The Value of Long-Term Operations of Nuclear Power Plants

A Case Study for Spain

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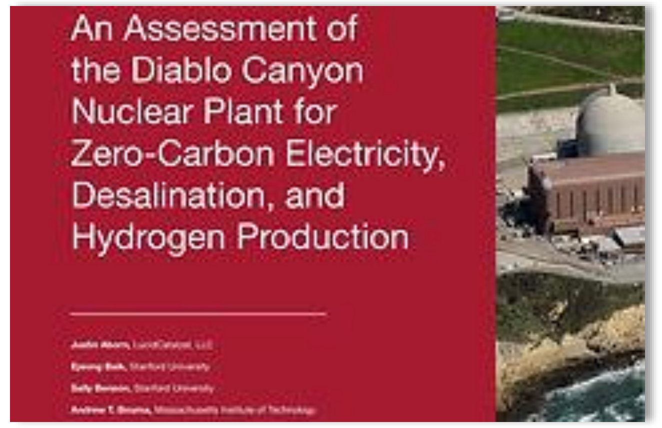
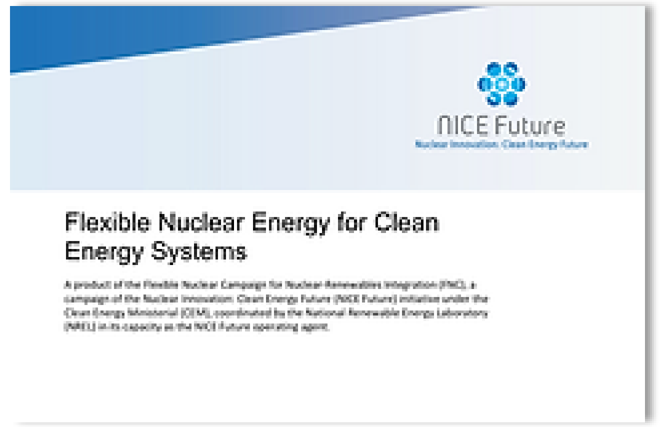
Outline

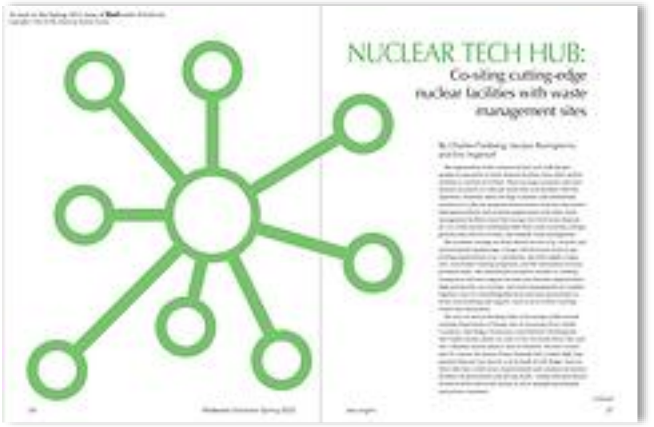
About LucidCatalyst

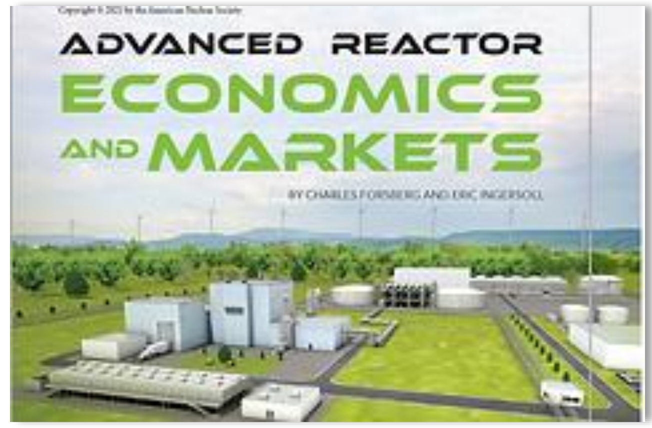
- Deep analysis of drivers of optimal strategies to control nuclear cost and risk in projects
- Identification and design of practices in nuclear plant delivery to enable commercial nuclear transactions
- Deep techno-economic analysis to direct advanced reactor product development and enable an investment case
- Partnership with clients to become an ‘intelligent customer’
- Identification and development of innovative design and delivery strategies that meet well-defined industrial energy user cost and performance requirements
- Development of transformative strategies to accelerate products to market, and drive cost and risk reduction
- Internal and external engagement around the nuclear energy value proposition

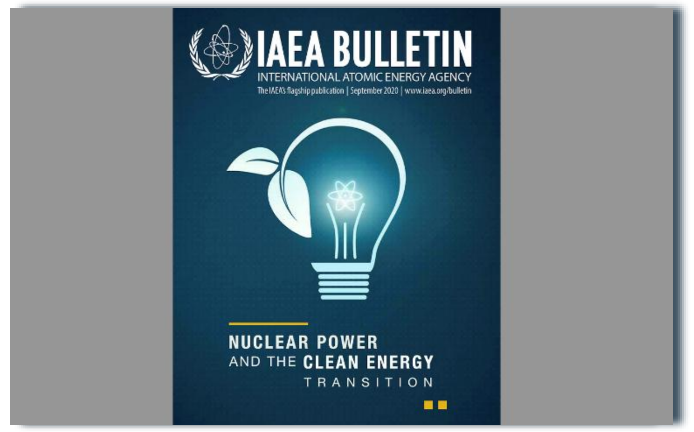
In addition to extensive operational support, LucidCatalyst has published extensively on nuclear cost drivers, market analysis to inform nuclear cost targets, and a series of reports on cost reduction opportunities through innovative design and delivery.





