Silesian University of Technology

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EXCELLENCE INITIATIVE
Ministry of Science and Higher Education

Coal-to-Nuclear energy transition pathway for Poland

Łukasz Bartela
Paweł Gładysz
Henryk Łukowicz

Seminar „Nuclear energy”
6. Priority Research Area Climate and environmental protection, modern energy Research sub-area POB6.12: Nuclear energy

DEsire Team:

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

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

PHASE B
Pre-implementation works

- EPK: Procedures for modernization and two feasiblity studies
- INSTYTUT SOBIESKIEGO: 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

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,*
- *it may be beneficial, for example, to transfer the rights to use water intakes, access to transmission lines and workforce.*

C2N#1 Brownfield

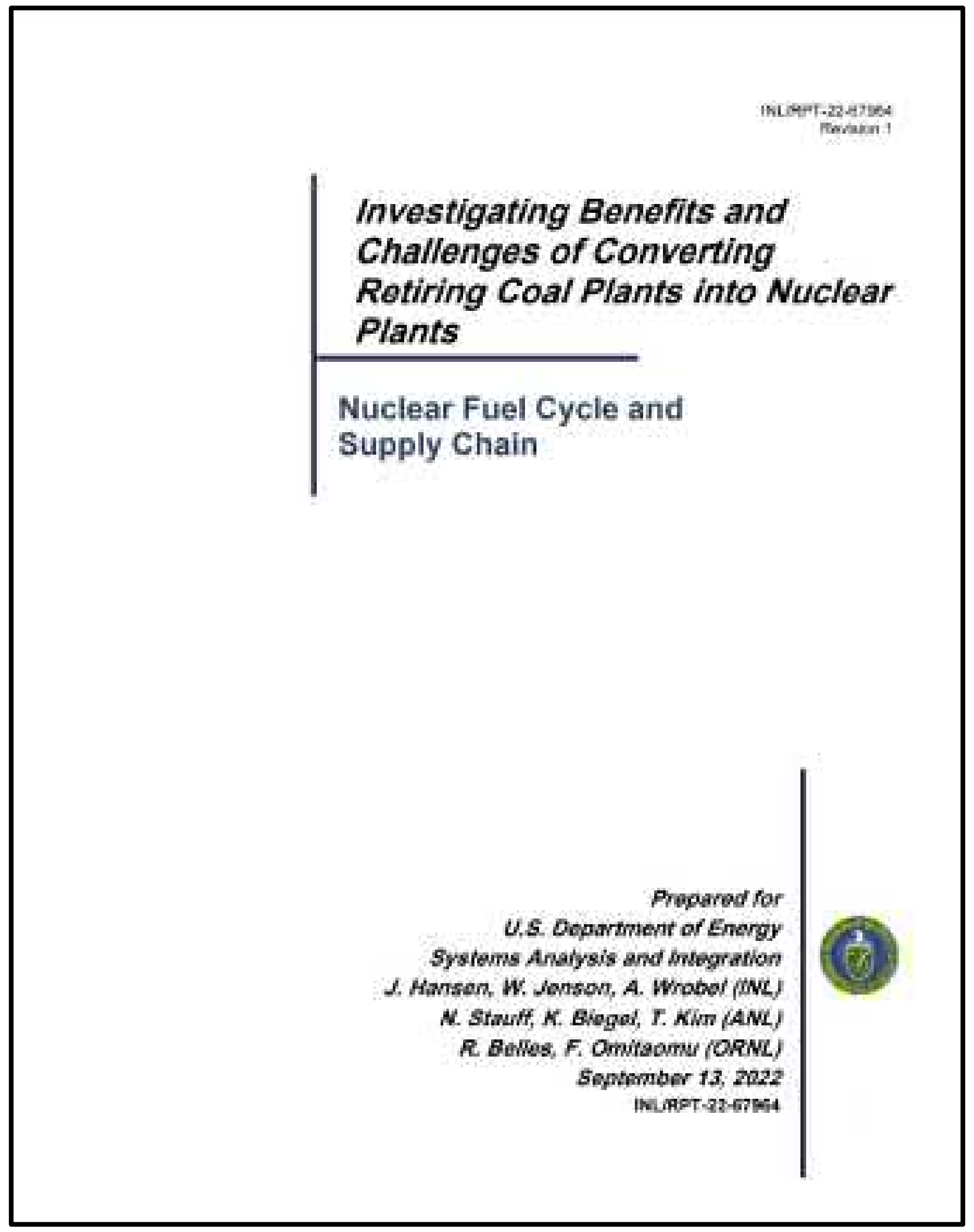
- *NPP is being built in place of the decommissioned CPP,*
- *space and support infrastructure are used,*
- *any type of nuclear reactor may be used.*

C2N#2 Direct

- *NPP is being built in place of the decommissioned CPP,*
- *space, support infrastructure and main infrastructure are used,*
- *direct coupling of the reactor island with the turbine island.*

C2N#3 Indirect

- *NPP is being built in place of the decommissioned CPP,*
- *space, support infrastructure and main infrastructure are used,*
- *direct coupling of the reactor island with the turbine island (steam generator + TES system)*


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
J. Hansen, W. Jenson, A. Wrobel (INL)
N. Stauff, K. Biegel, T. Kim (ANL)
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September 13, 2022
INL/RPT-22-67964

Repurposing | Full Repowering & Partial Repowering

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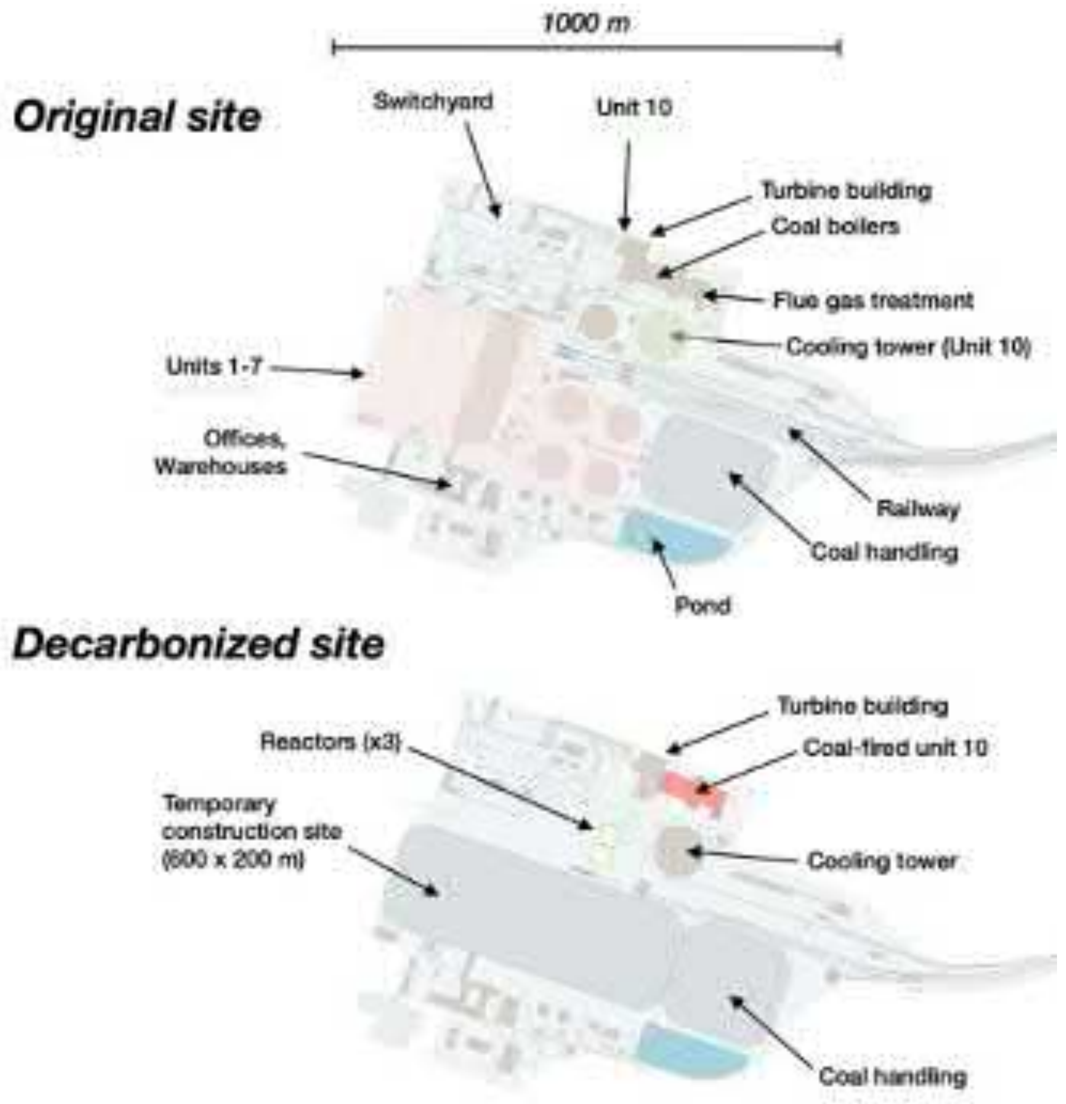

2019 – 2020

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

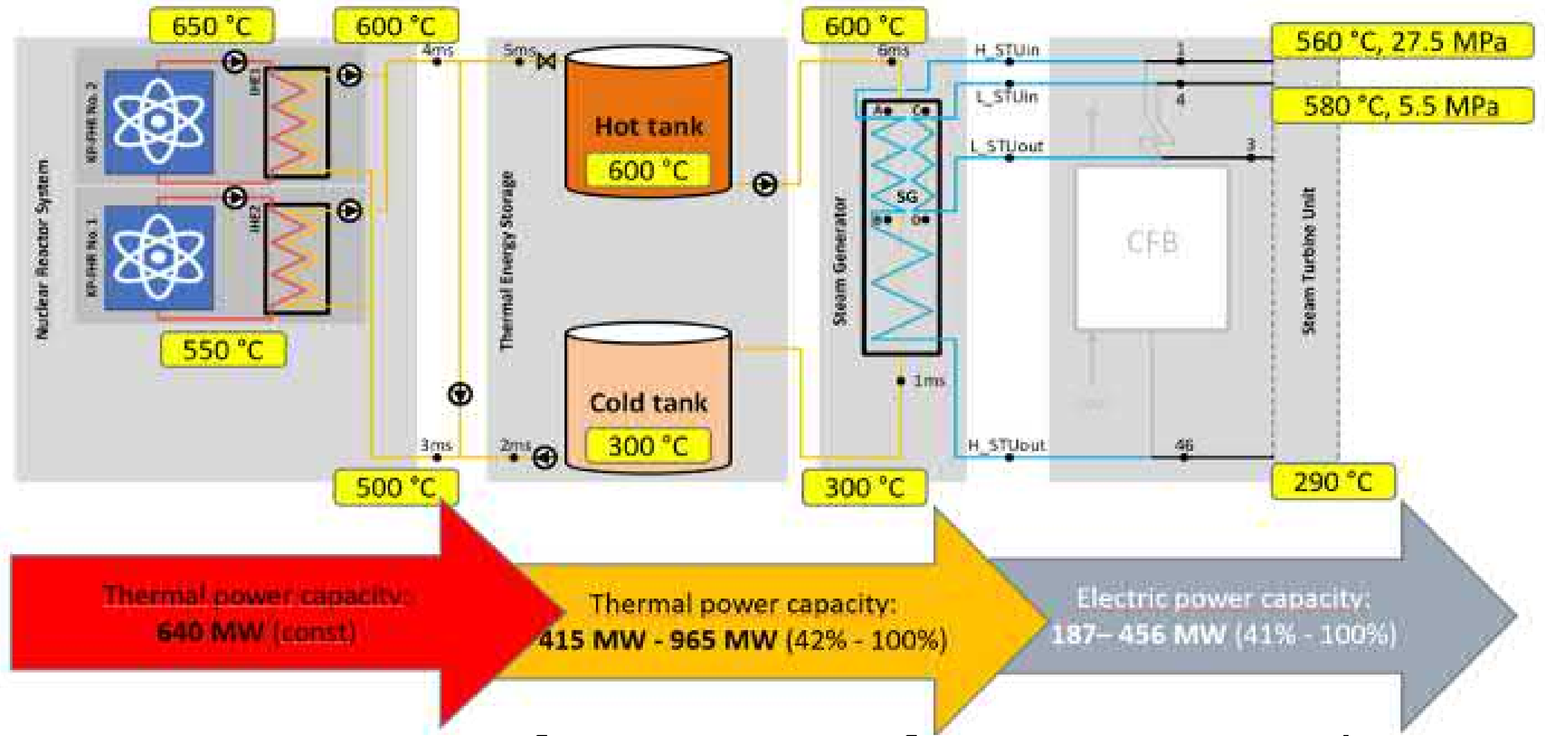

Fig. Diagram of integration of SMR system with TES at Łagisza unit

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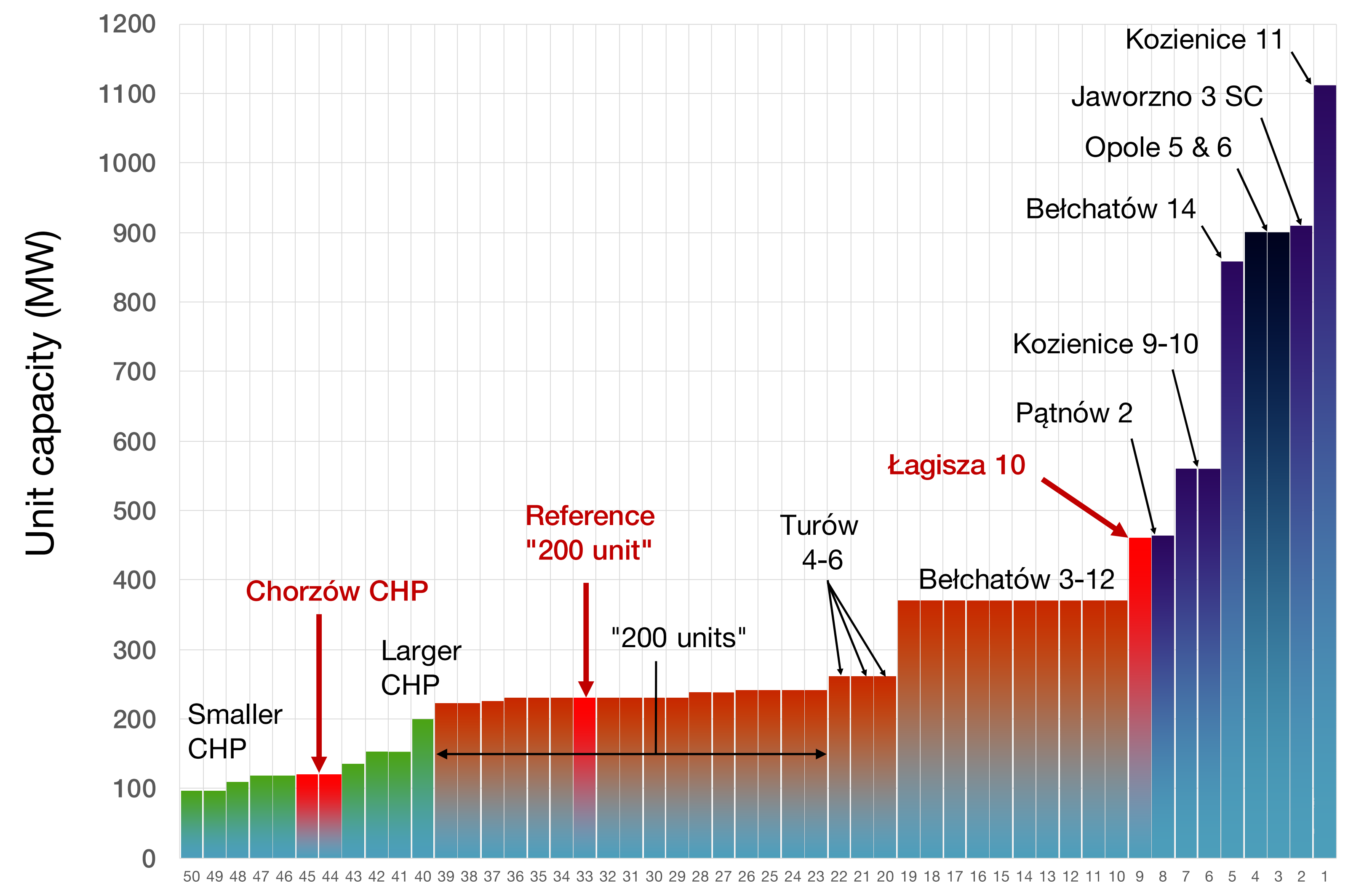

