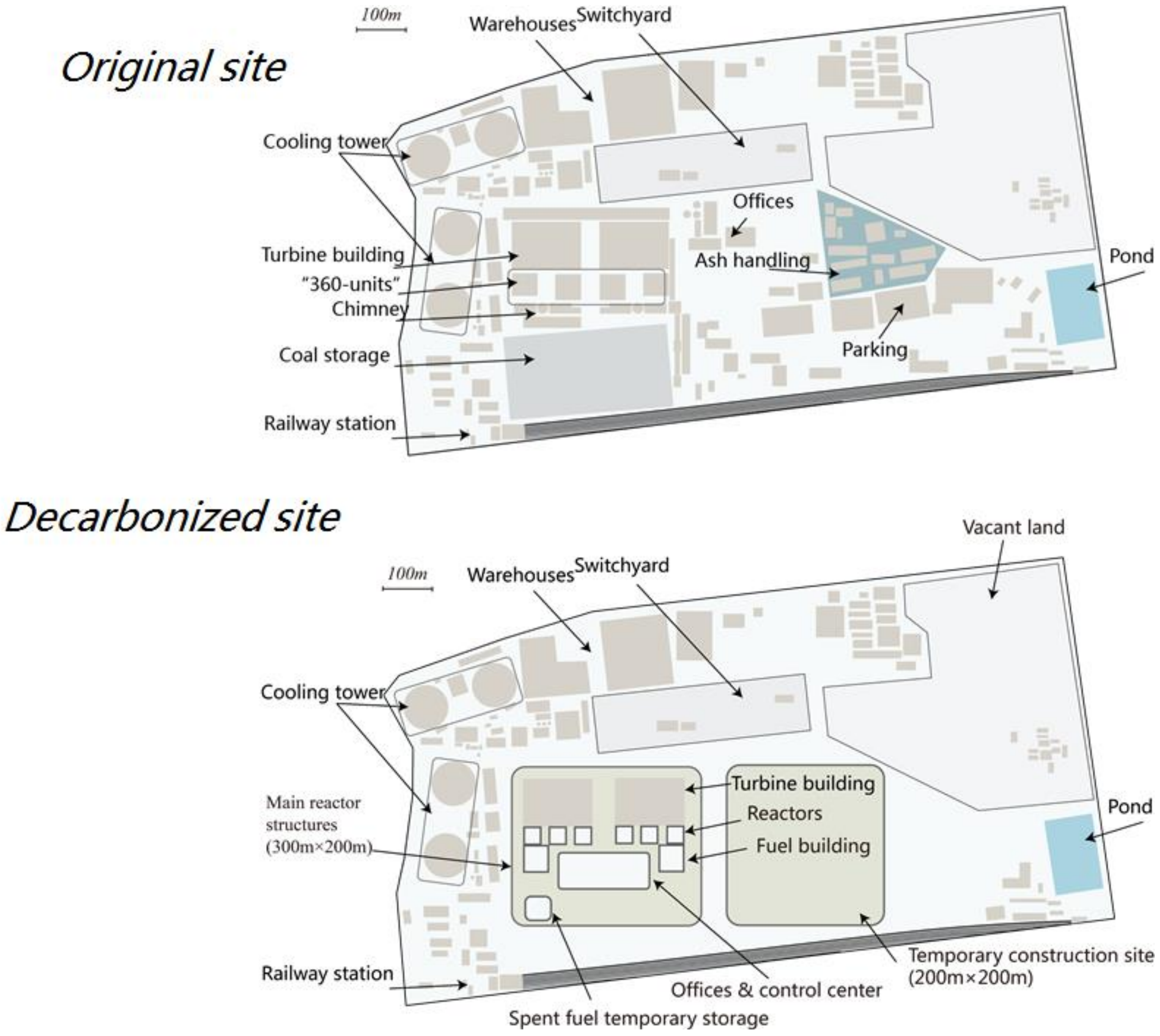


Fig. 10 Repowering a medium coal-fired power plant with 2×600 MWe HTR-PM modules.