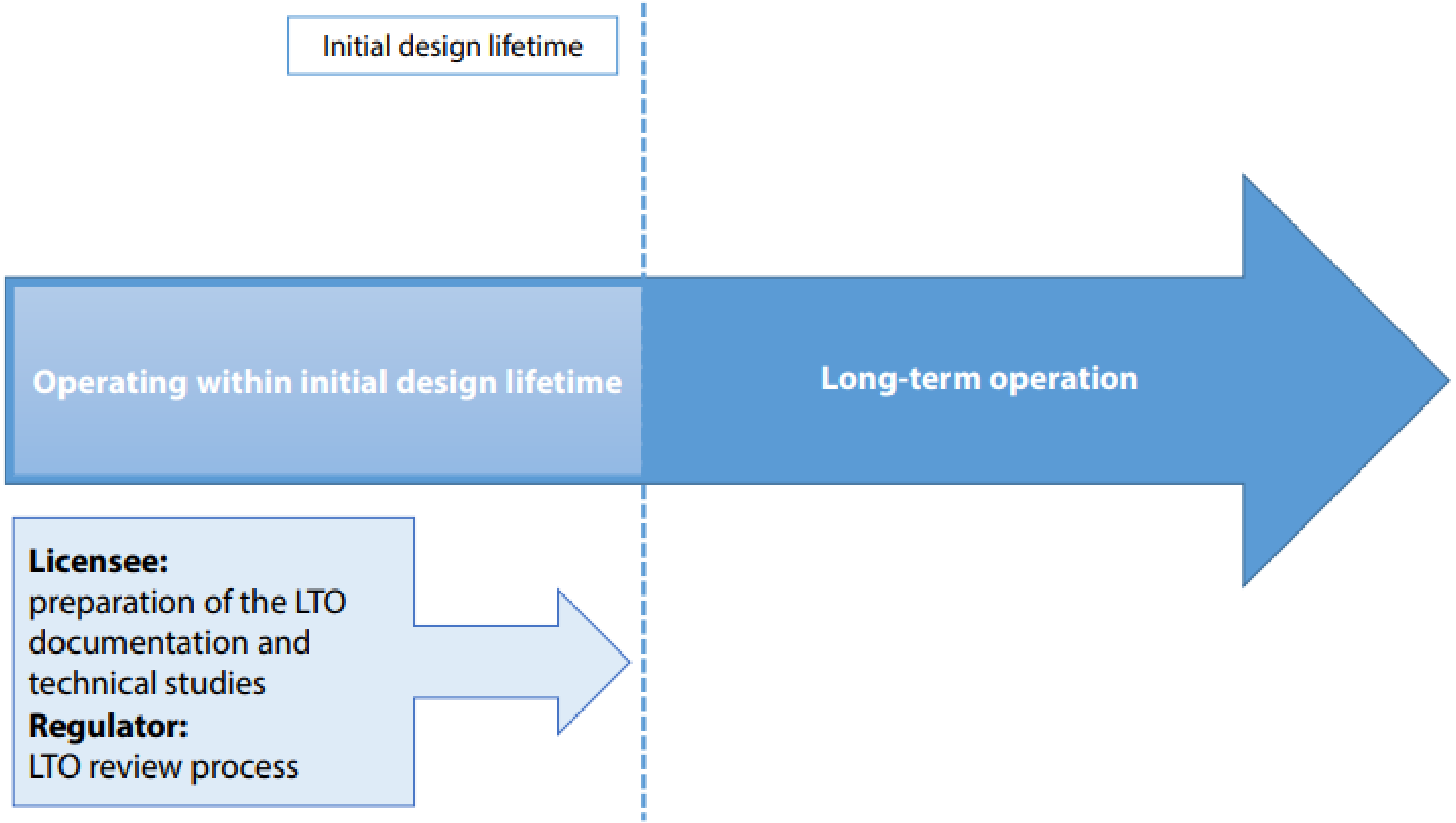






About Long-Term Operations

Definition of LTO

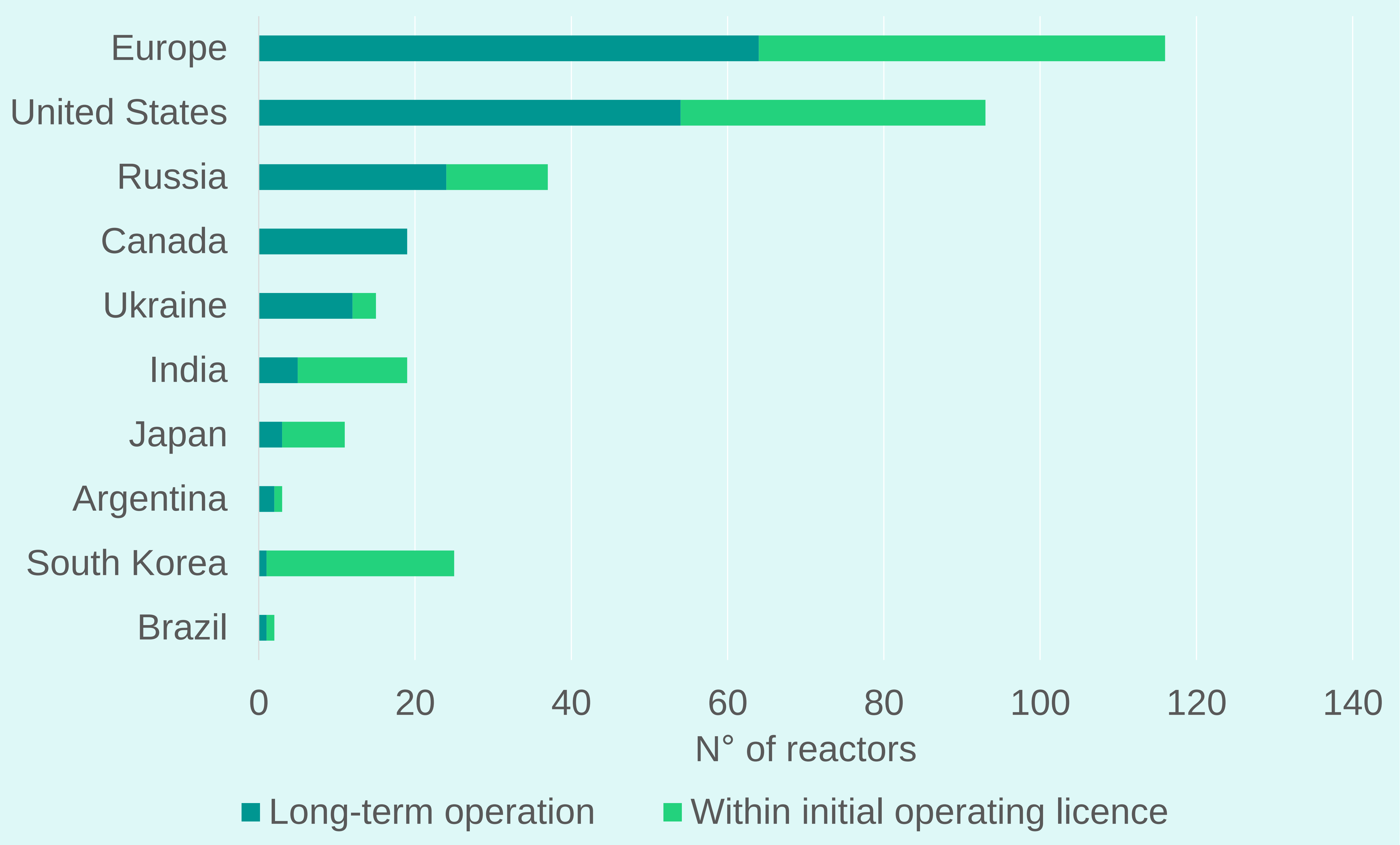


LTO experience is significant and growing worldwide

As of 2023	World
Average age	32 years
Share of reactors in LTO	45%
Share of reactors with more than 40 years of operation	32% (133 units)
Age of the older reactor	54 years, Beznau-1 in Switzerland

Globally, most reactors **will operate 60 years**, according to current long-term operation plans

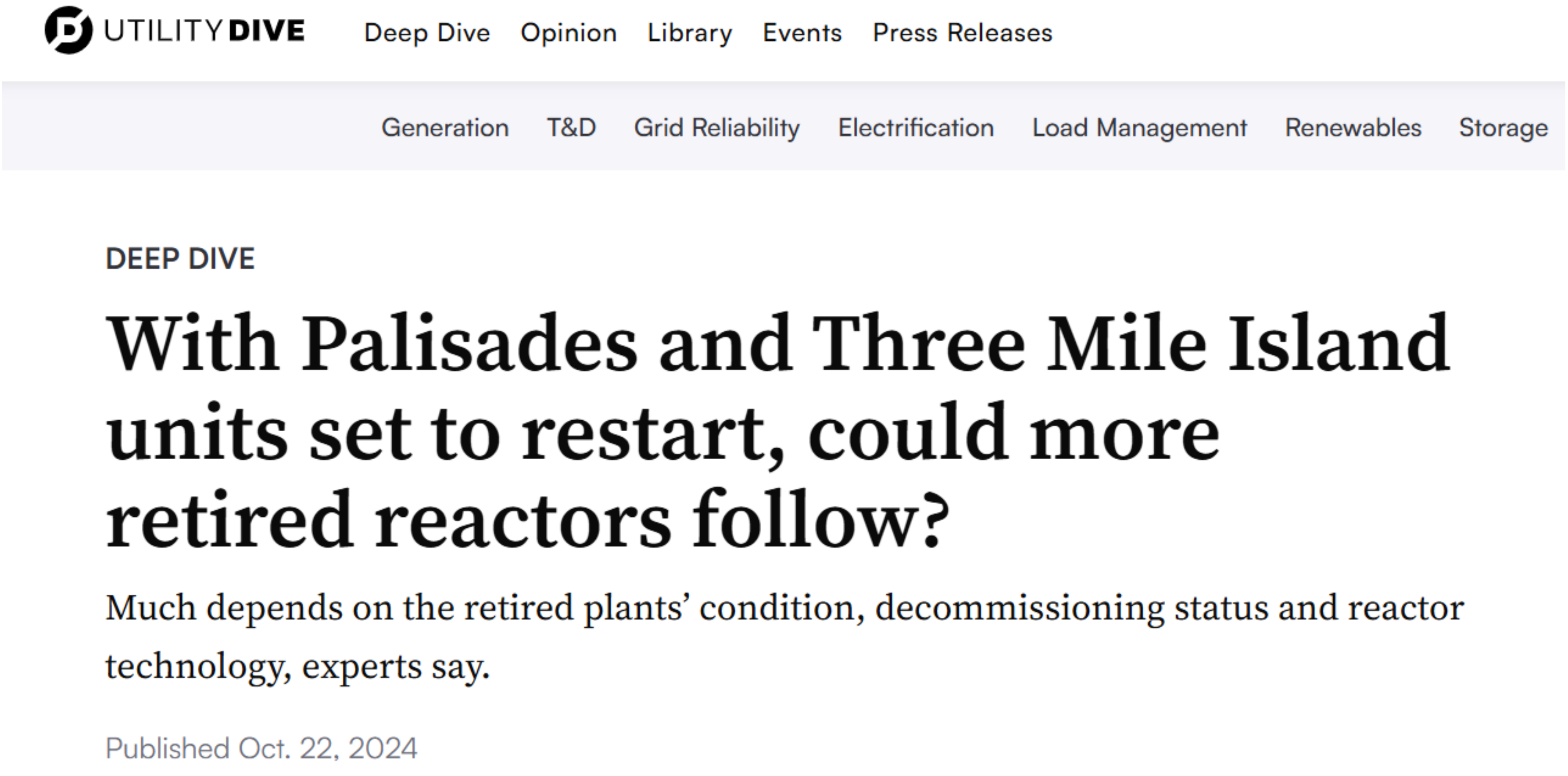
Figure 1: LTO trends in selected countries, 2023



Source: LucidCatalyst based on data from IAEA PRIS
Note: European figures include Swiss and UK reactors. The initial operating period is consistent with national regulations detailed in NEA (2019) and different reactor types.