Fig. Unit-by-unit retrofit decarbonization recommendation

- **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

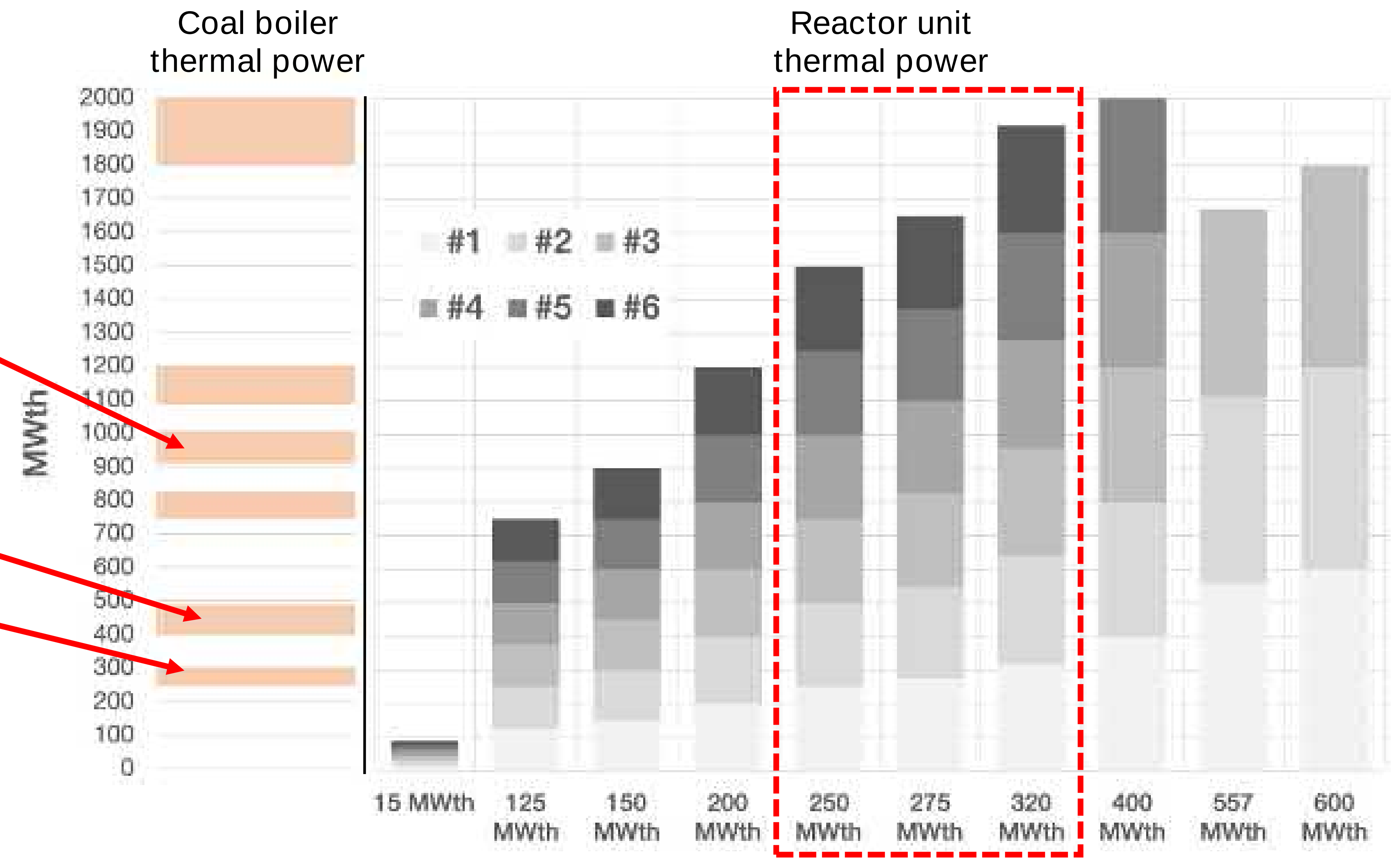

Fig. Matching the thermal power output of coal boilers with SMRs

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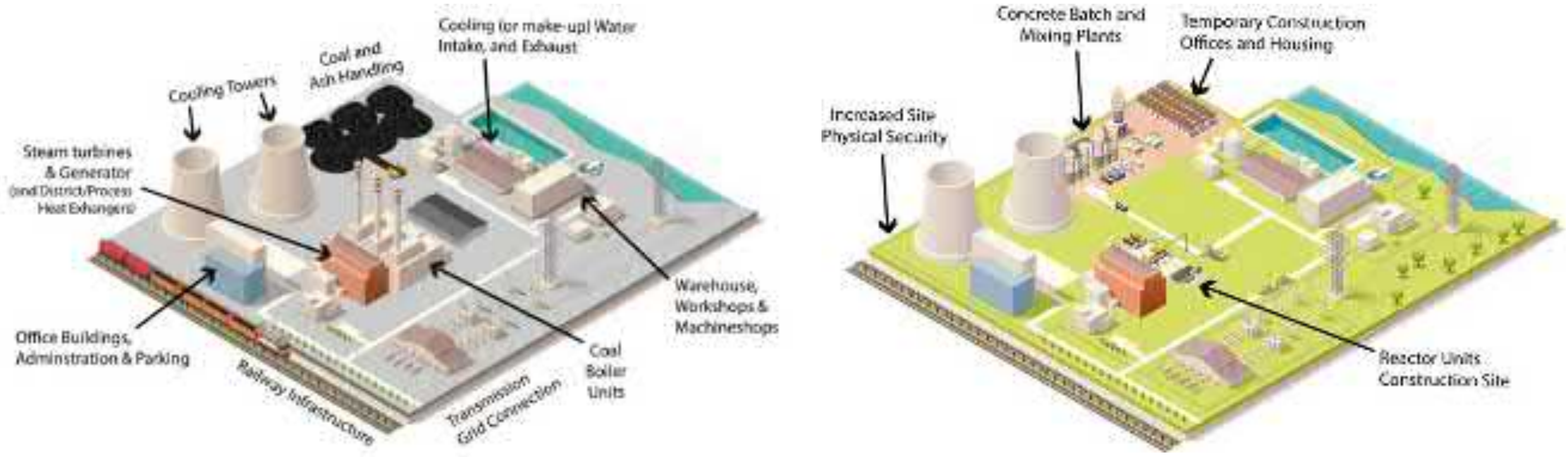

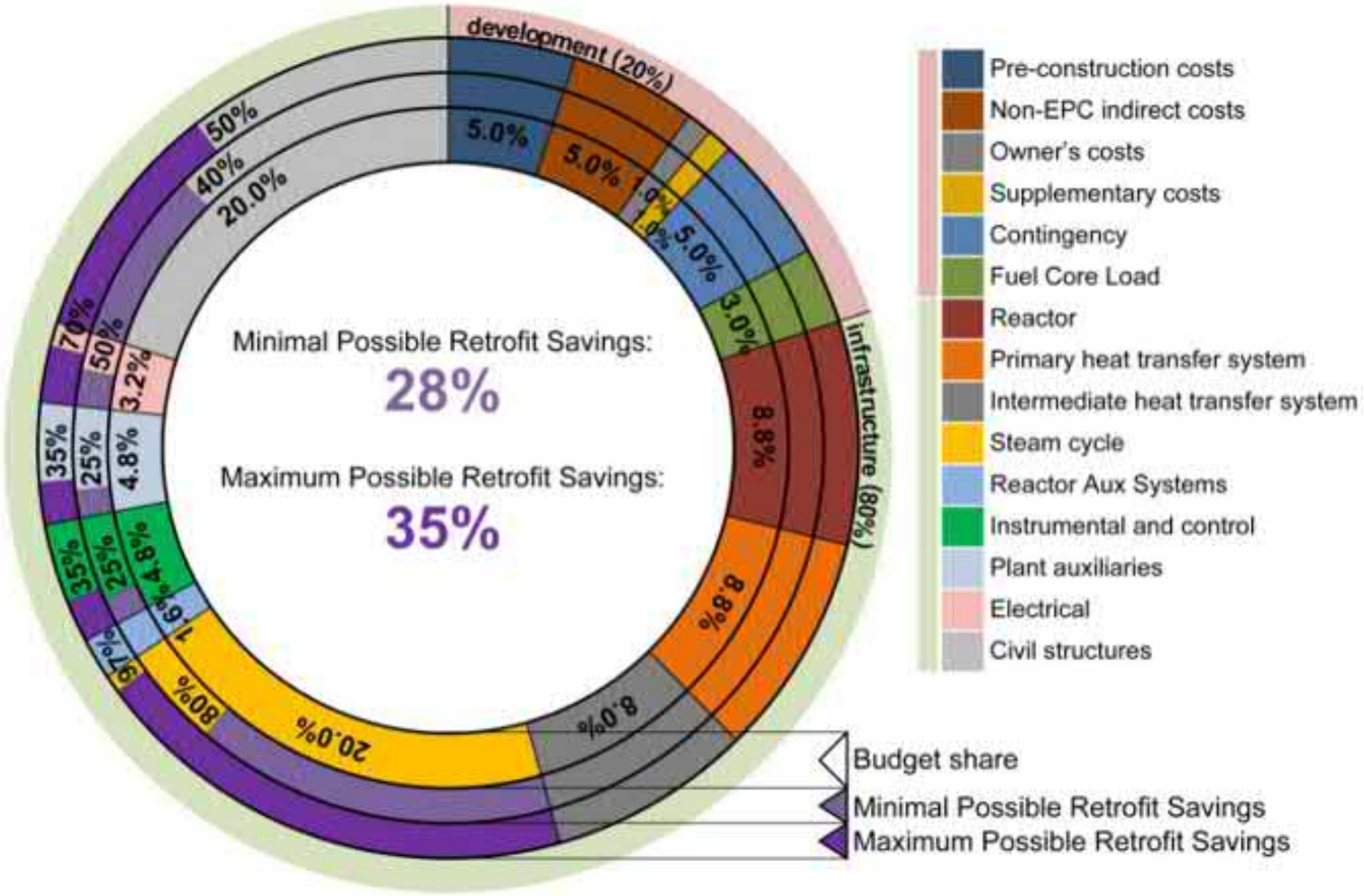

Fig. Possible investment savings due to the use of the existing infrastructure of the coal-fired power unit

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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$$\Delta NPV = \sum_{\tau=1}^{n} \frac{(NCF_{RET,\tau} - NCF_{REF,\tau})}{(1+r)^{\tau}} - TCIC_{RET}$$