Results – Footprint of repowering

Original site

Decarbonized site

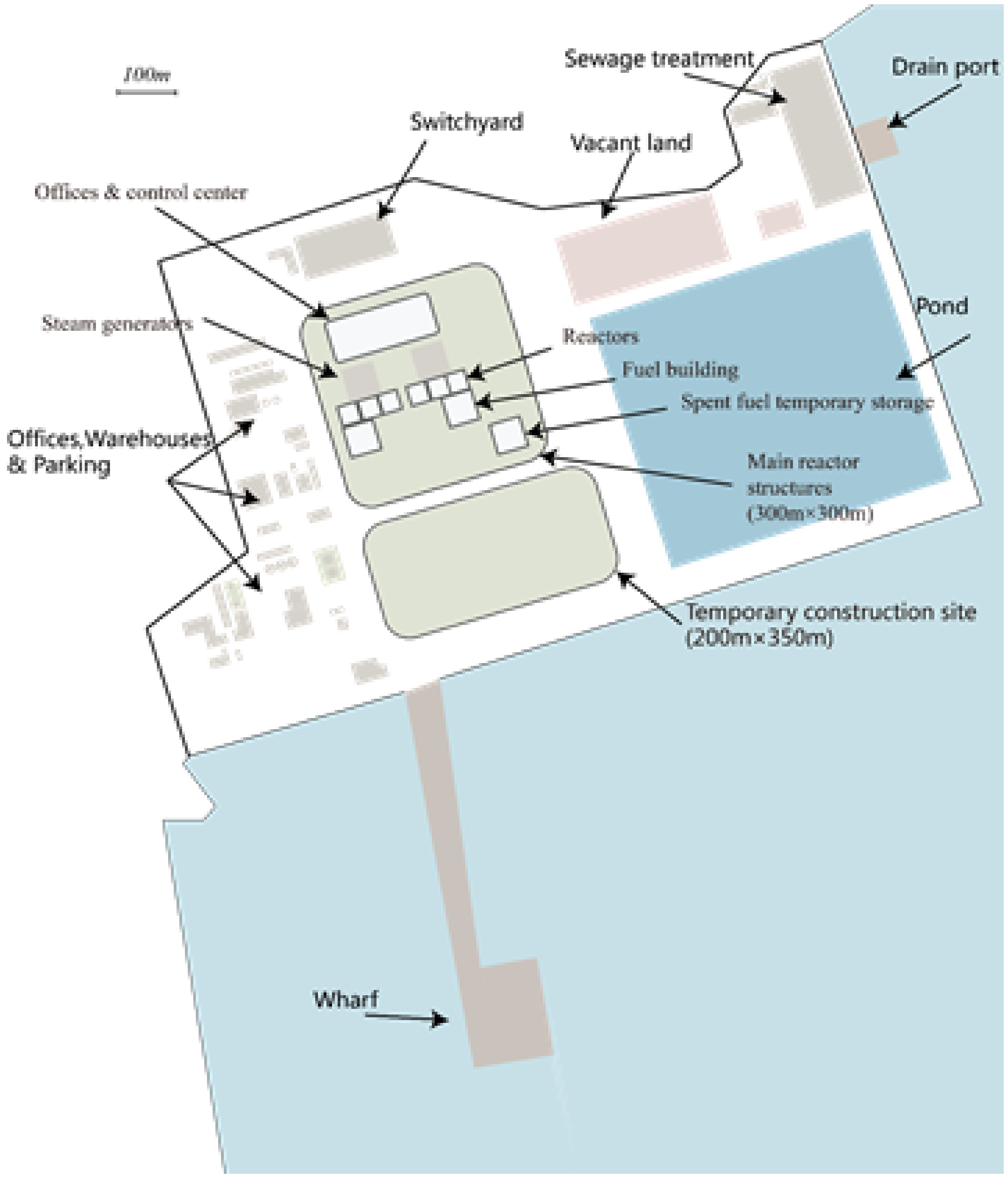


Fig. 11 Repowering a large coal-fired power plant with 2×600 MWe HTR-PM modules.