Some retired units are even slated to resume operations

- In the US, more than 10 GW of nuclear capacity has been retired over the last decade, primarily due to economic reasons
- Policy support and increasing energy demand from data center growth are now pushing utilities to bring retired plants back online
- The feasibility of restarting these plants depends on their decommissioning status, condition, and the price that energy users may be willing to pay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DEEP DIVE

With Palisades and Three Mile Island units set to restart, could more retired reactors follow?

Much depends on the retired plants' condition, decommissioning status and reactor technology, experts say.

Published Oct. 22, 2024

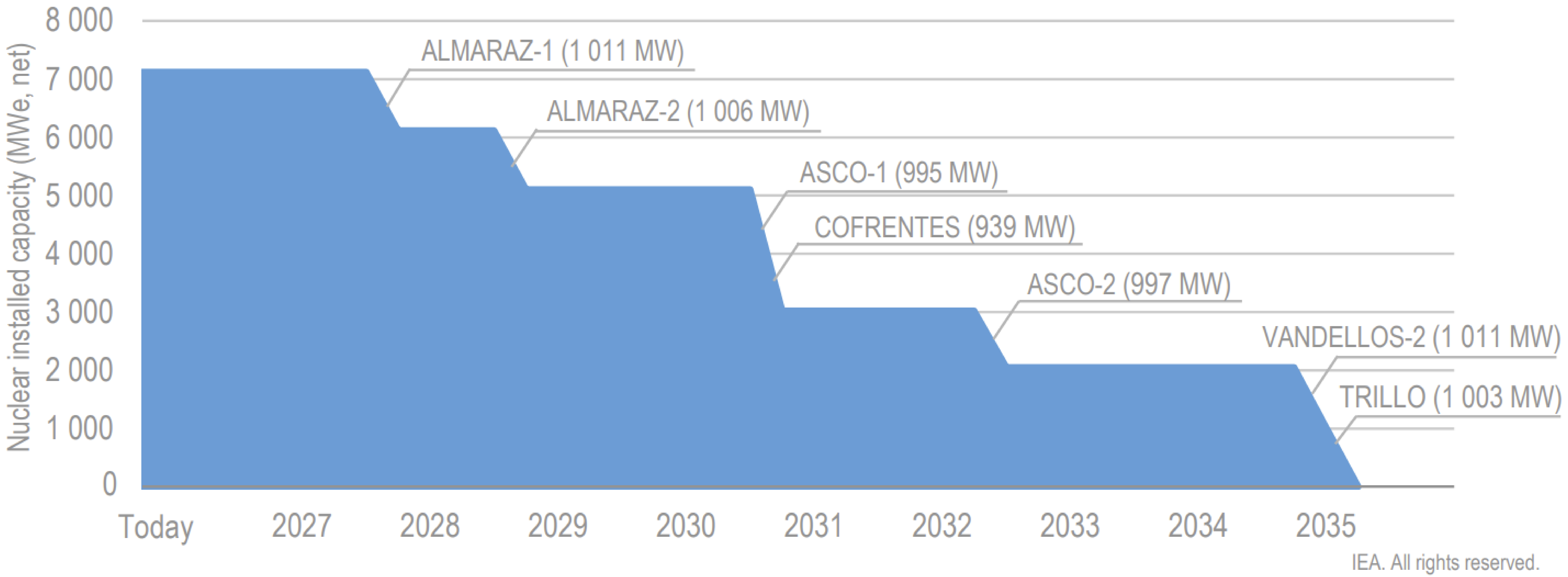
Source: https://www.utilitydive.com/news/palisades-three-mile-island-duane-arnold-nuclear-reactor-restart-holtec-nextera-constellation-nrc/730393/

Figure 2: Indicative investment costs for nuclear in the US

Source: LucidCatalyst based on DOE (2024), NEA (2021), Power Technology (2024) and IEA (2024) Note: The cost of new build correspond to a post-FOAK two-unit AP1000 project. Solar PV are 2023 values

A Case Study for Spain

Nuclear phase-out plan in Spain



Note: MW_e = megawatt electrical.

Source: Government of Spain's response to the IEA questionnaire.

Source: IEA (2021)

A Real Consulting Case

- **Prompt:** Your client is the Ministerio para la Transición Ecológica y el Reto Demográfico in Spain. In light of recent announcements from big tech companies in the US and nuclear revival in Europe, they are considering shifting their stance on nuclear power. However, they are unsure about the benefits that nuclear could bring to Spain. How would you help the ministry?
- **Objective**: Should Spain pursue LTO of existing nuclear power plants? (strategic decision)
  - Broad yes/no question interfering with many dimensions
  - Numbers and analysis will help inform the decision

Proposed Analytical Framework

1. Is LTO a commercially-viable solution?
- International trends and reasons for recent closures
- Technical feasibility and aging mechanisms
- Safety and performance with aging
- Regulatory frameworks

3. Any additional benefits from LTO?
- Gross domestic product
- Employment
- Tax contribution
- Waste management funds

2. Is LTO an asset for the energy transition?
- Emissions reductions
- Displacement of fossil fuels
- Economics and profitability
- Security of supply
- Renewable deployment risks
- Public acceptance

4. Is Spain capable of undertaking LTO projects?
- Supply chain capabilities
- Workforce adequacy
- Waste management infrastructure
- Utilities' willingness to invest
- Availability of investment funds