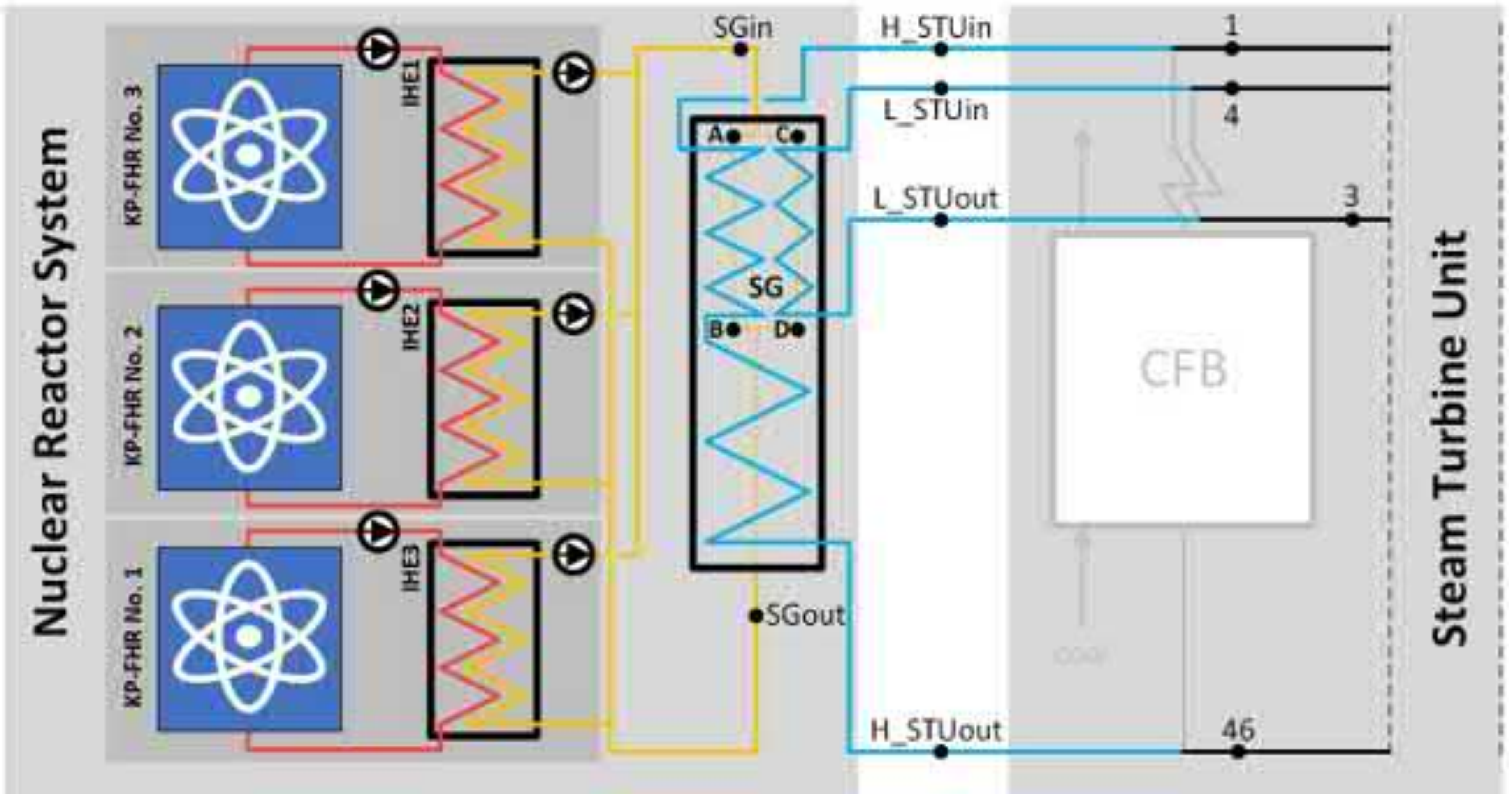

Fig. Diagram of integrations of SMR systems with a 460 MW Łagisza unit

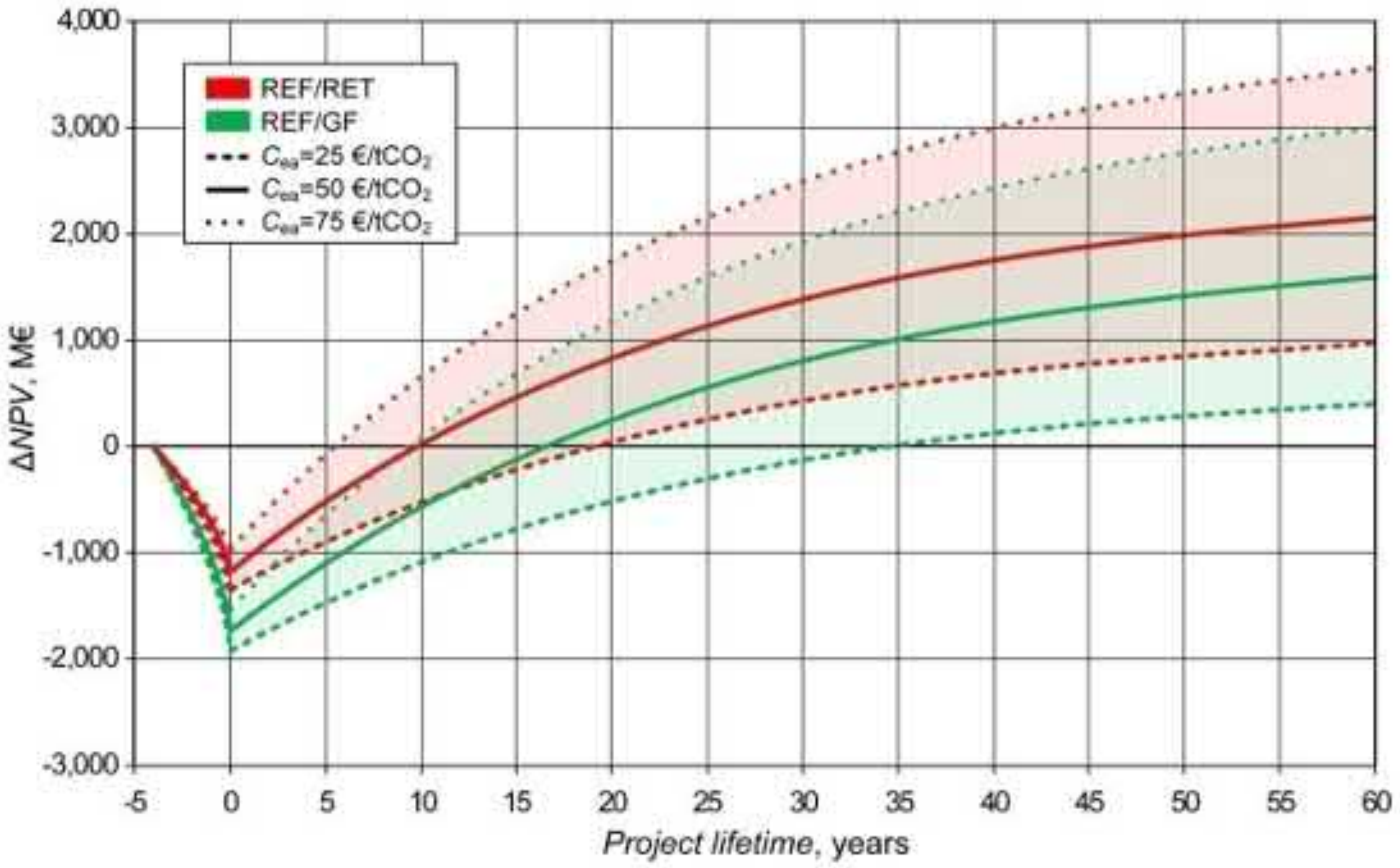

Fig. ΔNPV as a function of project lifetime for the GF and RET investment pathways for Łagisza unit

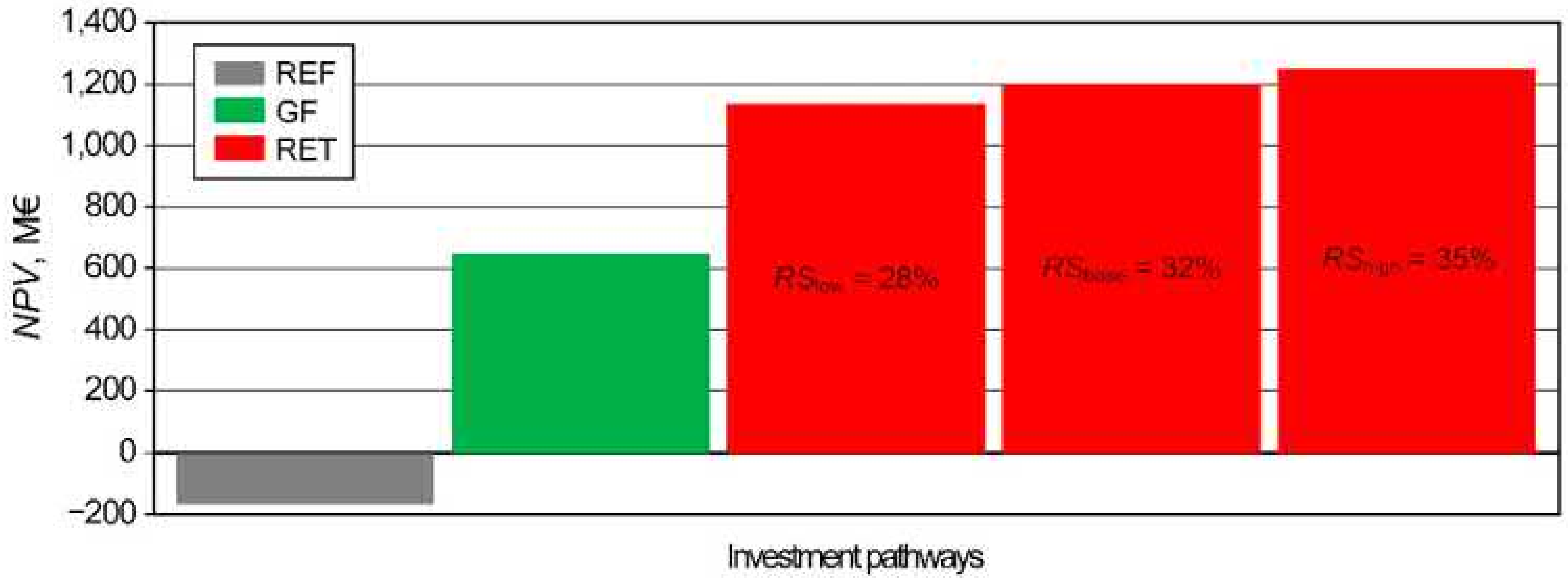

Fig. ΔNPV for base assumptions for three investment pathways (retrofit investment pathway for three different values of retrofit savings) for Łagisza 460 MW unit

Genesis of the DEsire project

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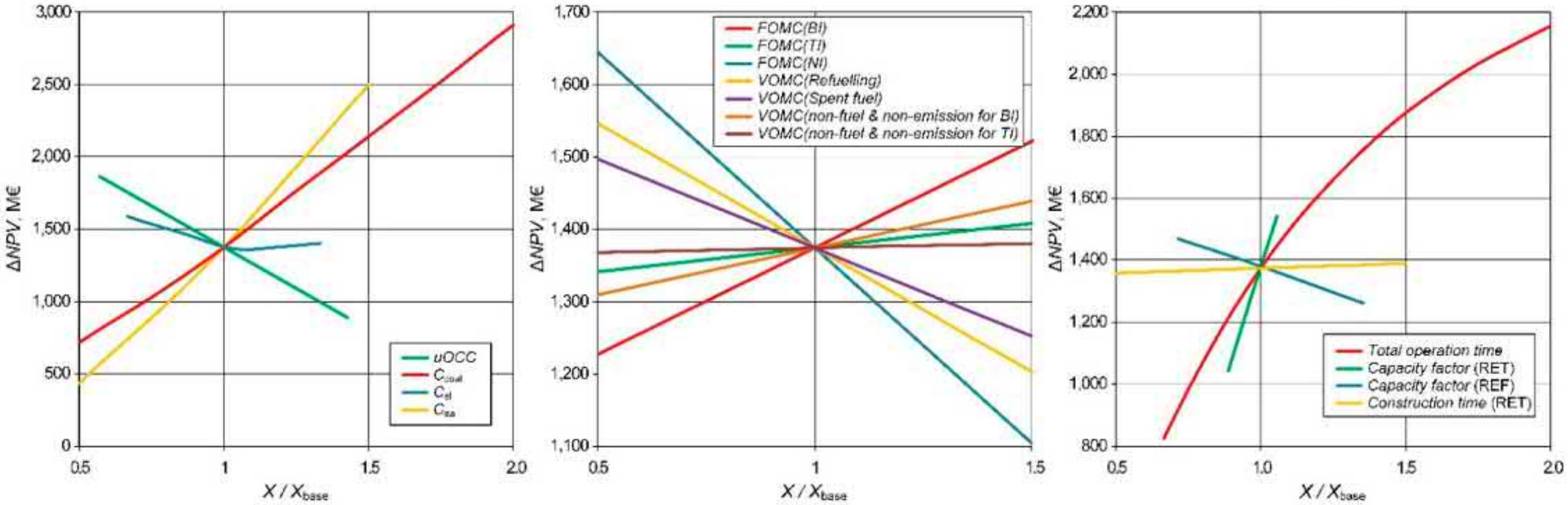
Table. Discount payback period for different electricity (el), coal and CO_2 emission allowance (ea) prices for two investment pathways for Łagisza unit

		Pathway of investment					
		GF			**RET**		
		C_{ea}, €/tCO_2			C_{ea}, €/tCO_2		
		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.

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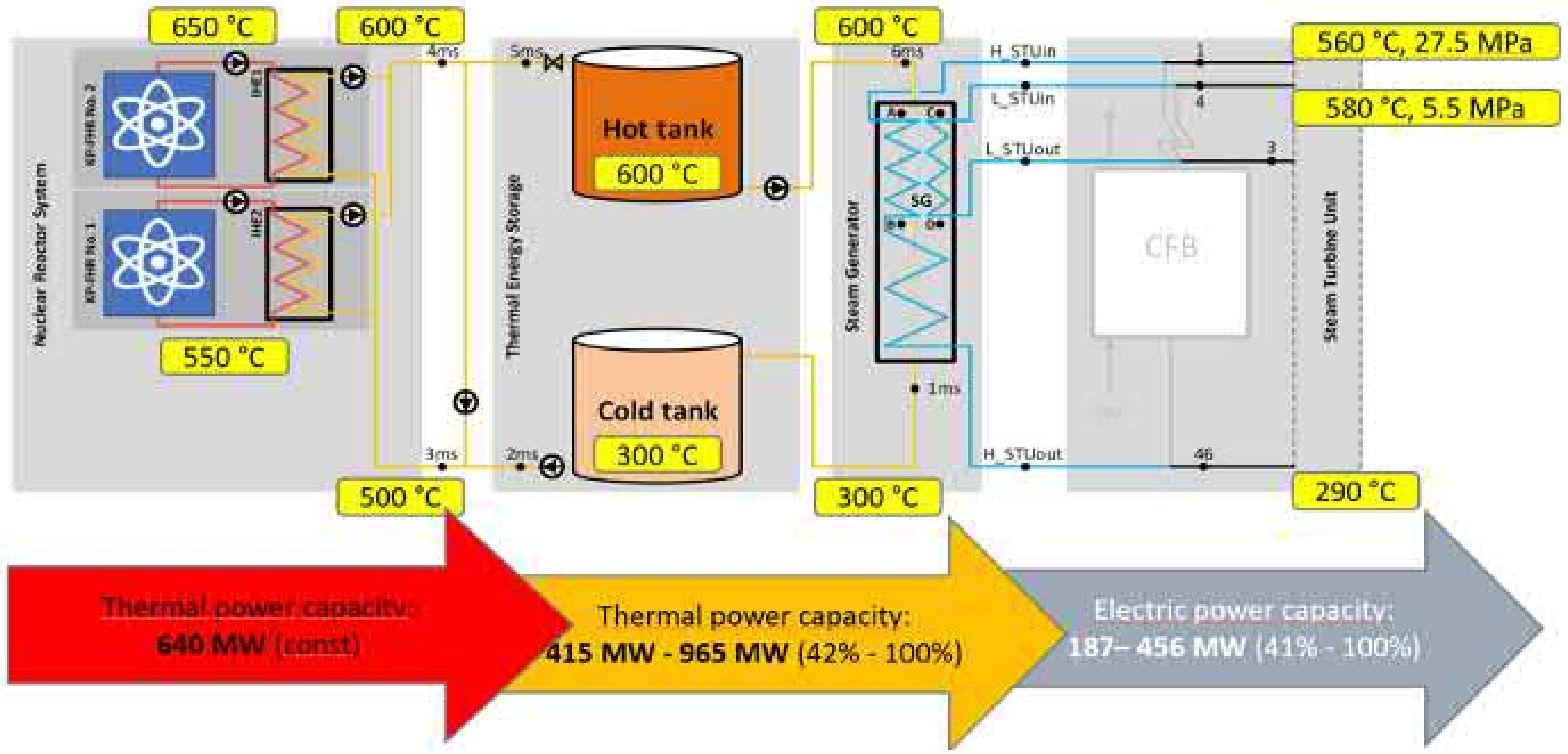
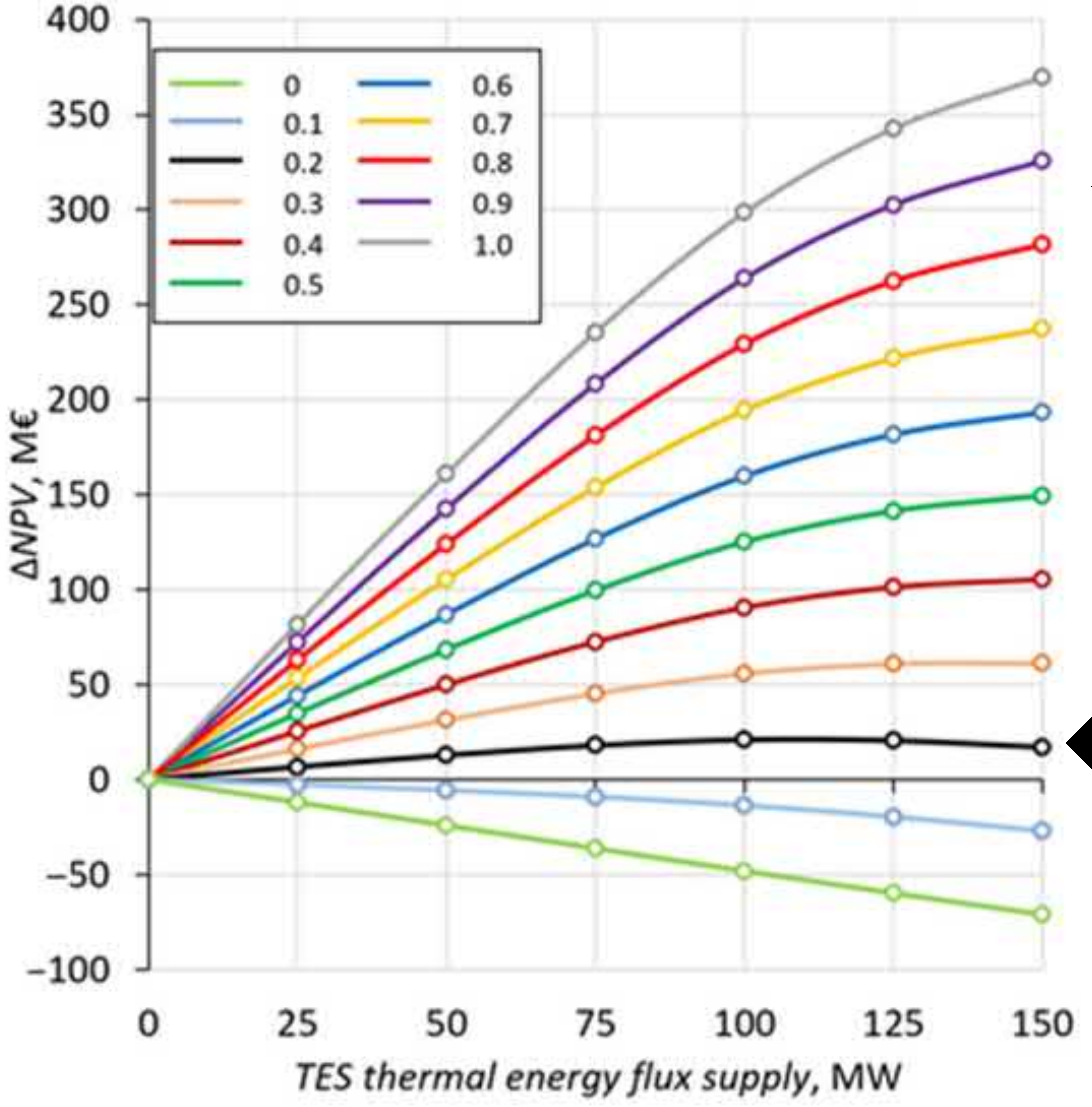
Fig. Diagram of integration of SMR system with TES at Łagisza unit