- The boiler and other areas were demolished and rebuilt into temporary construction areas on the original site.
- Using "combing N to 1" concept, HTR-PM can be used to repower coal power plants with different capacities.

Results – Potential saving

Reactor building—account 212 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	HTR adjustment	HTR cost
Excavating work	0	0	0	0		0
Substructure concrete/access ramp	0	6,384,763	6,082,548	12,467,311	→	12,467,311
Containment shell	0	14,861,294	8,343,960	23,205,254		
Containment dome	0	6,011,210	3,478,651	9,489,862		
Interior concrete	3,618,000	24,960,209	10,074,175	38,652,384		
Removable plugs	0	437,772	178,229	616,001		
Structural and miscellaneous steel	0	1,744,442	2,948,546	4,692,989		
Containment liner	28,944,000	19,404,000	970,200	49,318,200		
Painting	0	6,622,387	1,883,112	8,505,499		

Turbine-generator building—account 213 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	HTR adjustment	HTR cost
Excavation work	0	0	0	0		
Substructure concrete	0	8,238,324	4,293,048	12,531,372	→	0
Superstructure	0	14,237,318	21,666,715	35,904,034		
Plumbing and drains	28,481	2,362,495	678,218	3,069,194		
Heating, ventilation, air conditioning	1,251,715	1,043,398	204,017	2,499,130		
Fire protection	0	0	0			
Lighting and service power	0	874,188	412,219	1,286,407		
Elevator	211,200	58,414	5,842	275,455		
Account 213 total cost	**1,491,396**	**26,814,137**	**27,260,059**	**55,565,592**		

- Energy Economic Data Base (EEDB) developed by DOE-NE was used.
- Break-down and estimate the cost;
- Repowering the coal-fired plants can save about 20%.

Table. 4 Potential overnight cost saving

Cost	Percent	Potential saving
Design and engineering	5%	20-30%
Project management	7%	0
Nuclear island	28%	0
Conventional island	15%	80-95%
BOP	18%	20-40%
Land	20%	20-30%
Shipping	2%	0
First load fuel	5%	0
Overall	100%	20-28%