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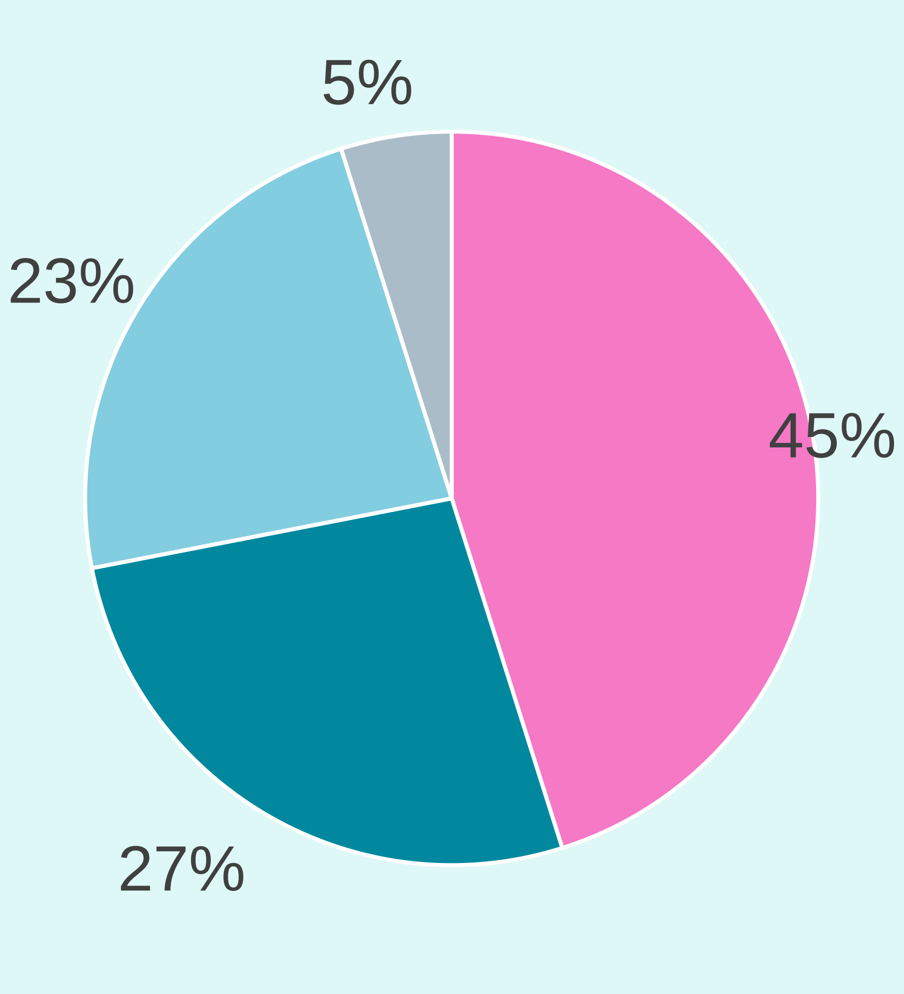
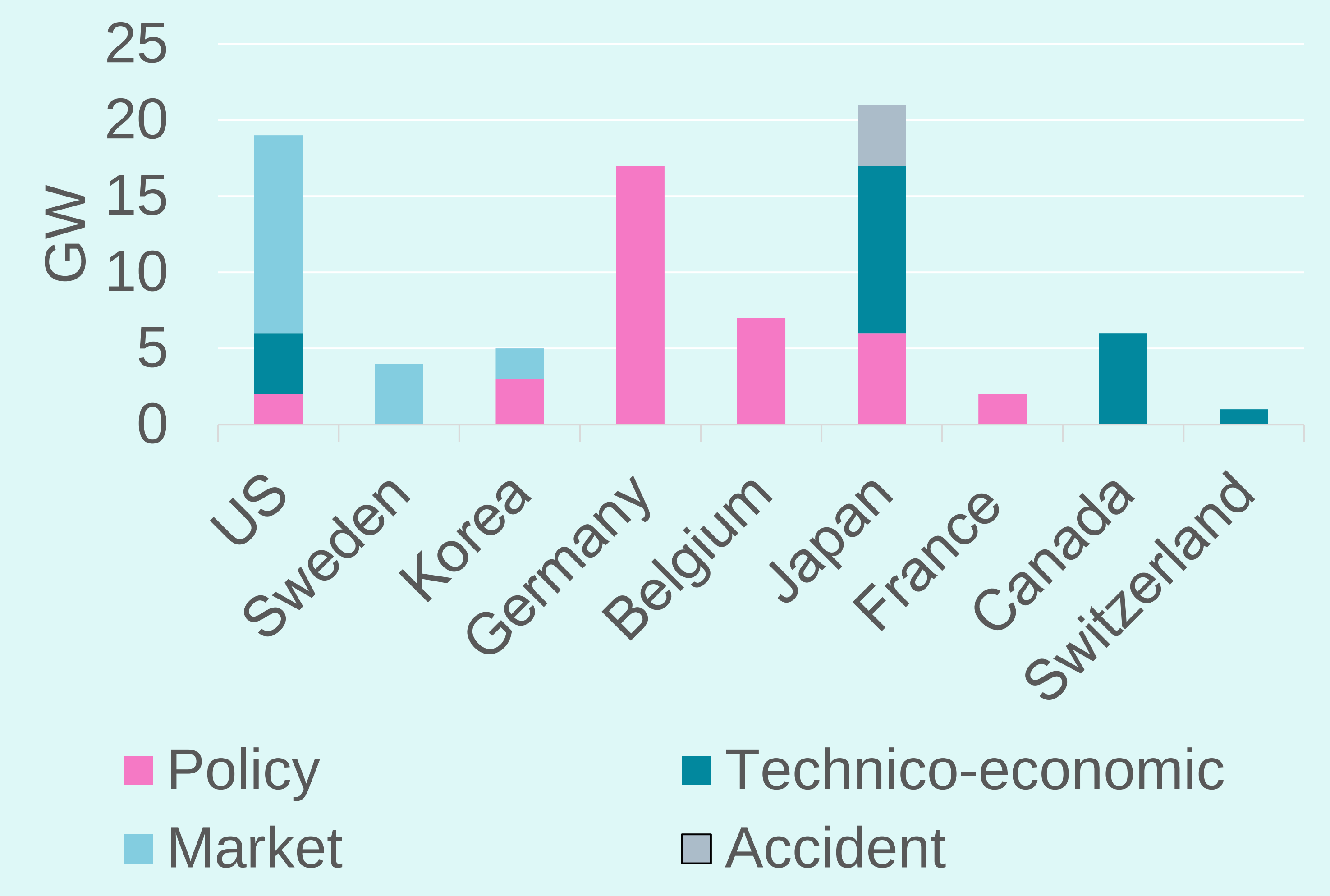
Nuclear power plants are primarily retired due to policy decisions and adverse market conditions

- The cumulative nuclear capacity that has been retired since 2011 could account around 70-80 GW by 2025 (~20% of the today's installed nuclear capacity) according to stated policies in OECD countries
- Over 60% of recent closures were motivated by policy decisions and challenges in existing market
- The security of supply crisis triggered by the war in Ukraine has led to nuclear policy shifts and/or strengthened support in many countries worldwide
- Policy support and increasing energy needs for data centers—driven by the AI revolution—are now leading to nuclear plant restarts

Figure 3: Plant closures by country and reason according to stated policies in OECD countries, 2011-2025

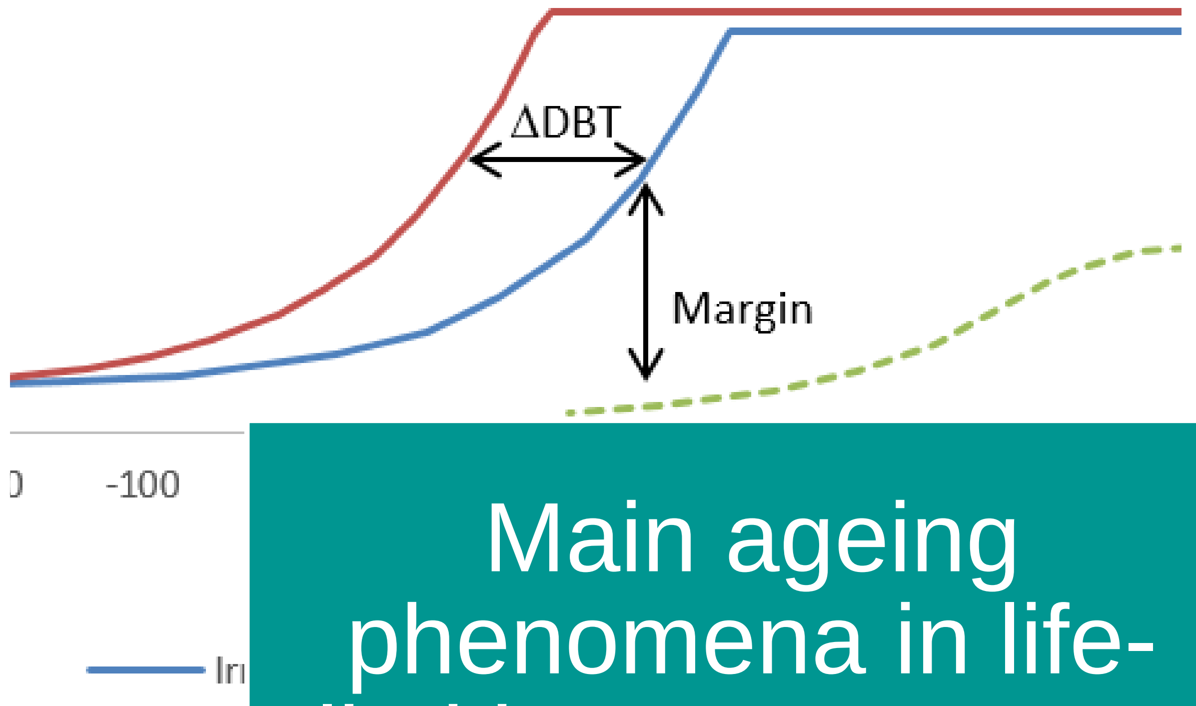




Source: NEA (2021)
Note: The technologies covered are LWRs and PHWRs. The plant closures in Japan due to policy reasons were decided by the utilities considering the request from national and/or local government.