Deviation index – module of the relative deviation of electricity prices occurring in the energy valley and during the peak demand period relative to the average price

*Fig. ΔNPV as a function of TES thermal energy flux supply for the eleven values of **deviation index** (from 0 to 1, with step 0.1).*



… and with further introduction of variable RES in energy system

average for PL

Case	Live Steam Pressure	Live Steam Temperature	Reheated Steam Temperature	Inlet Temperature to Boiler/SG	Boiler/SG Thermal Power
Original plant	**28 MPa**	**560 °C**	**580 °C**	**290 °C**	**957.1 MW**
Repowered plant	**7 MPa**	**285 °C**	**Varies**	**Varies**	**Varies**

Aside of the DEsire project

- works done by the Qvist-Łukowicz-Gładysz-Bartela team

Repowering a Coal Power Plant Steam Cycle Using Modular Light-Water Reactor Technology

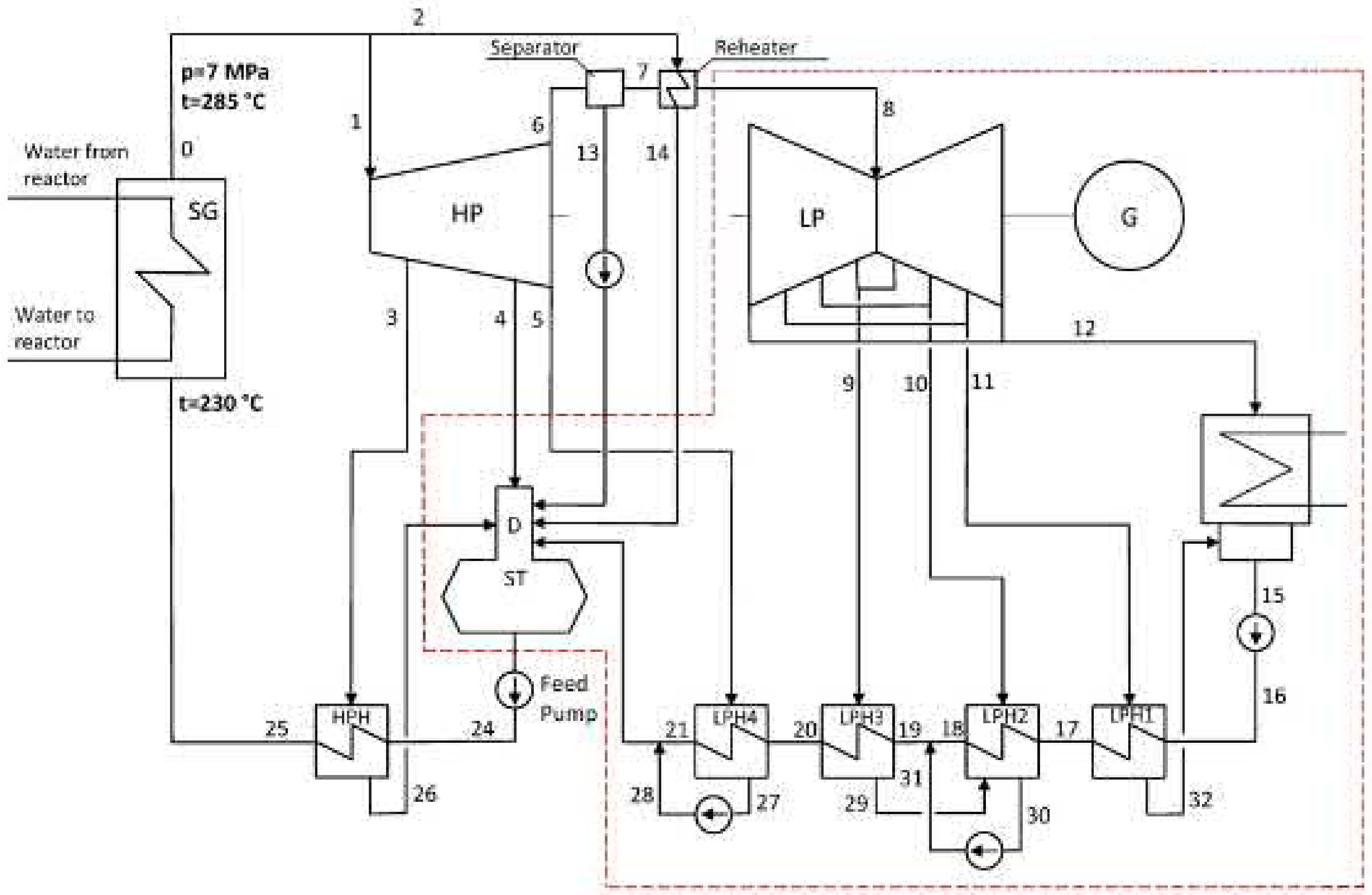


Fig. Diagram of the steam cycle with marked calculation points after modernization of the power unit (ed dashed line - components previously used in the coal-fired power unit)

Analysed cases:

- **original IP section** (case A – C):

A. **no reheater – saturated steam at SG (4.06 MPa/251.2 °C)**
B. **1-stage reheat – superheat steam at SG (4.04 MPa/285 °C)**
C. **2-stage reheat – superheat steam at SG (4.04 MPa/285 °C)**

- **new HP Section** (case D)

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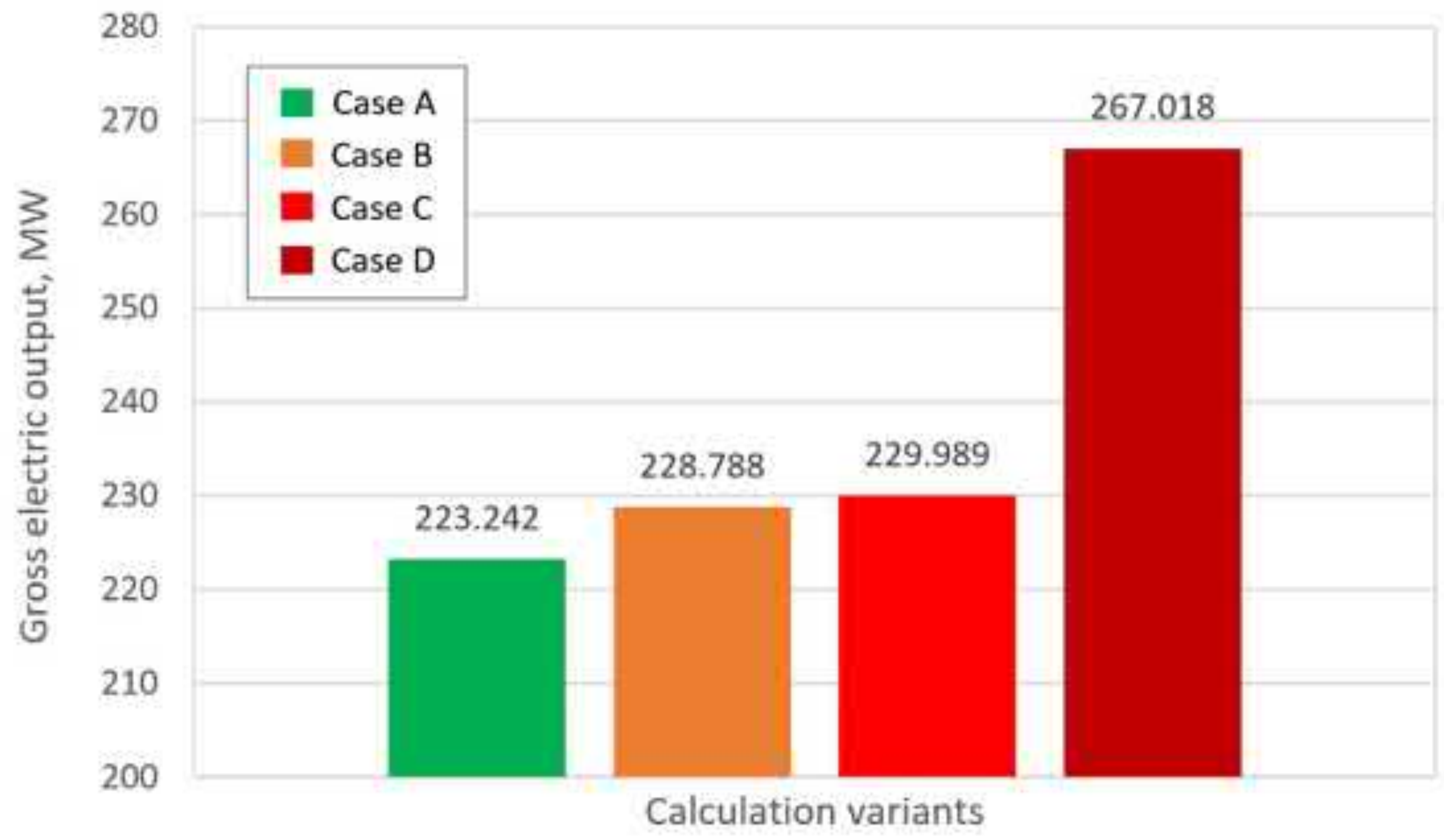

Fig. Gross electric power output for different parameters of steam feeding the turbine

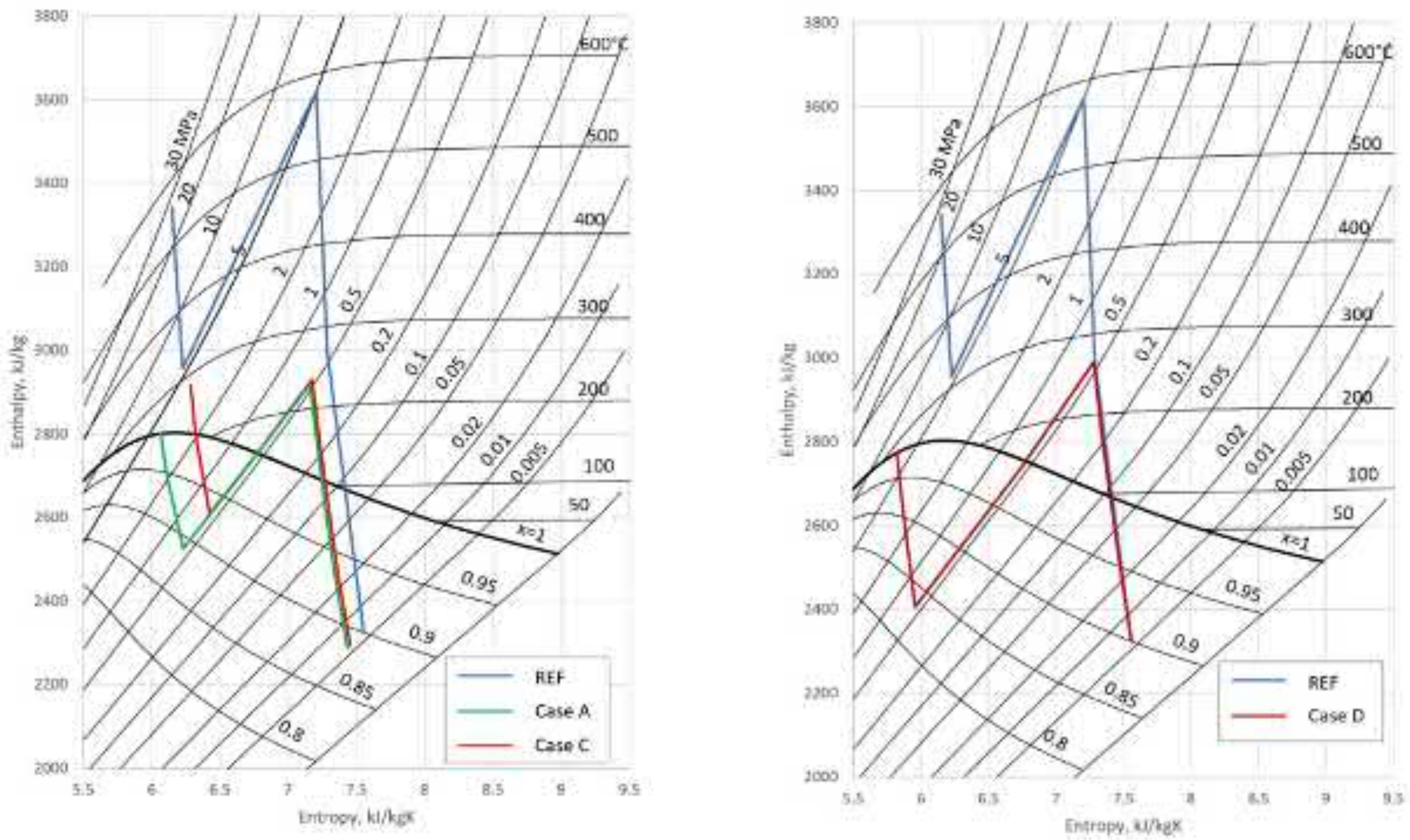

Fig. Steam expansion line in the turbine of the 460 MW power unit (REF) and post-modernization state (Casa A, Case C, Case D)