Results – Cost analysis

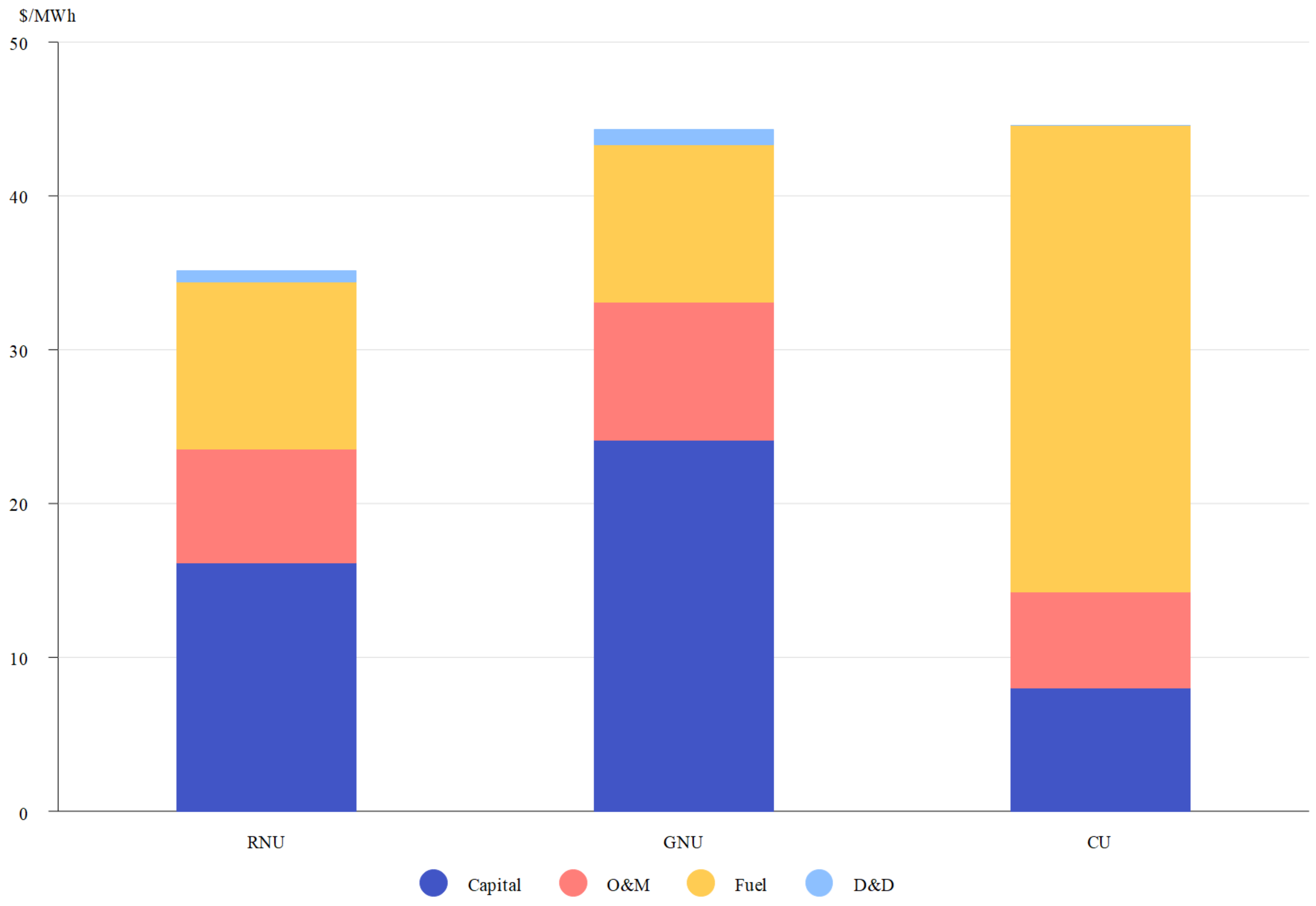


Fig. 12 LCOE of Repowering Nuclear Unit, Greenfield Nuclear Unit and Coal Unit

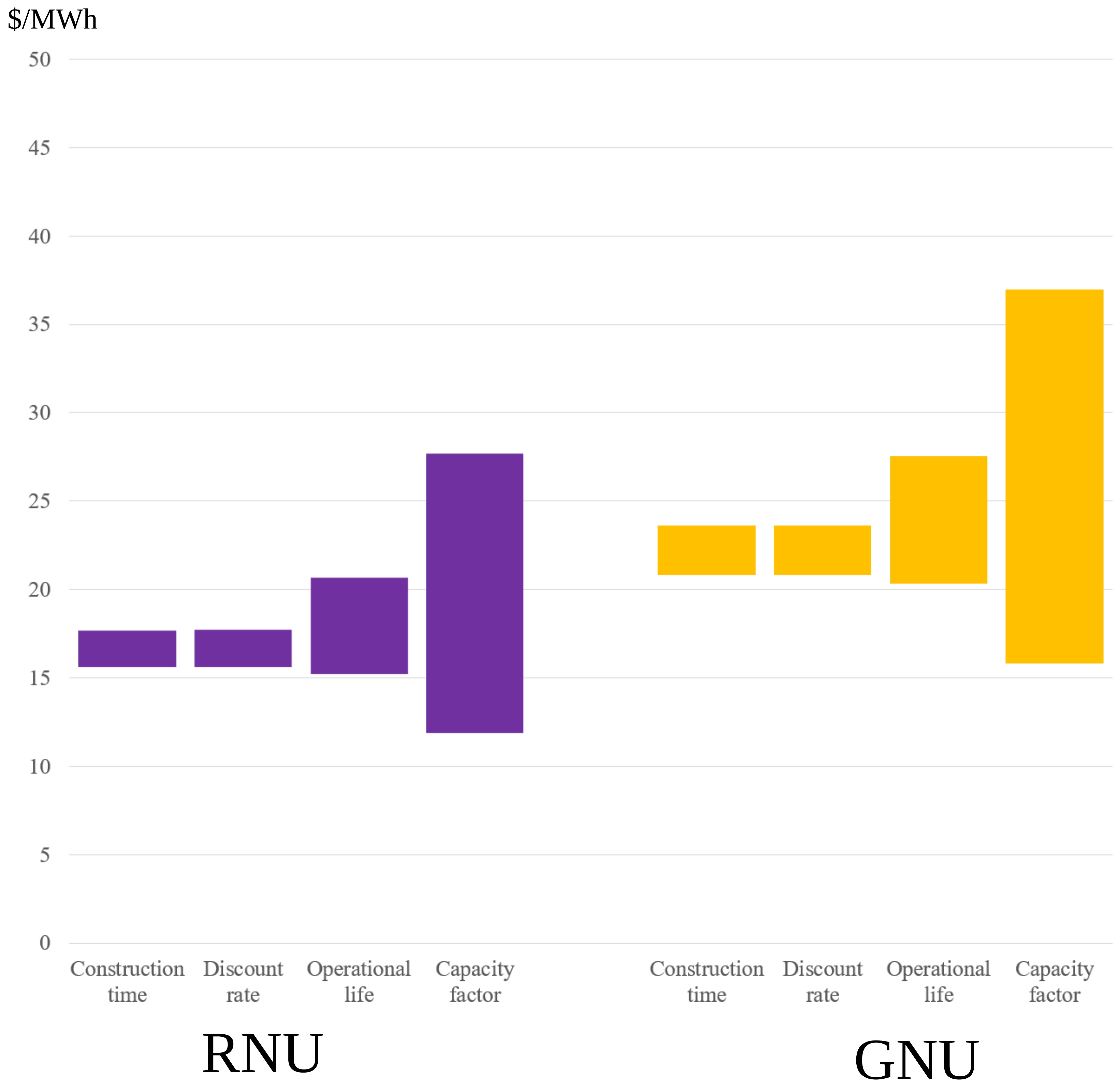


Fig. 13 Sensitivity analysis of capital cost

- The cost of GNU and CU are the same under the assumption that the coal units have a penalty of $50/t$CO_2$;
- RNU saves roughly 20% of the cost compared to GNU.

- The capacity factor is most influential to capital cost;
- Operational life also has an obvious impact.

Conclusions

- We suggest a three-step approach that replaces existing coal power plant boilers with high-temperature nuclear heat;
- In the 1st step, about 80 GW can be repowered;
- HTR-PM is the most suitable type of reactor to repower coal fired power plants now;
- The cost of a greenfield nuclear power plant can be reduced by about 20% .

Discussions

- There are other challenges:
  - The licensing issue;
  - General acceptance from local communities;
  - Specific site requirements.

On-going work

- The 1st step is now happening in China:
  - China Power Engineering Consulting Group Co., LTD. starts investigating the repowering work;
  - East China Electric Power Design Institute is doing the specific work;
  - The first objective is a retiring coal fired power plant by the coast in Zhejiang.

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Thank you!

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The Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

Webinar Series: Introducing Repurposing Strategies for Retired Fossil-Fired Power Plants with Nuclear Power Plants

Webinar on the Economic Aspects of Repurposing Coal-Fired Power Plants with Nuclear Power Plants

IAEA

Q&A Session

Mr Henri Paillere
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Ms Kirsty Gogan
Founder and management partner of TerraPraxis
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Mr Lukasz Bartela
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China

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