No major technical showstopper for longer operating periods and adaptations

Almost all components can be replaced



Main ageing phenomena in life-limiting components well-understood

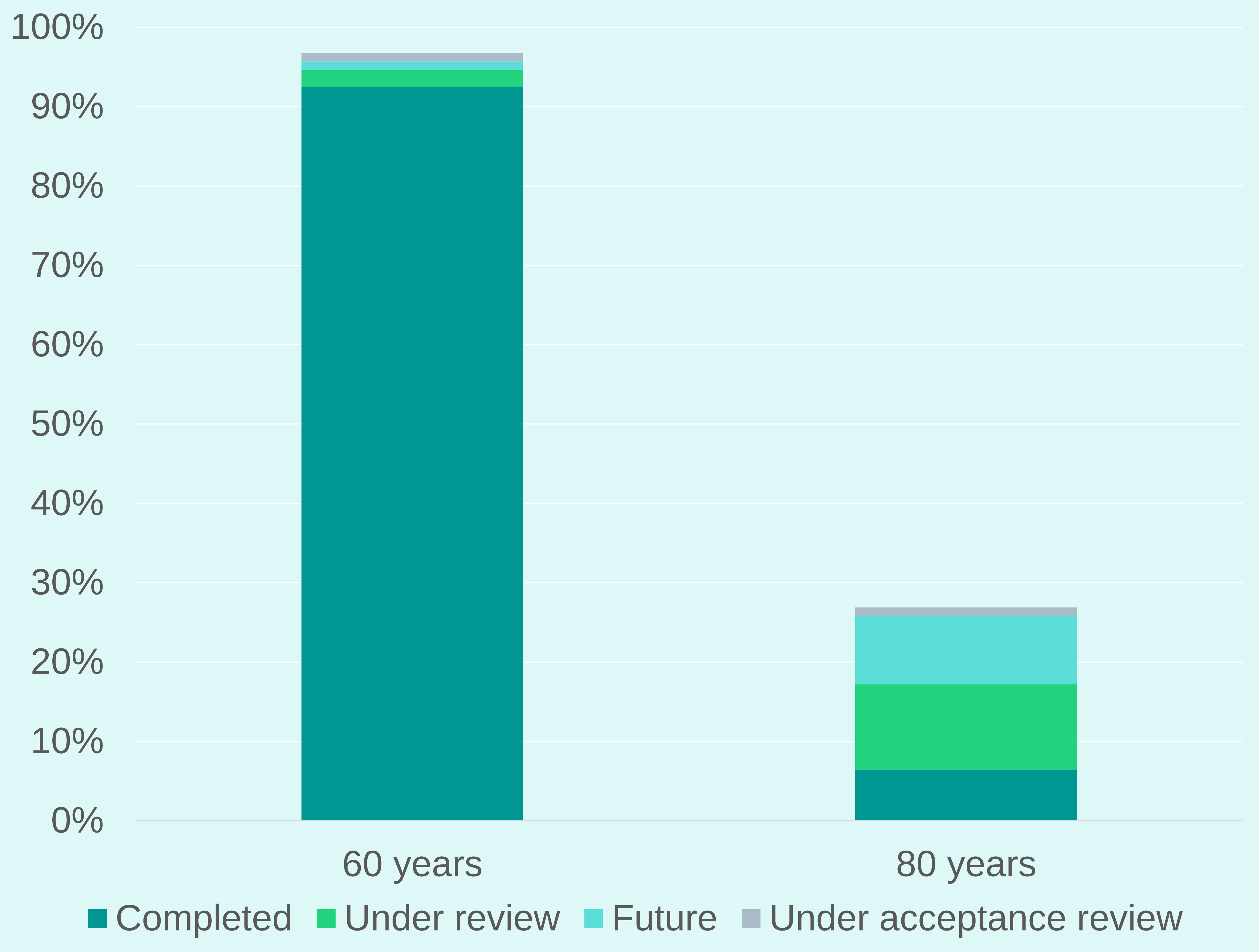
Safety upgrades are typically combined with plant enhancements (e.g. power uprates)

LTO should not face major generic technical barriers if utilities implement enhanced ageing management programs using the technical evidence already available while performing the necessary repairs and replacements.

Operation beyond 60 years in the United States

- Technical uncertainties for operations beyond 60 years are decreasing:
    - 6 reactors approved and intent covers more than 20% of the US fleet
- Technical evidence exists but more efforts needed to track:
    - Increased susceptibility to existing ageing phenomena
    - New degradation modes
- Final decision mainly driven by policies and market conditions rather than technical challenges

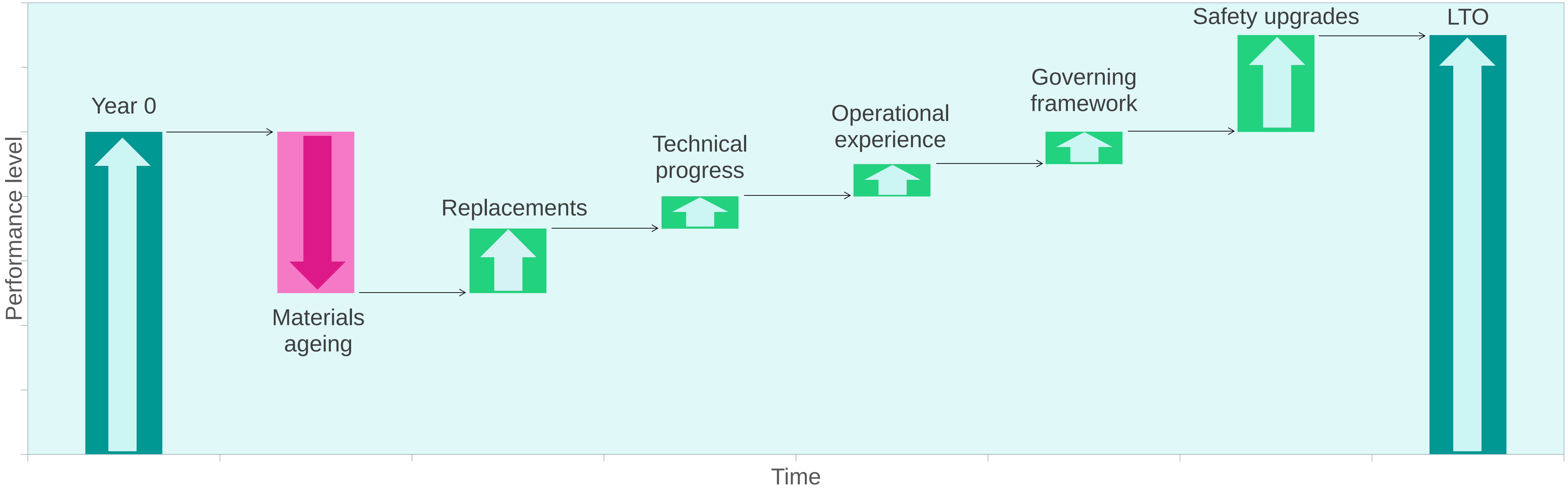
Figure 4: License renewals trends in the United States, 2023



Source: LucidCatalyst based on NRC (2023)

Safety and operations can improve despite ageing

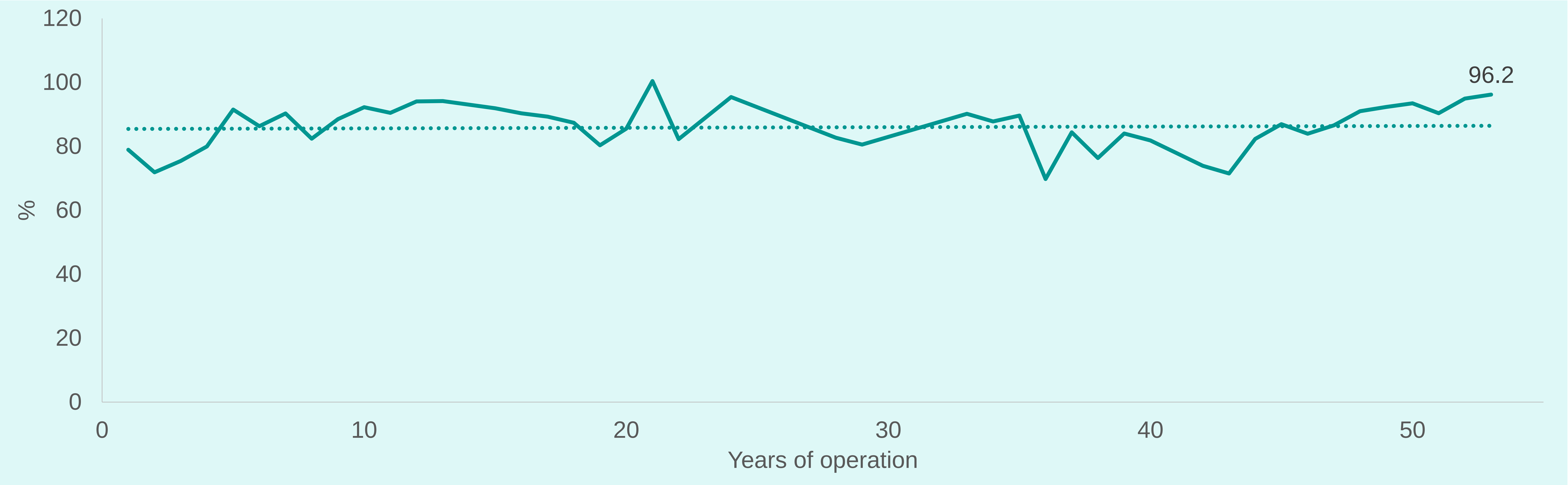
Figure 5: Qualitative evolution of the performance level of a nuclear power plant over time



The performance level of a nuclear facility results from the combination of several factors, including organisational aspects, that enable continuous safety and operational improvements.