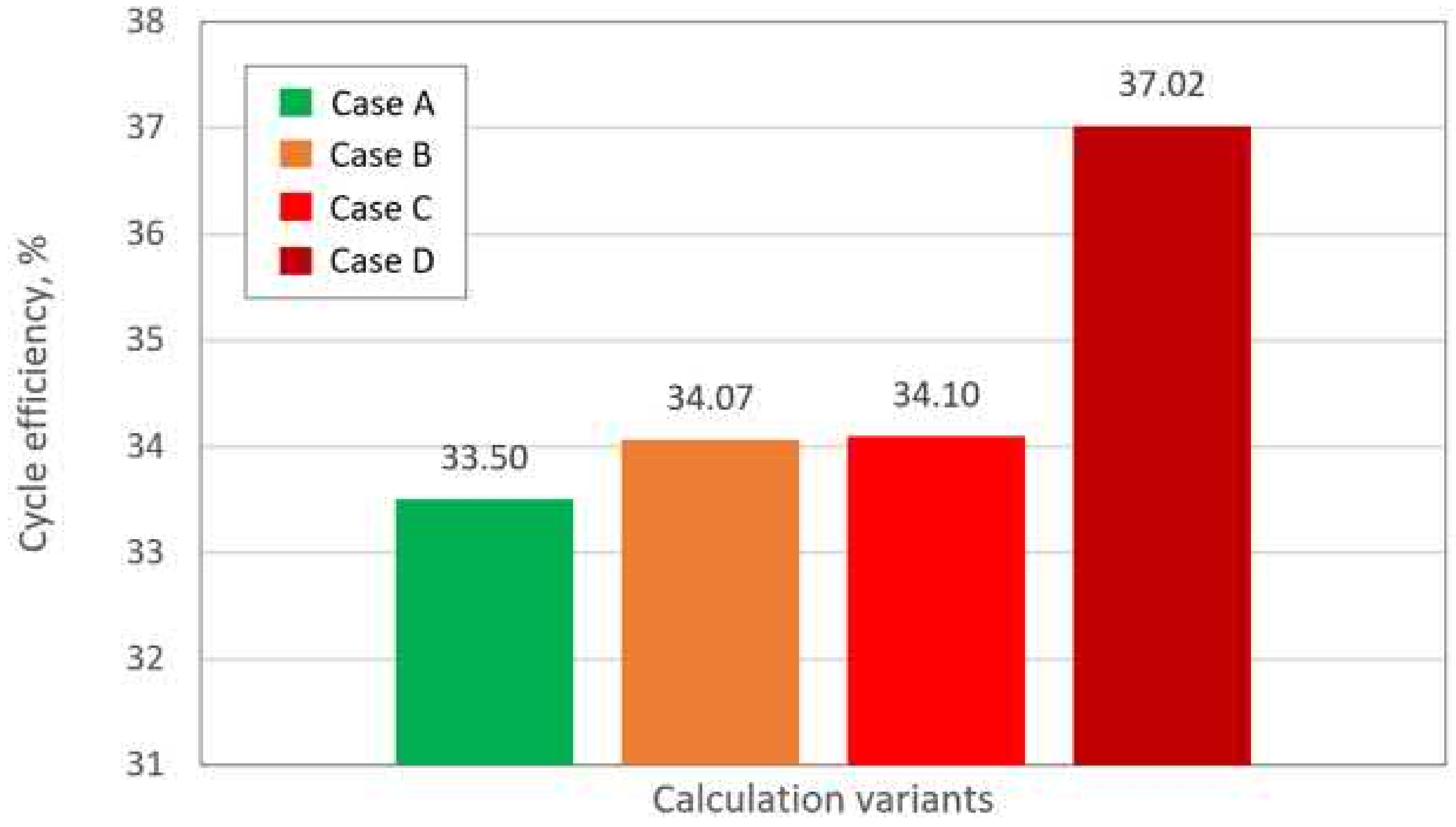

Fig. Cycle efficiency for different parameters of steam feeding the turbine

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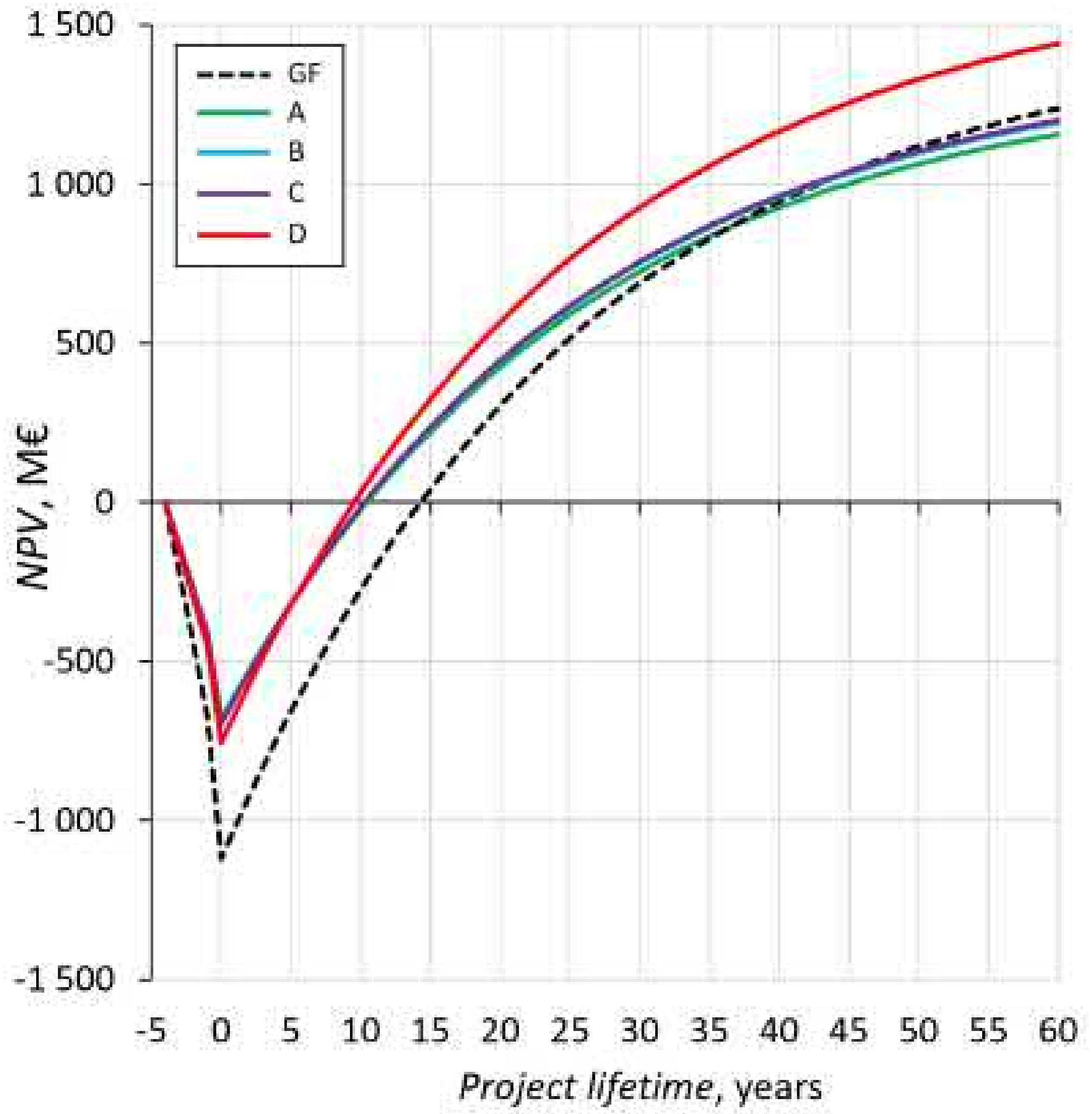

Fig. NPV as a function of project lifetime for steam cycle modernization cost index MC_{ST} = 0.5 for average level of RS

Component of Costs	Category	Symbol of Component	Budgeted Share *, %	Minimal Retrofit Savings, %	Mid-Level Retrofit Savings, %	Maximum Retrofit Savings, %
	-	i	$sOCC_i$ or $sTIC$	$(RS_{OCC_i})_{min}$ or $(RS_{TIC})_{min}$	$(RS_{OCC_i})_{av}$ or $(RS_{TIC})_{av}$	$(RS_{OCC_i})_{max}$ or $(RS_{TIC})_{max}$
Initial fuels inventory	R	IFI	7.0	0.0	0.0	0.0
Other costs (transmission, owner's, etc.)	T	OC	10.0	100.0	100.0	100.0
Land and land rights	R + T	LLR	0(~0)	100.0	100.0	100.0
Structure and improvements	R	S&I	15.0	0.0	12.0	24.0
Reactor plant equipment	R	RPE	18.0	0.0	0.5	1.0
Turbine plant equipment	T	TPE	15.0	0.0	49.5	99.0
Electric plant equipment	T	EPE	5.0	42.0	60.0	78.0
Miscellaneous plant equipment	R + T	MPE	2.0	6.0	48.5	91.0
Main condenser and heat rejection system	T	MCHR	3.0	0.0	50.0	100.0
Total indirect costs	R + T	TIC	25.0	16.0	27.5	39.0

Tab. Overall capital costs and total indirect costs for respective components of investment subject

Coal-to-Nuclear classification – DEsire project

C2N

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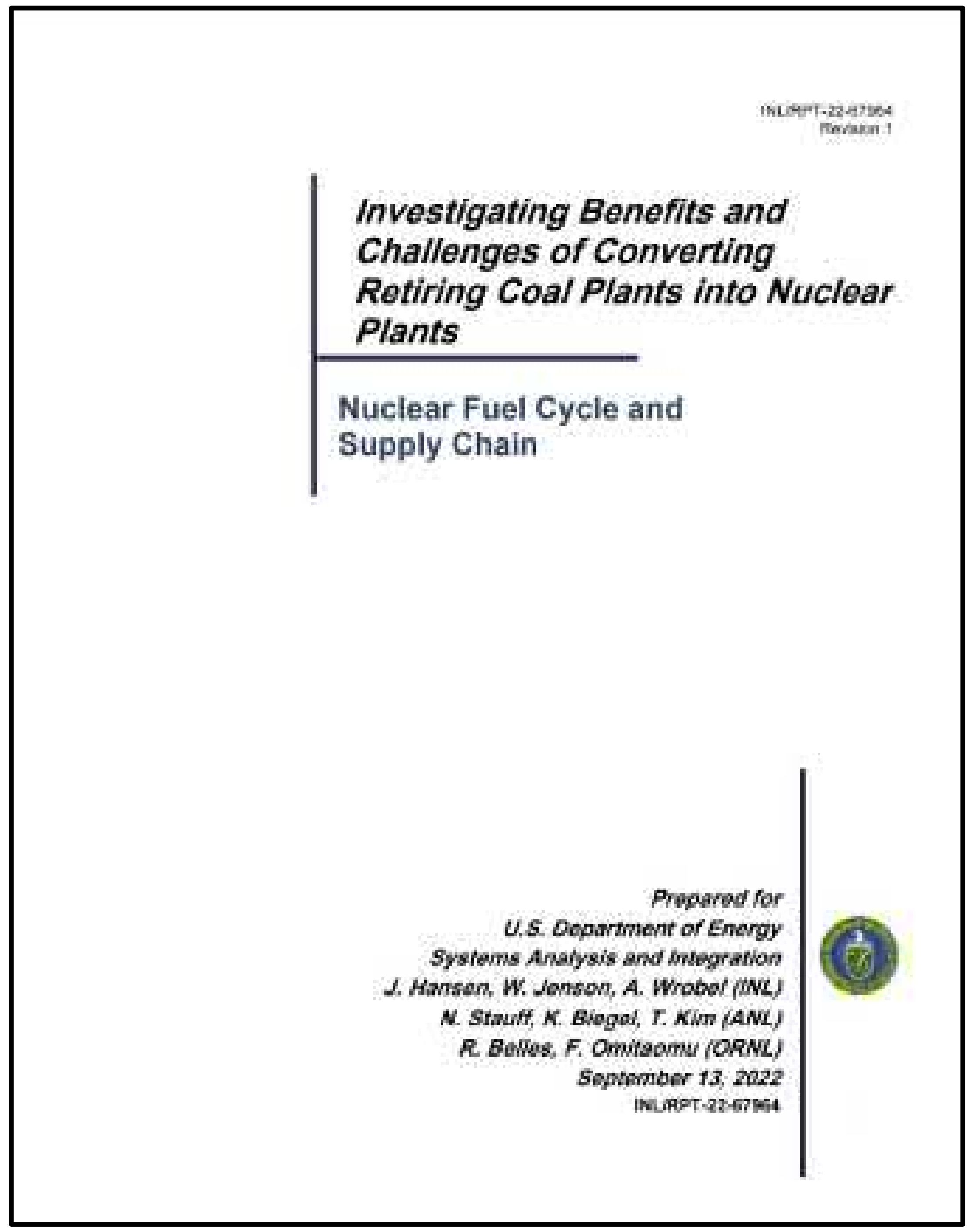
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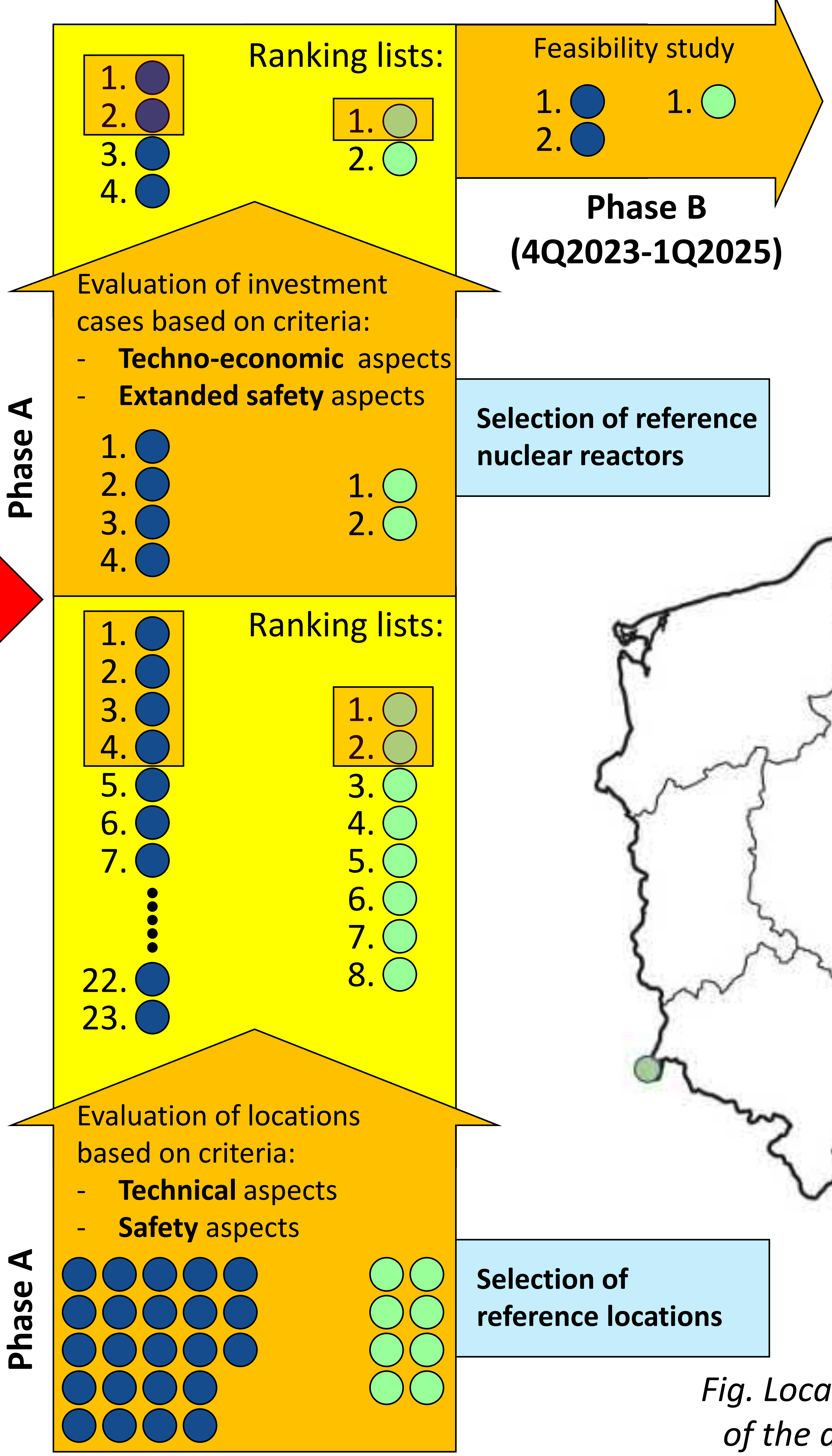
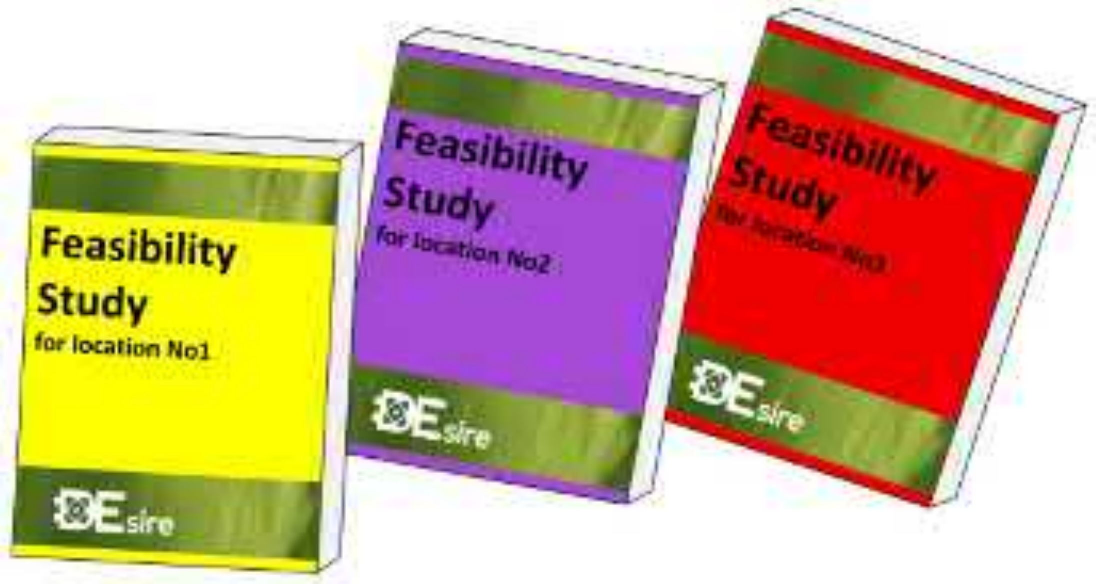
Locations

23 locations:

We are here

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





8 locations:

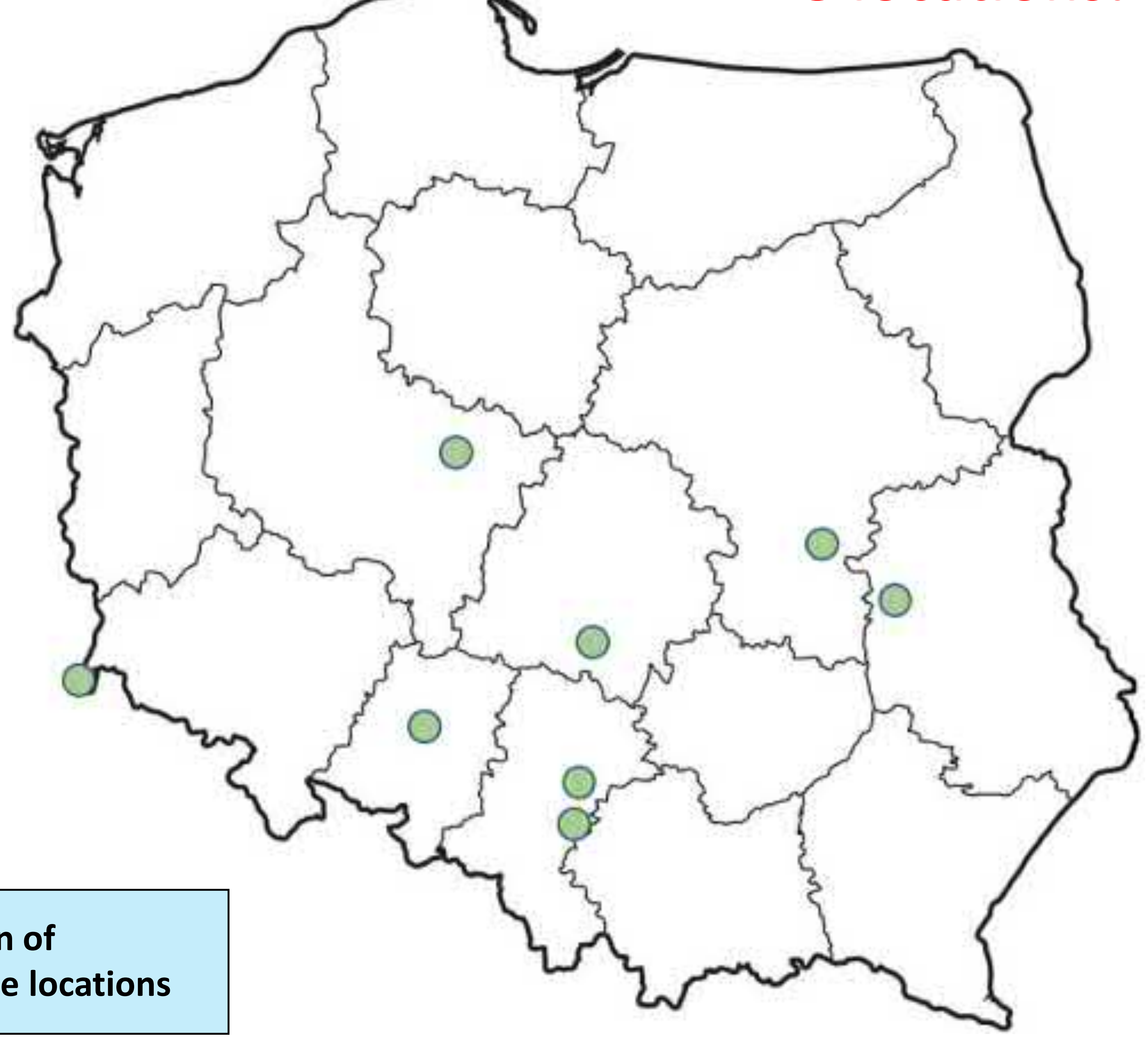


Fig. Locations of CPUs selected for the assessment of the direct C2N conversion pathway potential

Locations

C2N#1
Brownfield

23 locations:

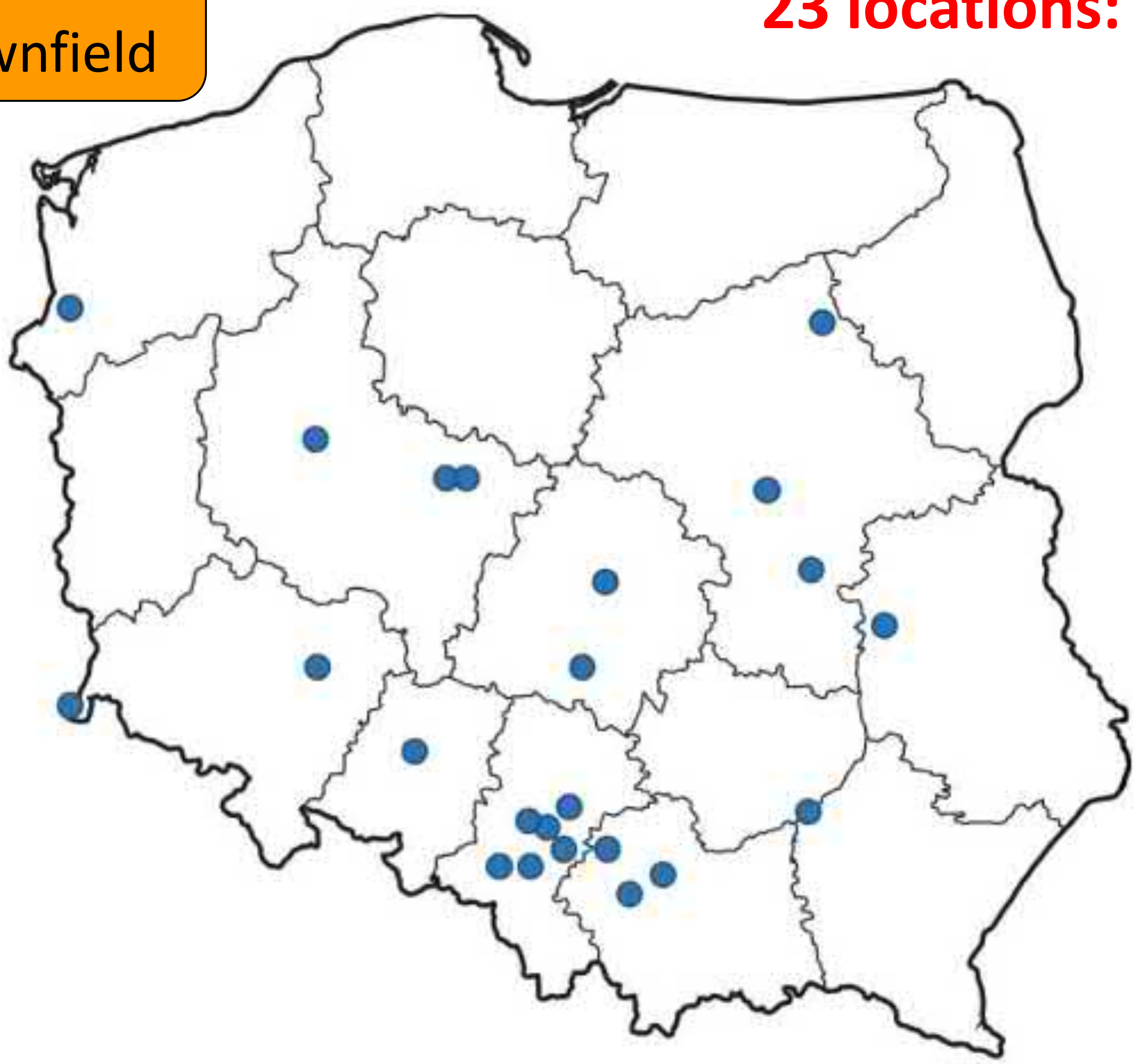


Fig. Locations of CPPs selected for the assessment of the brownfield C2N conversion pathway potential

1. Bełchatów
2. Chorzów
3. Dolna Odra
4. Jaworzno
5. Katowice
6. Karolin
7. Konin
8. Kozienice
9. Kraków
10. Łagisza
11. Łaziska
12. Łódź
13. Opole
14. Ostrołęka
15. **Pątnów**
16. Połaniec
17. Puławy
18. Rybnik
19. Siekierki
20. Siersza
21. Skawina
22. Turów
23. Wrocław

∑ 92 units
∑ 22.4 GW_{el}

C2N#2
Direct

8 locations:

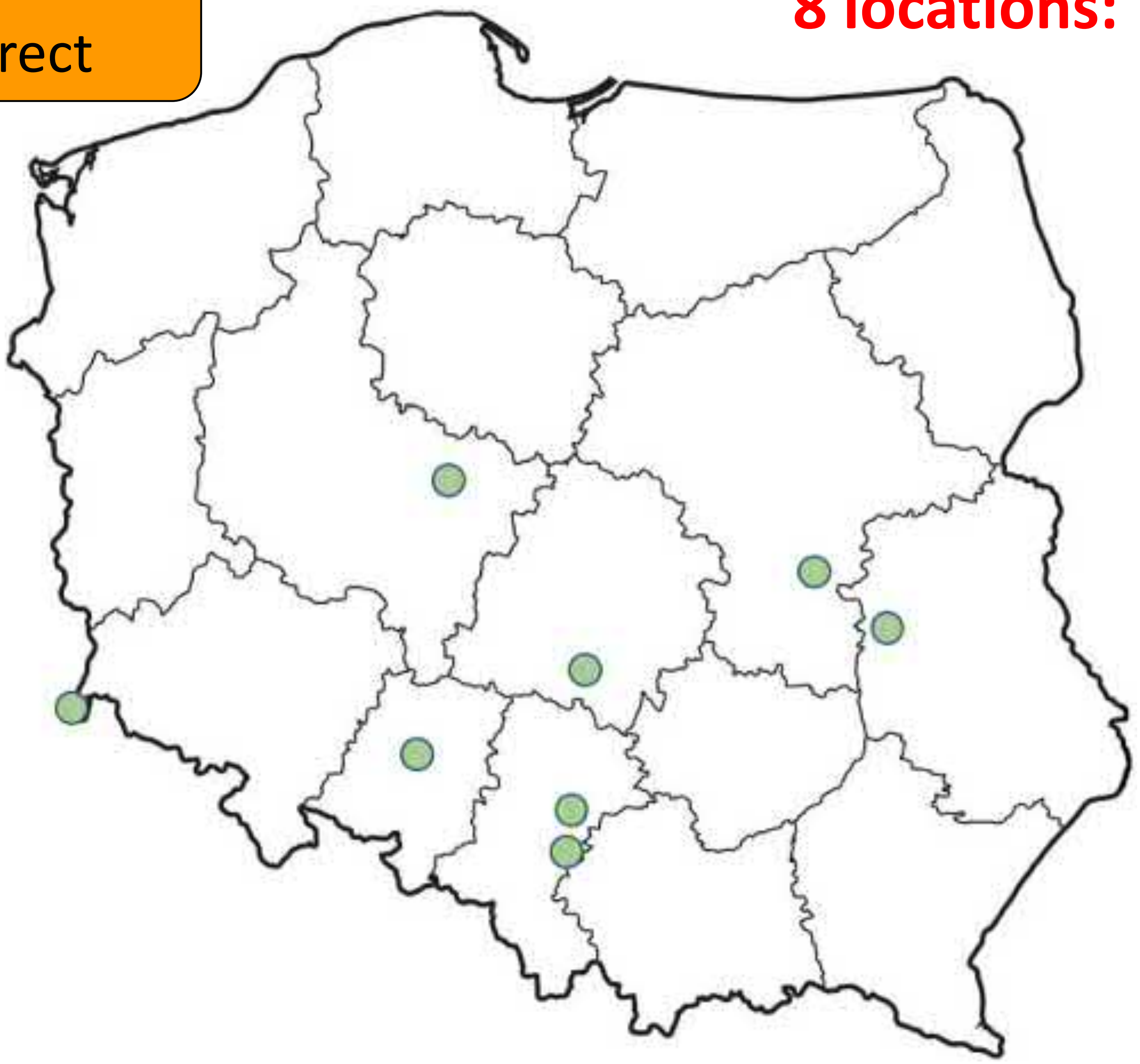


Fig. Locations of CPUs selected for the assessment of the direct C2N conversion pathway potential

1. Bełchatów
2. Jaworzno
3. Kozienice
4. Łagisza
5. Opole
6. **Pątnów**
7. Puławy
8. Turów

∑ 9 units
∑ 6.2 GW_{el}

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})

Coal-to-Nuclear
repowering / repurposing
as part of a
Just Transformation of Coal Regions

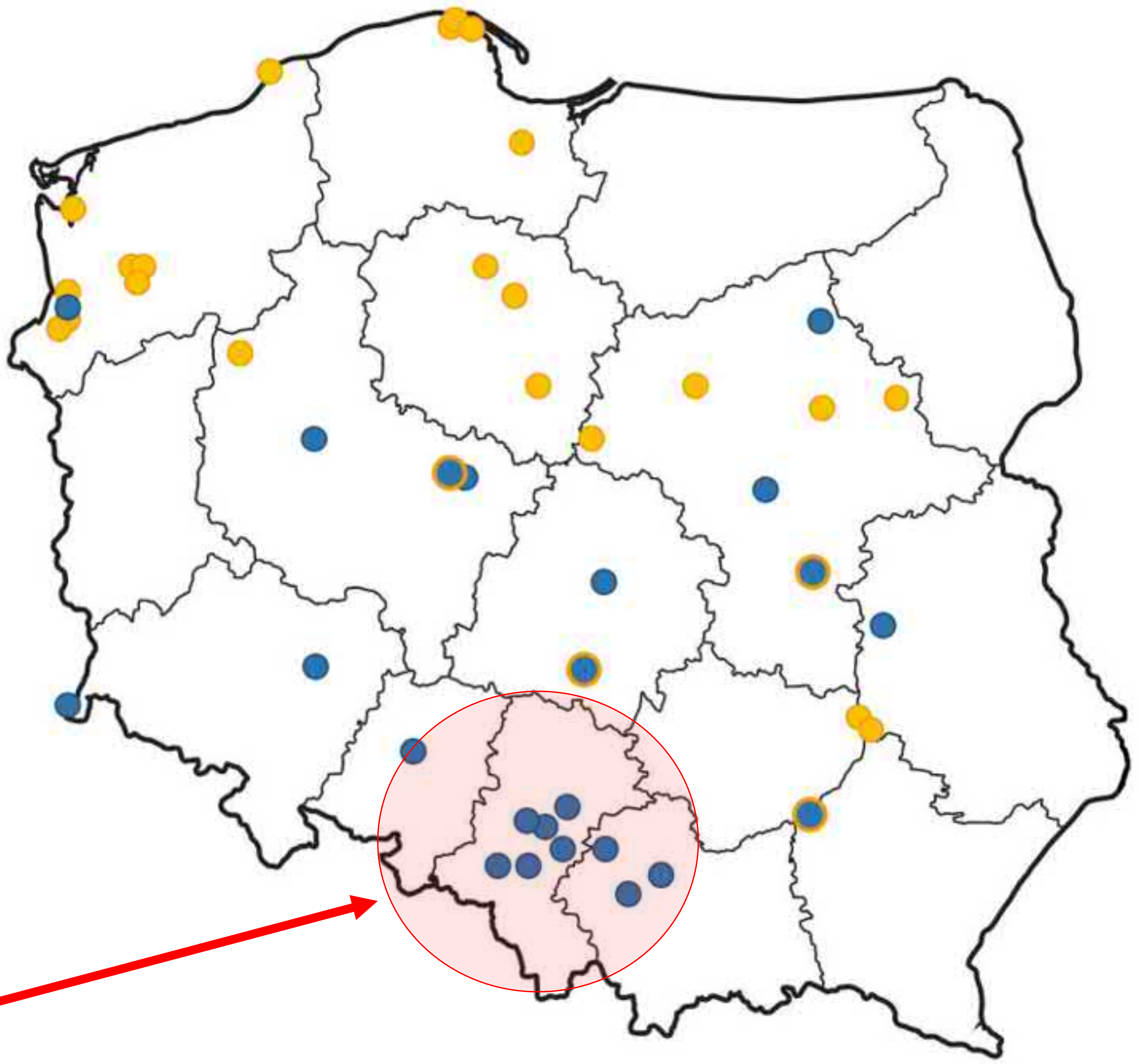


Fig. Locations indicated in the Polish Nuclear Power Programme and analyzed in the DEsire project