Capacity factors remain high despite ageing

Figure 6: Capacity factor by reactor age for the global existing fleet, 2023



Source: LucidCatalyst based on [IAEA PRIS]

There is no age-related variation in reactor capacity factor. Reactors with 50 years of operational history perform at the same level as newer ones

LTO is enshrined in most regulations as part of a continuous improvement logic

Table 1: Overview of LTO regulatory regimes

Country	Initial length term	Notes on initial length term	Term length for LTO	Notes on term length for LTO
United States	40 years	-	20 years	No limit on the number of renewals
France	Indefinite	Initial design hypothesis for certain equipment is 40 years	Indefinite	No limit on operation as long as it fulfils its safety obligation, as reviewed during decennial periodic reviews
Canada	10 years	Determined on a case-by-case basis; the initial design life of reactors is approximately 30 years	10 years	Refurbishment process can extend the life of a reactor for several decades (e.g. another 30 years)
Spain	10 years	Determined on a case-by-case basis; the initial design life of reactors is approximately 40 years	10 years	Determined on a case-by case basis
United Kingdom	Indefinite	-	Indefinite	No limit on operation as long as it fulfils its safety obligation, including a decennial PSRs

- Typical term length for LTO: 10-20 years

Source: NEA (2019)
Note: PSR (Periodic Safety Review)

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A nuclear phaseout could lead to higher gas consumption and carbon emissions

- When a nuclear plant is retired, the capacity gap is usually filled in the short term by a combination of renewables, gas, and batteries necessary to maintain the same level of service
- In Spain, the closure of the nuclear fleet could lead to:
  - An additional cumulative consumption of ~130 TWh of gas[1] between the period of 2027-2050, representing a total additional cost of $4.3 billion[2]
  - Additional cumulative emissions of ~30 $MtCO_2$[3] between the period of 2027-2050, representing an additional cost of $2 billion[4]

Figure 7: Cumulative additional gas consumption induced by the nuclear phaseout in Spain

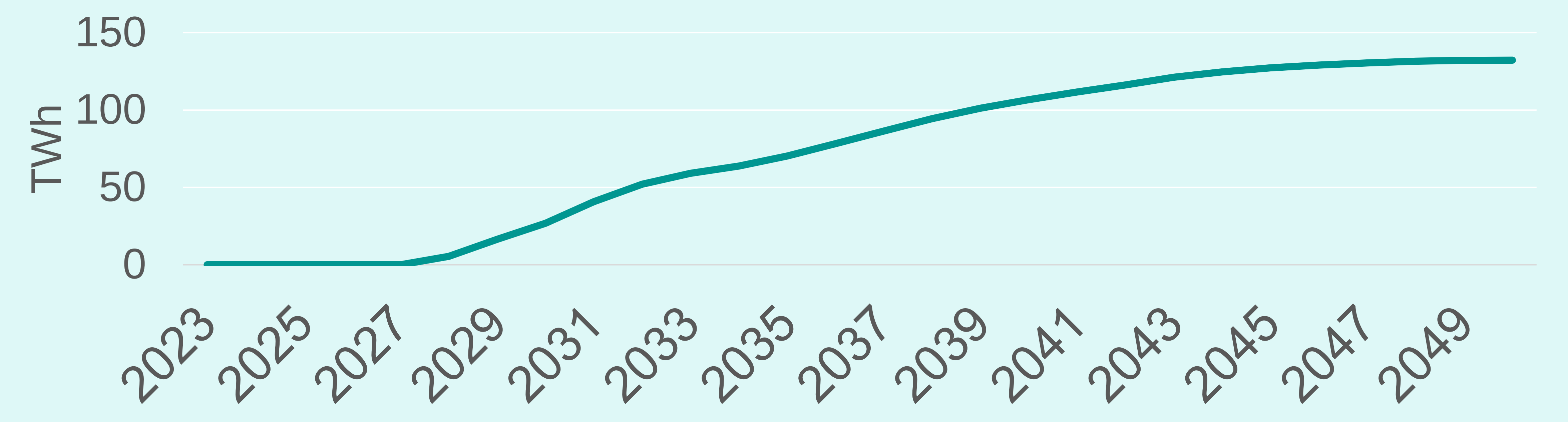
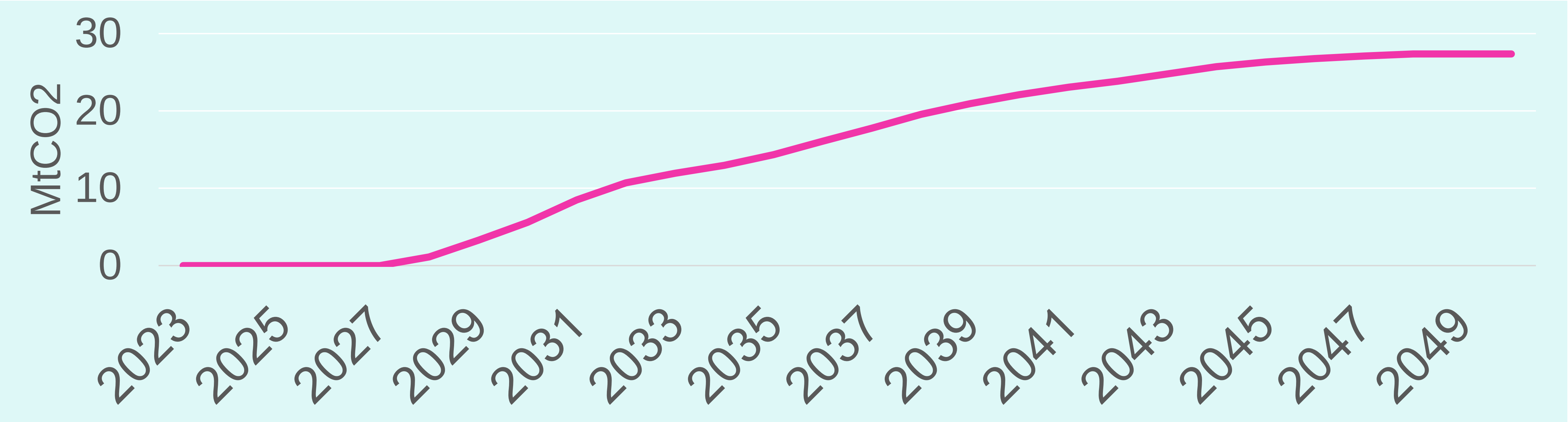


Figure 8: Cumulative additional carbon emissions induced by the nuclear phaseout in Spain

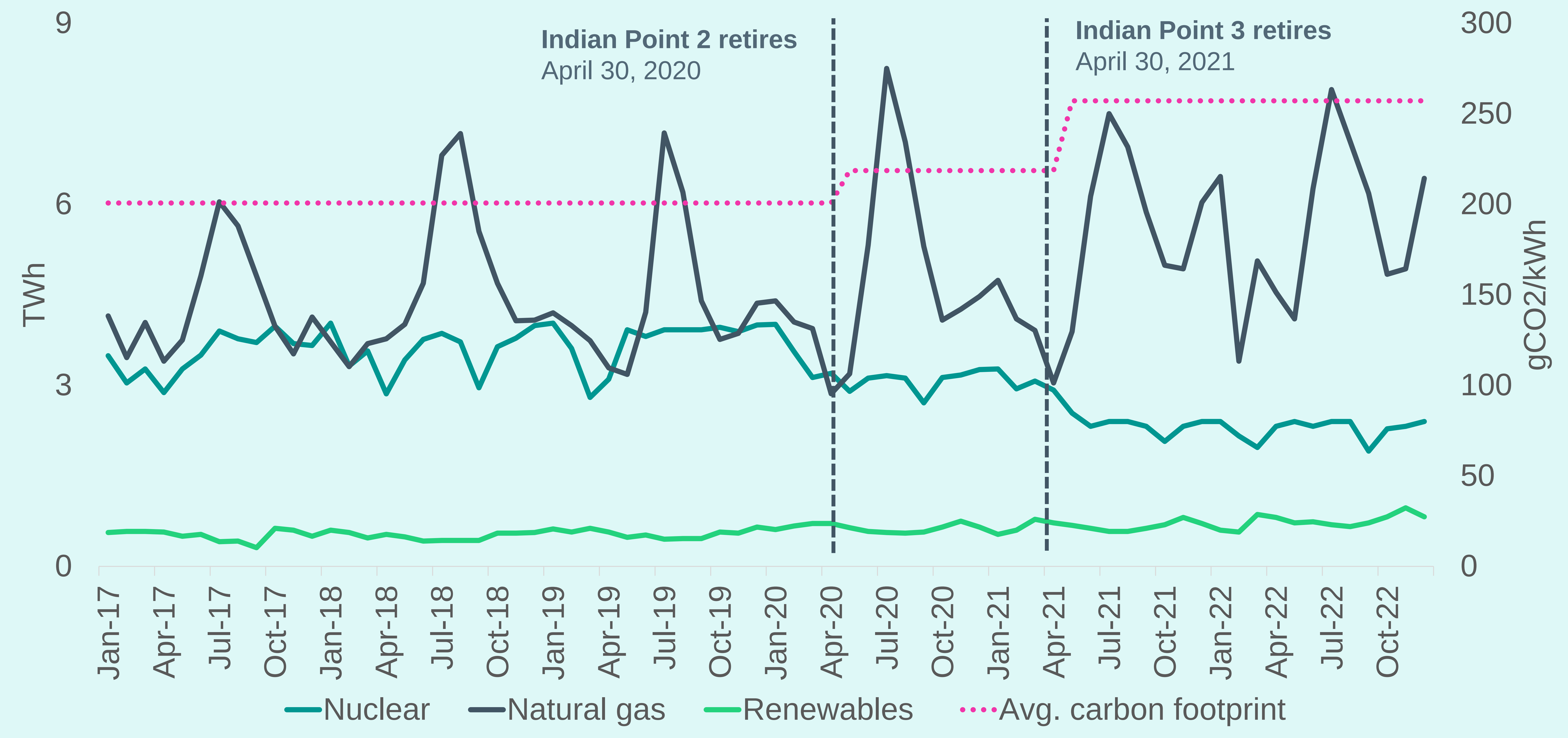


Source: LucidCatalyst based on AFRY (2023) Note: The additional gas consumption and carbon emissions are derived by comparing "Cierre nuclear" and "Prorroga nuclear" in the scenarios modelled in AFRY (2023)

1. AFRY (2023) estimates around 70 TWh of additional electricity generation from combined cycle gas turbines which have a thermal efficiency of around 55%.
2. Assuming a gas price of $33/MWh (based on historic MIBGAS prices)
3. From AFRY (2023)
4. Assuming a carbon price of $66/MWh (based on EU-ETS prices)

There are real examples showing higher reliance on gas after nuclear retirements

Figure 9: Electric power generation by fuel New York ISO, Jan-2017-Dec 2022 (generation left axis, emissions right axis)



For effective decarbonisation strategies: i) avoid the closure of existing low-carbon assets providing firm capacity and ii) combine low-carbon firm capacity with variable renewables and storage options to displace fossil fuels more effectively and minimize risks

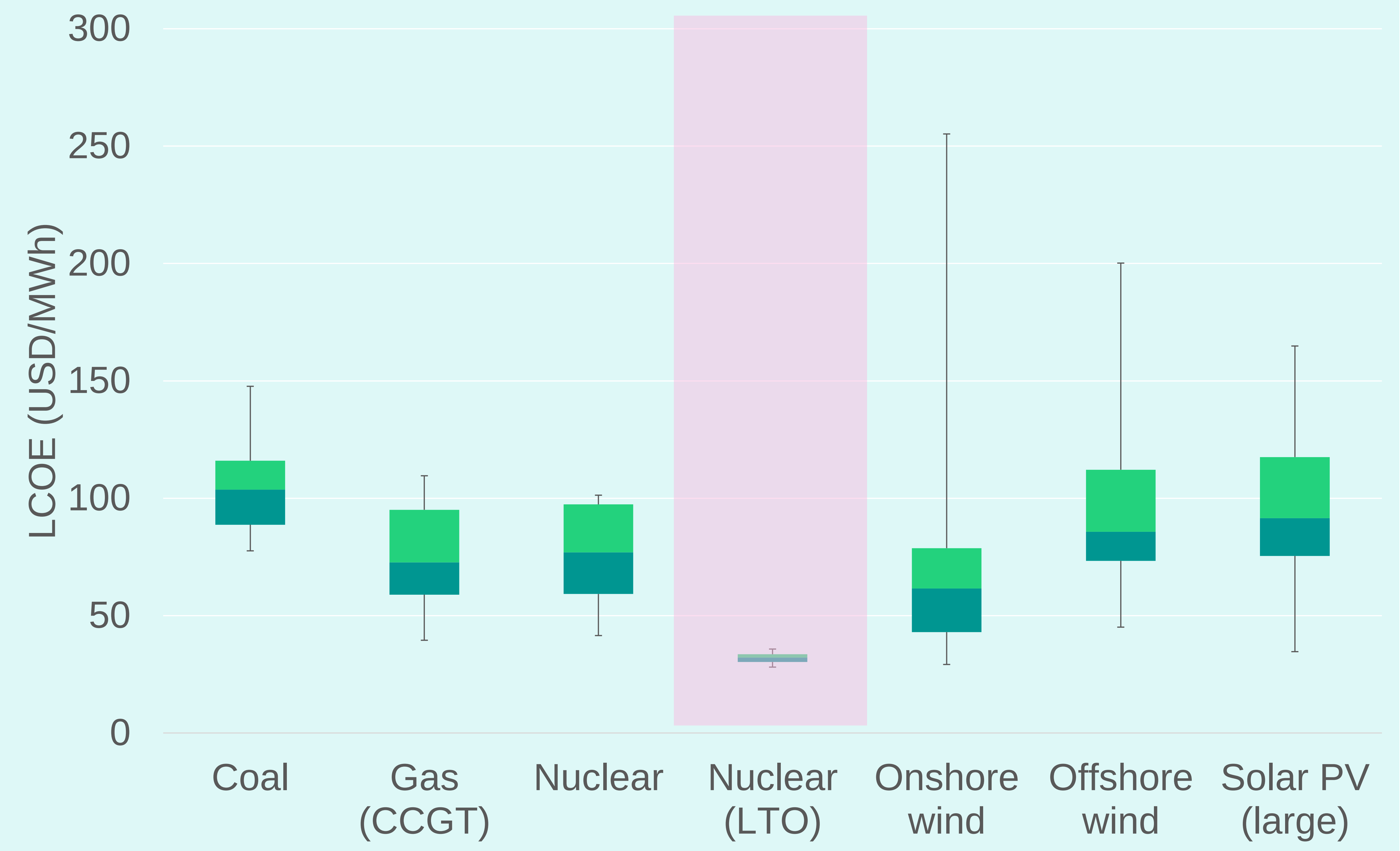
Source: NEA (2021)
Note: Carbon intensity has been computed using the mean values for each technology from Bruckner (2014).