Locations

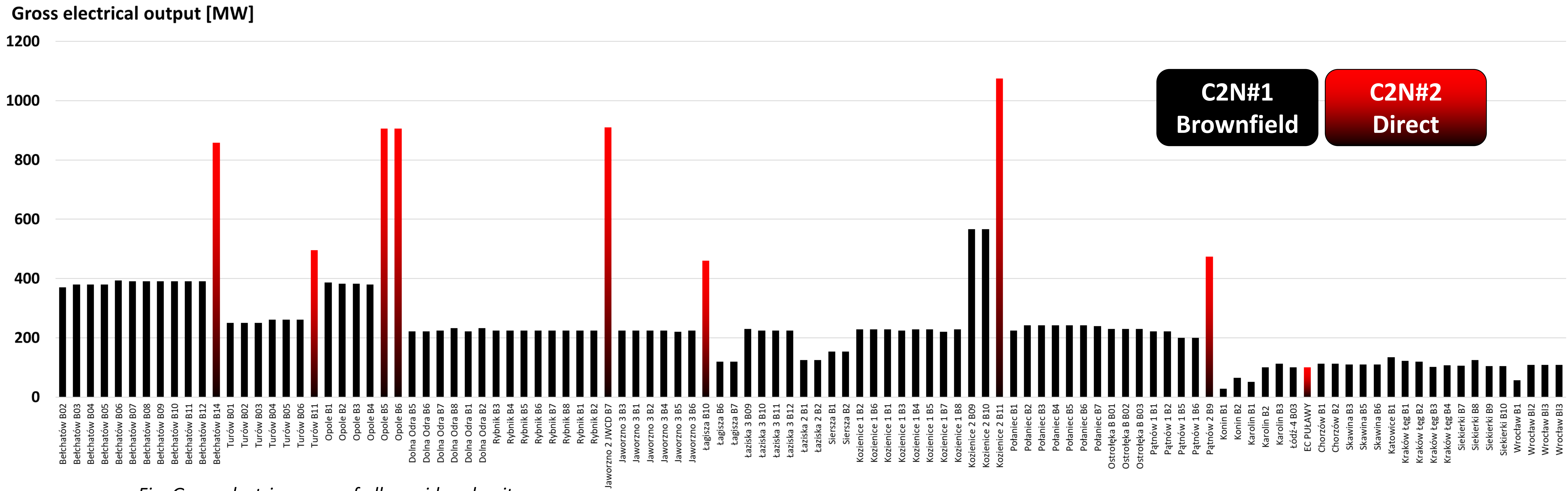


Fig. Gross electric power of all considered units

Stage I – evaluation criteria

C2N#1 Brownfield

C2N#2 Direct

- different **weighting factors** for evaluation criteria depending on the pathway (C2N#1 vs C2N#2)
- final conclusions based on **unified approach**
- first step for **CtNRL** (Coal-to-Nuclear Readinnes Level)

Technical aspects:

- **CO_2 emissions** to be avoided
- power output **infrastructure** (electrical grid capacity)
- access to transport **infrastructure** (sea, railroad, highways)
- assess to **cooling water** (sea, lakes, rivers)
- **area availability** (dates, complexity)
- **demand for heat** (district heating systems, industrial heat demand)

Safety aspects:

- **formal requirements** and recommendations imposed by international and national organizations on the design and operation of nuclear power systems (e.g. seismic activity, floods, mineral deposits, selected types of facilities)
- potential **nuclear hazards** to the personnel of the unit and the **local population** (e.g. population density)
- applied solutions for **reactor protection systems**, steam turbine thermal cycle, and auxiliary infrastructure (technology advancement, redundancy of safety systems)
- management of **spent nuclear fuel and radioactive waste** (management technology/facilities, enrichment of nuclear fuel)

Stage I – some results

C2N#1
Brownfield

Preliminary recommendations for power plants and C2N#1 (brownfield) pathway:

- **Kozienice** power plant
- **Połaniec** power plant
- **Dolna Odra** power plant
- **Ostrołęka** power plant

Opole, Bełchatów and Pątnów also obtained high scores, but for this pathway only four locations were assumed for further studies within DEsire project. **Thus, it does not mean that other locations are not suitable, just less favourable then those four**.

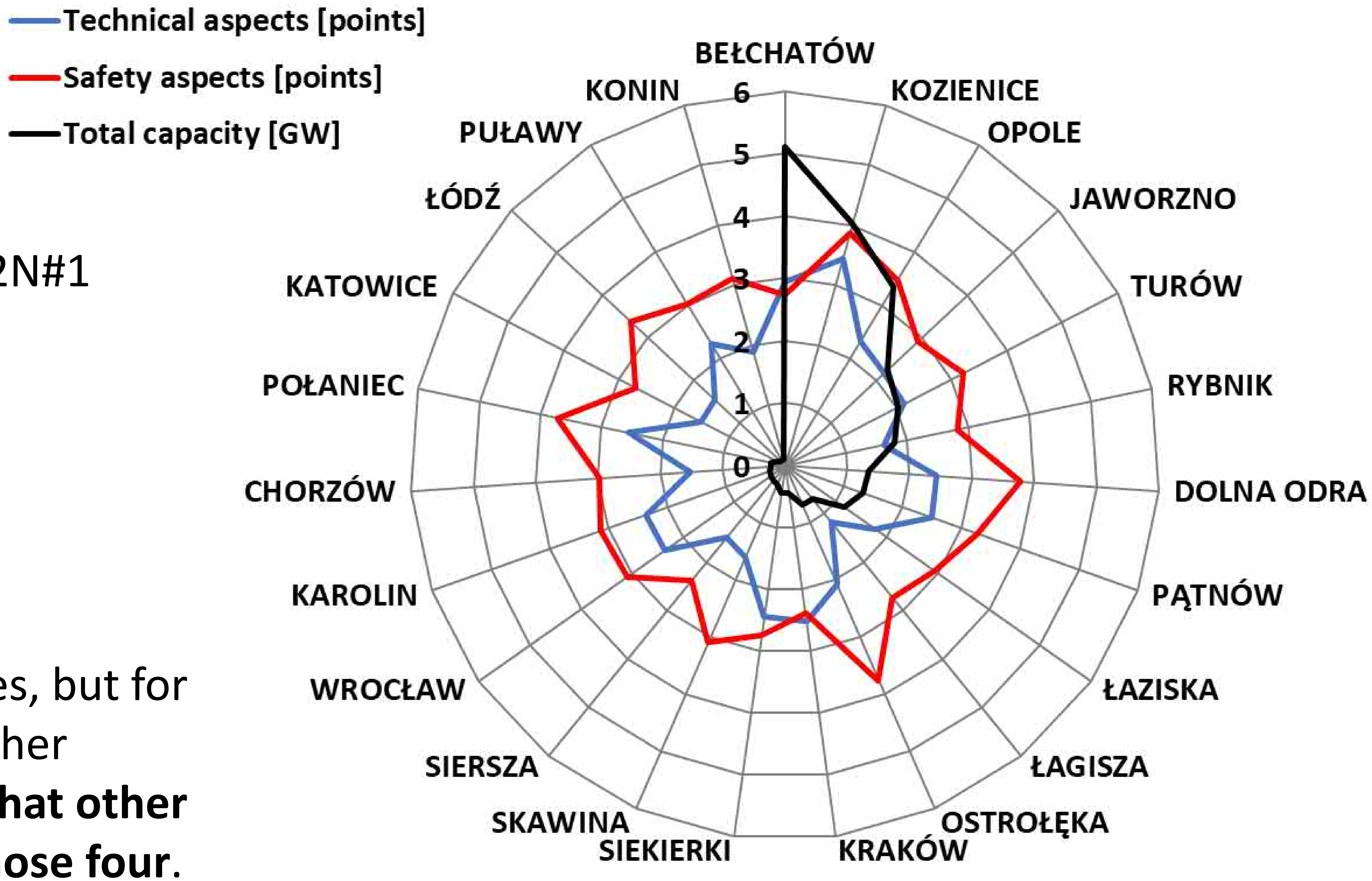


Fig. Technical and safety preliminary results

Stage I – some results

C2N#2 Direct

Preliminary recommendations for power plants and C2N#2 (direct) pathway:

- **Kozienice 2 B11** unit
- **Opole B6/B5** units

EC Puławy and Turów B11 also obtained high scores, but for this pathway only two locations were assumed for further studies within DEsire project. **Thus, it does not mean that other units are not suitable, just less favourable then those two preselected**.

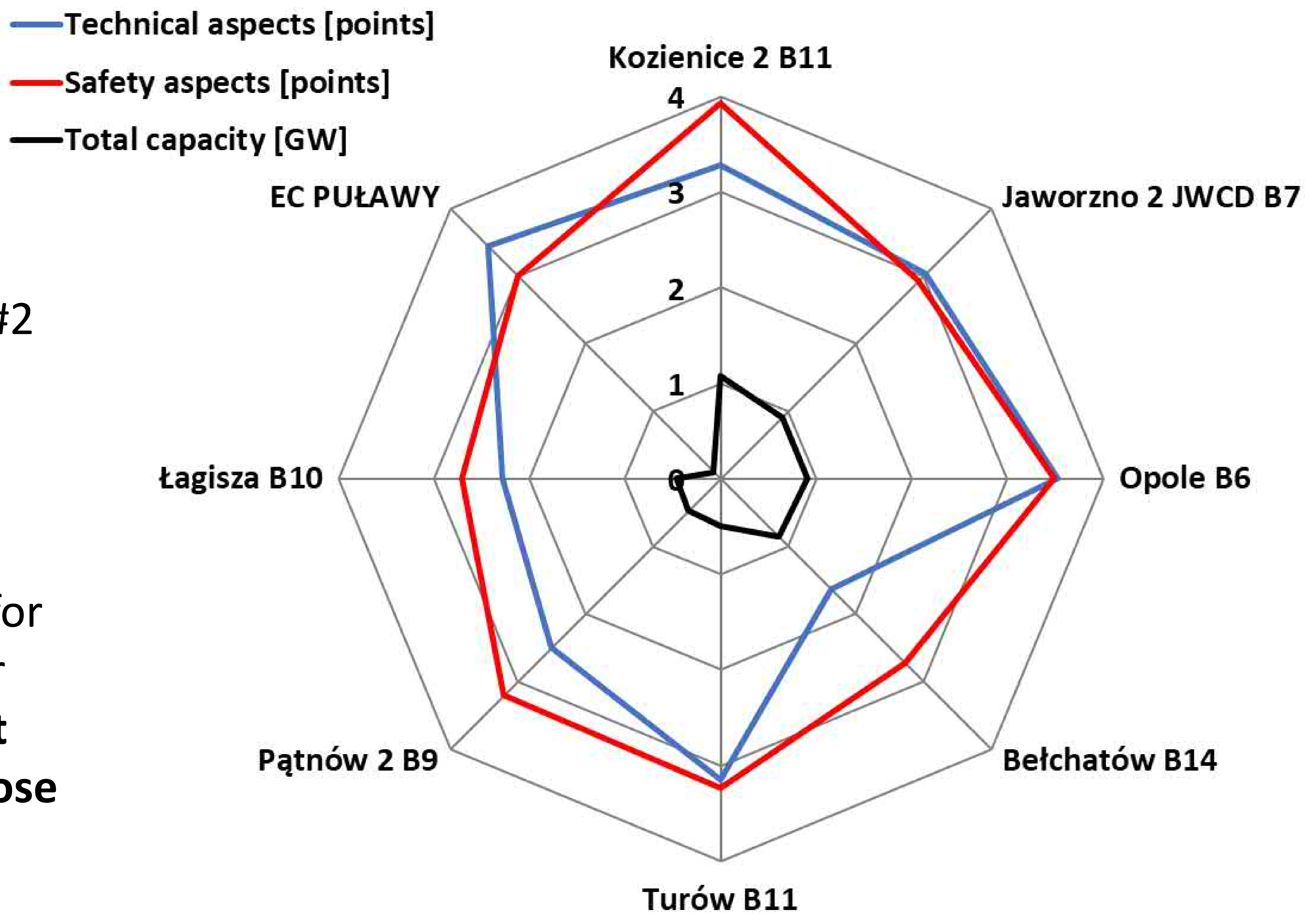


Fig. Technical and safety preliminary results

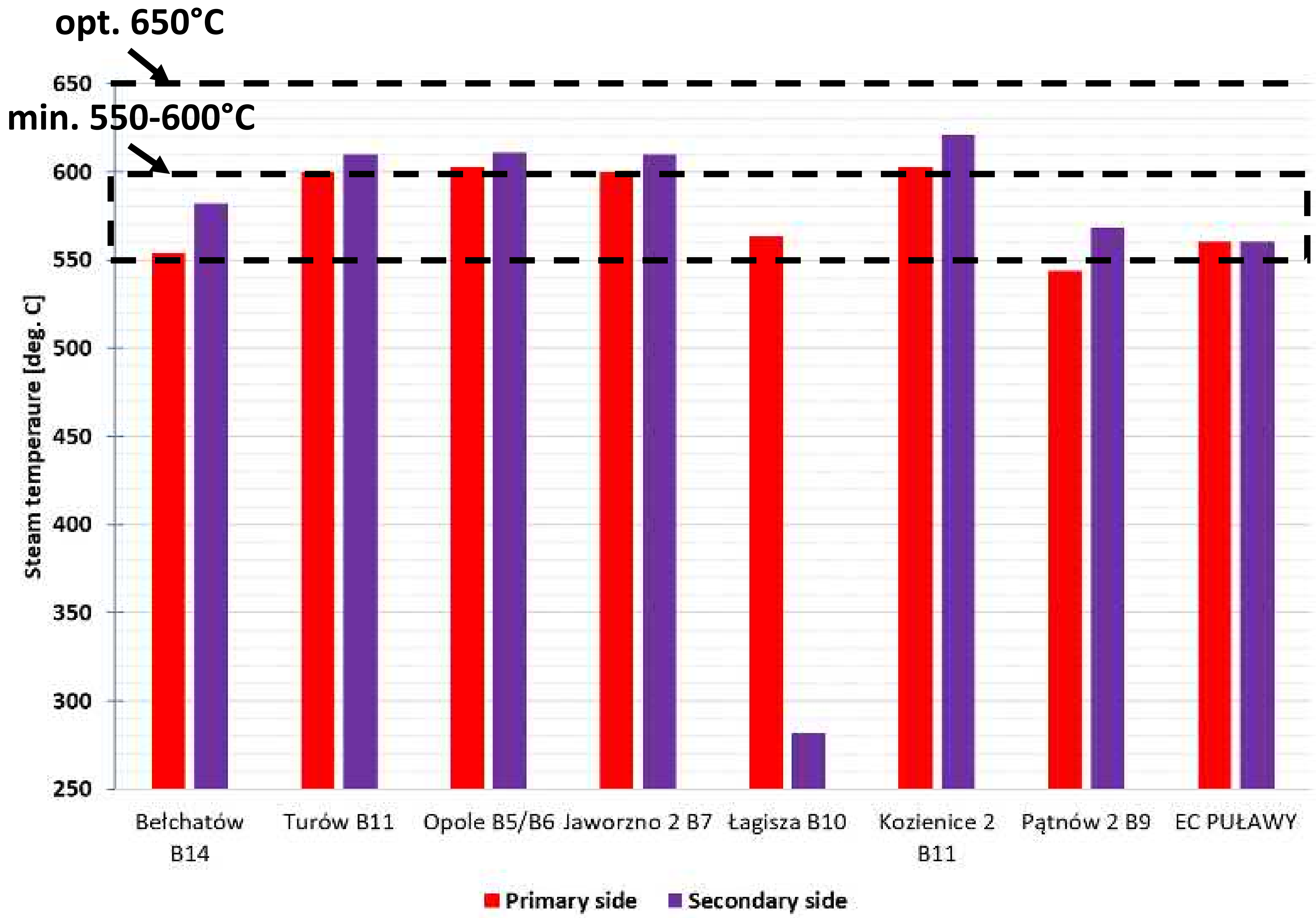
Stage I – reactors matching

C2N#1 Brownfield

Provider	Name	Type of reactor	Electrical power (gross / net)	Efficiency	Status (in operation / in construction)
Westinghouse (USA)	**AP-1000**	**pressurized water reactor (PWR)**	**1250 / 1150 MW**	**34%**	**4 / 2**
KHNP (South Korea)	**APR1400**	**pressurized water reactor (PWR)**	**1420 / 1350 MW**	**36%**	**4 / 6**
EDF (France)	**EPR**	**pressurized water reactor (PWR)**	**1720 / 1600 MW**	**38%**	**3 / 3**
EDF (France)	EPR-1200	pressurized water reactor (PWR)	c.a. 1200 MW	b/d	0 / 0
KHNP (South Korea)	**APR1000**	**pressurized water reactor (PWR)**	**c.a. 1000 MW**	**b/d**	**0 / 0**

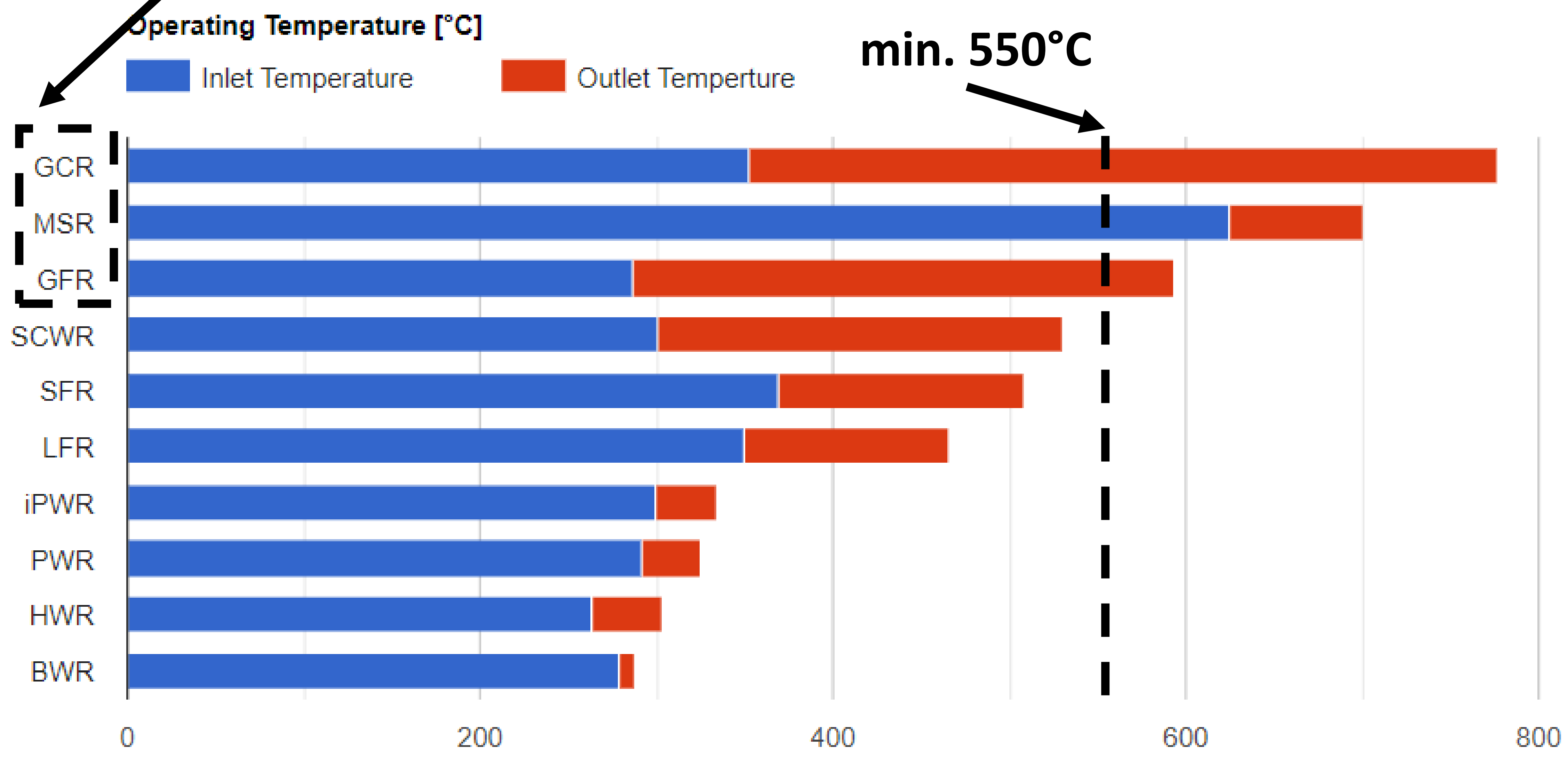
Stage I – reactors matching

C2N#2 Direct



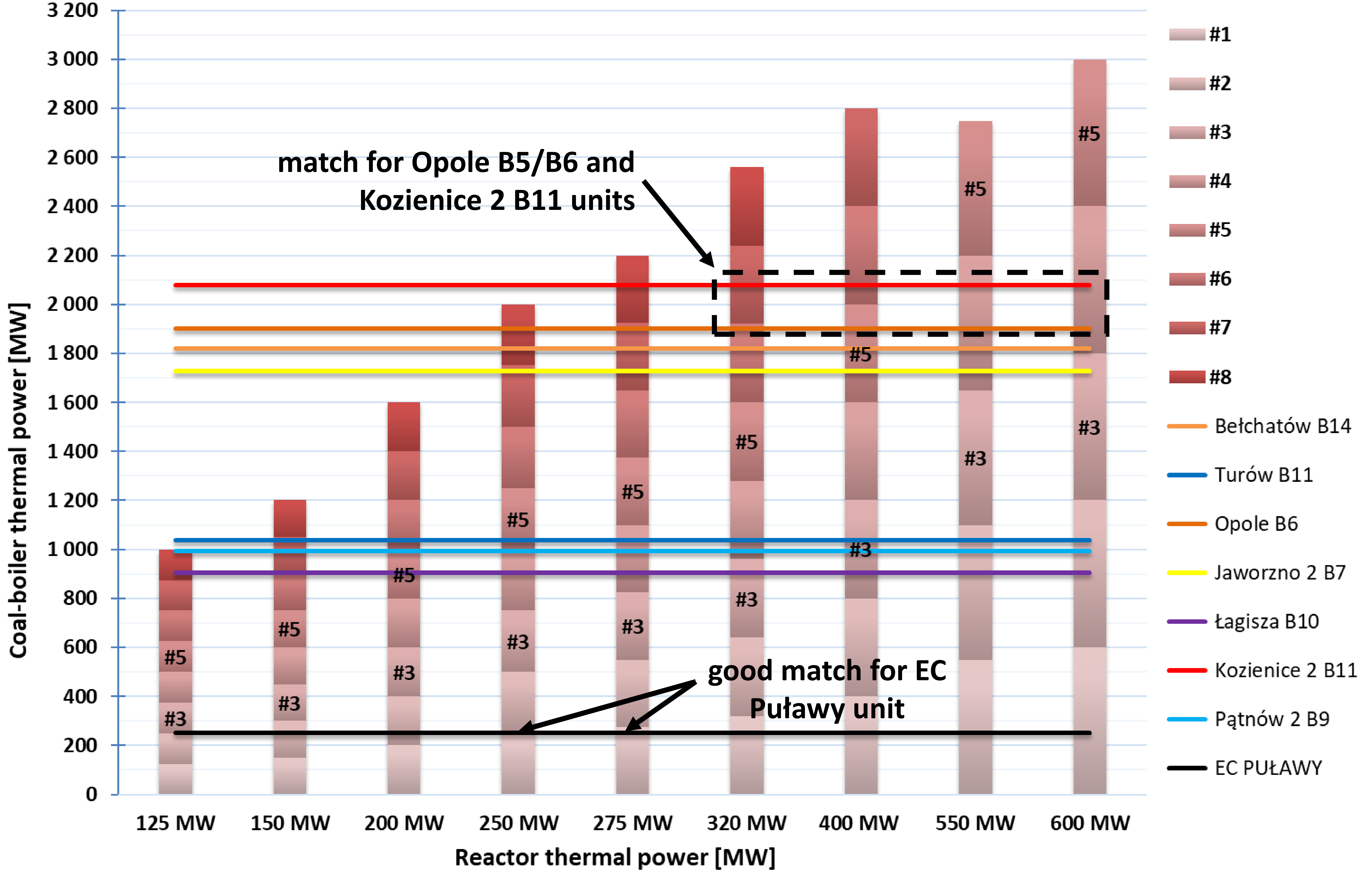
Preselection of SMRs:

- **GCR** (gas cooled reactors);
- **GFR** (fast gas-cooled reactors);
- **MSR** (molten salt reactors).



Stage I – reactors matching

C2N#2 Direct



Preselection of SMRs:

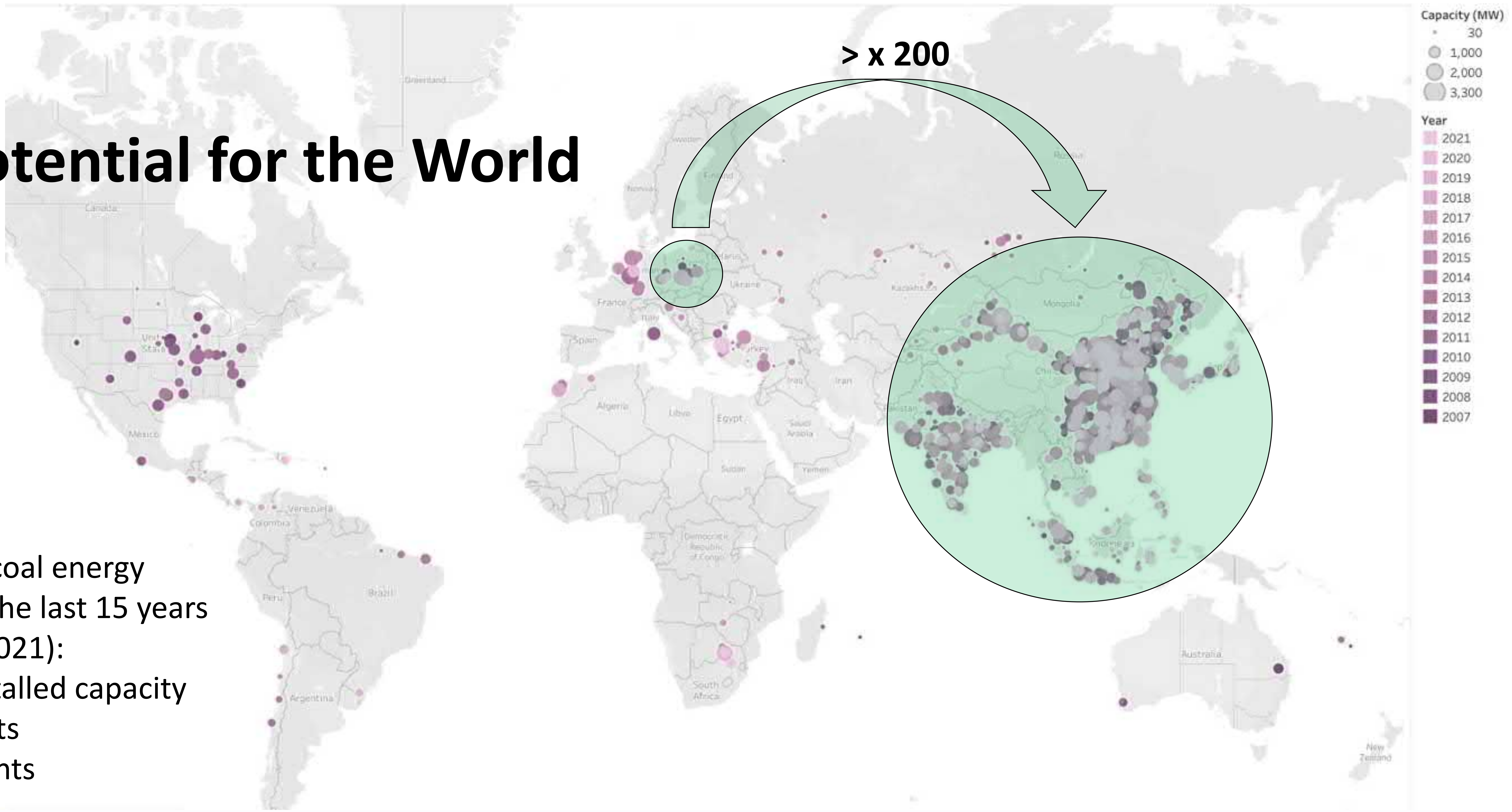
- we do not consider reactors smaller then **250 MW$_{th}$**;
- for prelimiary selected units, we would need to install **4 – 6 reactors**;
- **500 MW$_{el}$ class units** (Turów B11, Pątnów 2 B9 and Łagisza B10) would be more suitable for C2N#2 direct retrofit option.

Stage I – reactors matching

C2N#2 Direct

Name	Country	Type	Moderator	Coolant	Fuel	Reactor thermal power	Coolant outlet temperature	Status and predictive dates	
HTR-PM	China	GCR	graphite	helium	8,5% LEU	2x250 MW	750°C	in operation	2022
SC-HTGR	USA				14,5% HALEU	625 MW	750°C	preliminary design	2033
GTHTR300	Japan				14% HALEU	600 MW	950°C	basic design	2040s
IMSR400	Canada	MSR		fluoride salts	<5,0% LEU	440 MW	700°C	detailed design	2031
ITMSF	Japan				2,0% LEU	450 MW	704°C	basic design	b/d
ThorCon	USA			molten salts	<5,0% LEU	557 MW	704°C	basic design	2028
KP-FHR	USA				19,7% HALEU	320 MW	650°C	conceptual design	2026 demo
LFTR	USA				^{233}U Th	600 MW	650°C	conceptual design	b/d
MCSFR	USA		-	chloride salts	15% HALEU	125/500/ 1000/3000	750°C (950°C)	conceptual design	2030

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

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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

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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

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DEsire Team:

Silesian University of Technology

Ministerstwo Klimatu i Środowiska

THANK YOU!

website:

https://projektdesire.pl/en

lukasz.bartela@polsl.pl