LTO is one of the most attractive low-carbon investment options in many regions

Table 2: Key economics features of nuclear LTO

By 2030	Long-term operation
Overnight costs (USD/kWe)	450-950
LCOE (USD/MWh)	25-50
Cost structure	Closer to fossil-generators
Construction lead time	Several months with some activities being performed during normal outages and the reactors online
Scope complexity	Low, with lower amount of critical components and civil works.
Learning curve	Extended learning with predictable and well-contained construction costs

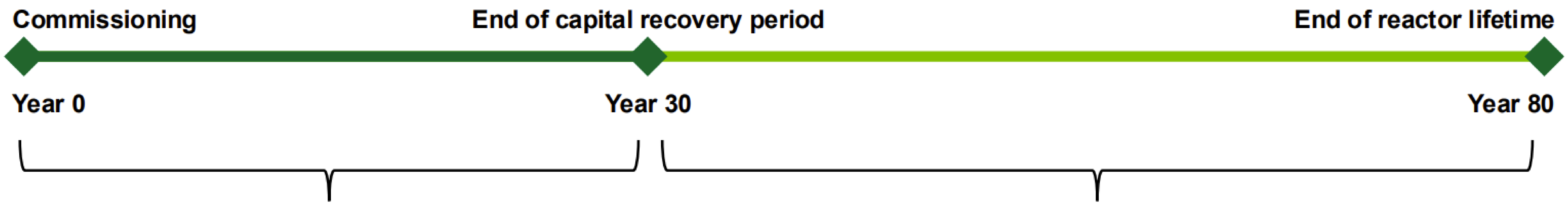
Figure 10: Levelized Cost of Electricity by technology, 2025



Source: LucidCatalyst based on IEA/NEA (2020), NEA (2021)
Note: Coal includes lignite plants. Discount rate of 7% and carbon price of $30/tCO2. Nuclear only includes large nuclear Gen III+ design and not SMRs.

Once a nuclear power plant is paid off, they generate power with low and predictable operating costs

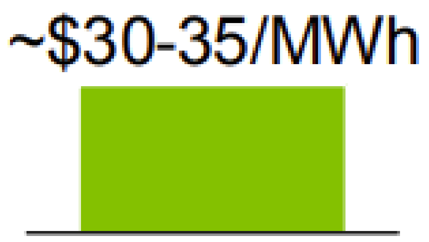
Costs over nuclear plant lifetime



LCOE during capital recovery period (~30 years)

During a nuclear plant's first ~30 years of operations, paying back debt and equity investments is reflected in a **higher initial LCOE**

Generating costs after capital repayment (~50 years)[1]



However, once nuclear plants are paid off, they generate power for the remainder of their lifetime with **low and predictable operating costs**

Source: DOE (2024).

An LTO project is not a new nuclear build project

Table 3: Comparison of nuclear LTO and new build economics

By 2030	Long-term operation	New large nuclear build
Overnight costs (USD/kWe)	450-950	5100-2800
LCOE (USD/MWh)	25-50	140-80
Cost structure	Closer to fossil-generators	Investment and fixed costs dominate and are higher than those of LTO
Construction lead time	Several month with some activities being performed during normal outages and the reactors online	Various years without any revenue generation in between
Scope complexity	Low, with lower amount of critical components and civil works.	High, involving more critical components and significant amounts of civil works with dense concrete & rebar structures
Learning curve	Extending learning with predictable and well-contained construction costs	Initial stages of the learning curve

Source: LucidCatalyst based on NEA (2021), IEA (2024)

Note: Overnight costs and LCOE by 2030. This is a simplification for explanatory purposes based on major global trends. Some values may vary depending on specific projects

Taxes make LTO unprofitable in Spain

- Around 30% of the total generation cost of nuclear power plants in Spain consists of taxes.
- While nuclear reactors are competitive based on their LCOE plus levies for waste management, they become unprofitable once taxes are added.
- Approximately 60% of these taxes are not justified, as they represent a double-counting of externalities already covered by the Tasa Enresa. This includes, for example, the Ecotasas and the Impuesto sobre la producción de combustible nuclear gastado.[1]
- Assuming LTO of up to 60 years, the Tasa Enresa could also be reassessed downward, as the extended timeframe would allow more time to collect levies—further enhancing the competitiveness of the nuclear fleet

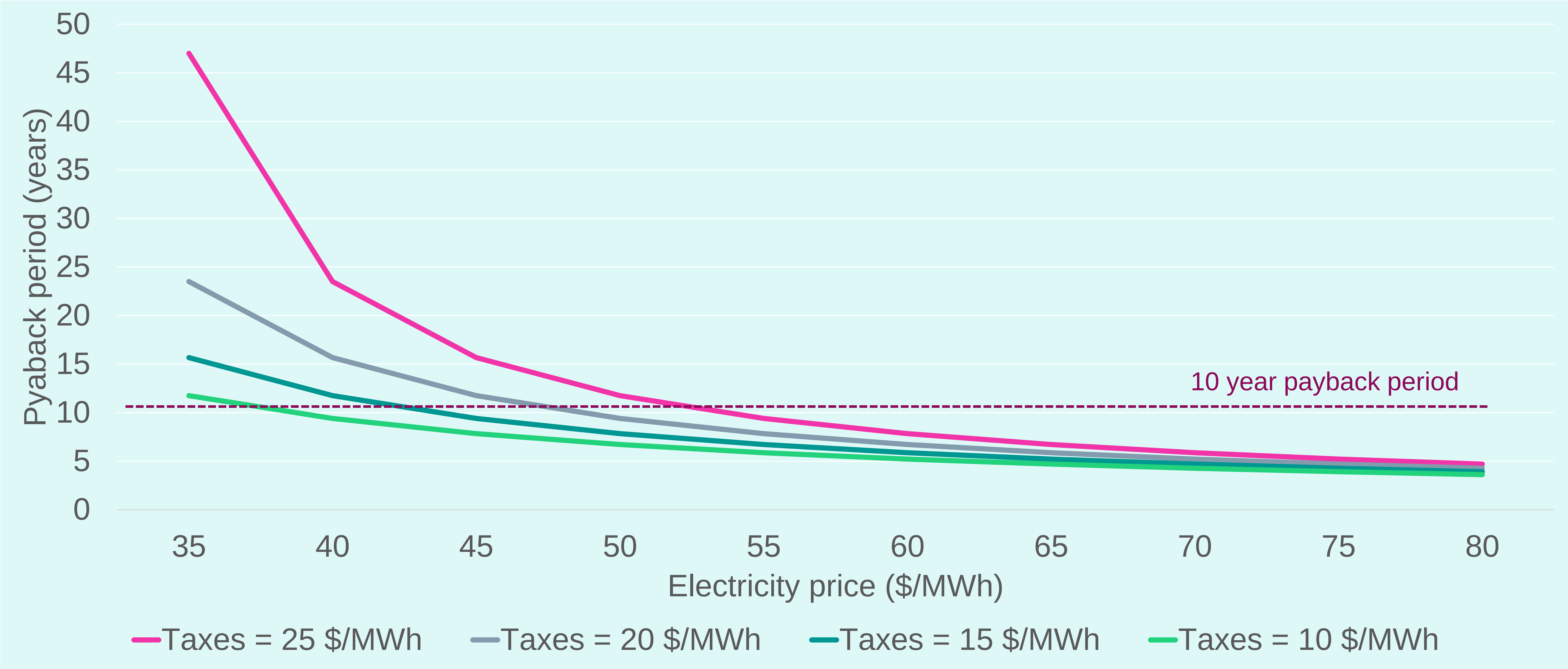
1. PwC (2024)

Figure 10: Competitiveness of the Spanish nuclear under different assumptions

Source: LucidCatalyst based on PwC (2024)

Taxes also have a strong impact on LTO investment payback

Figure 11: LTO investment payback as a function of electricity prices and the level of taxes



Source: LucidCatalyst analysis
Note: Total investment for a 10-year LTO of $1.8 billion for a 1 GW unit, including both the investment and fixed operational and maintenance cost over 10 years. Fuel costs of $5/MWh. Capacity factor of 85%

- For example, with taxes of $15/MWh and a contract for difference or PPA of $55/MWh[1,2], the LTO investment payback is ~7 years

1. Contracts for difference and PPAs for existing nuclear are allowed under the 2023 European Market reform.
2. In Belgium, the agreement reached between the government and owner considers a contract for difference for the extended operation of Doel 4 and Tihange 3 units.

LTO can also save billions from a system cost perspective

- Replacing firm nuclear capacity with variable renewables while maintaining the same level of service requires investments in capacity, storage, and grid infrastructure. This can make the overall system more expensive.
- System costs become more acute as the system moves closer to zero emissions with high shares of variable renewables
- In Spain, closing nuclear reactors would lead to over $30 billion in additional infrastructure investment between 2029–2040, with 77% going to new generation and 23% to grid expansion[1]

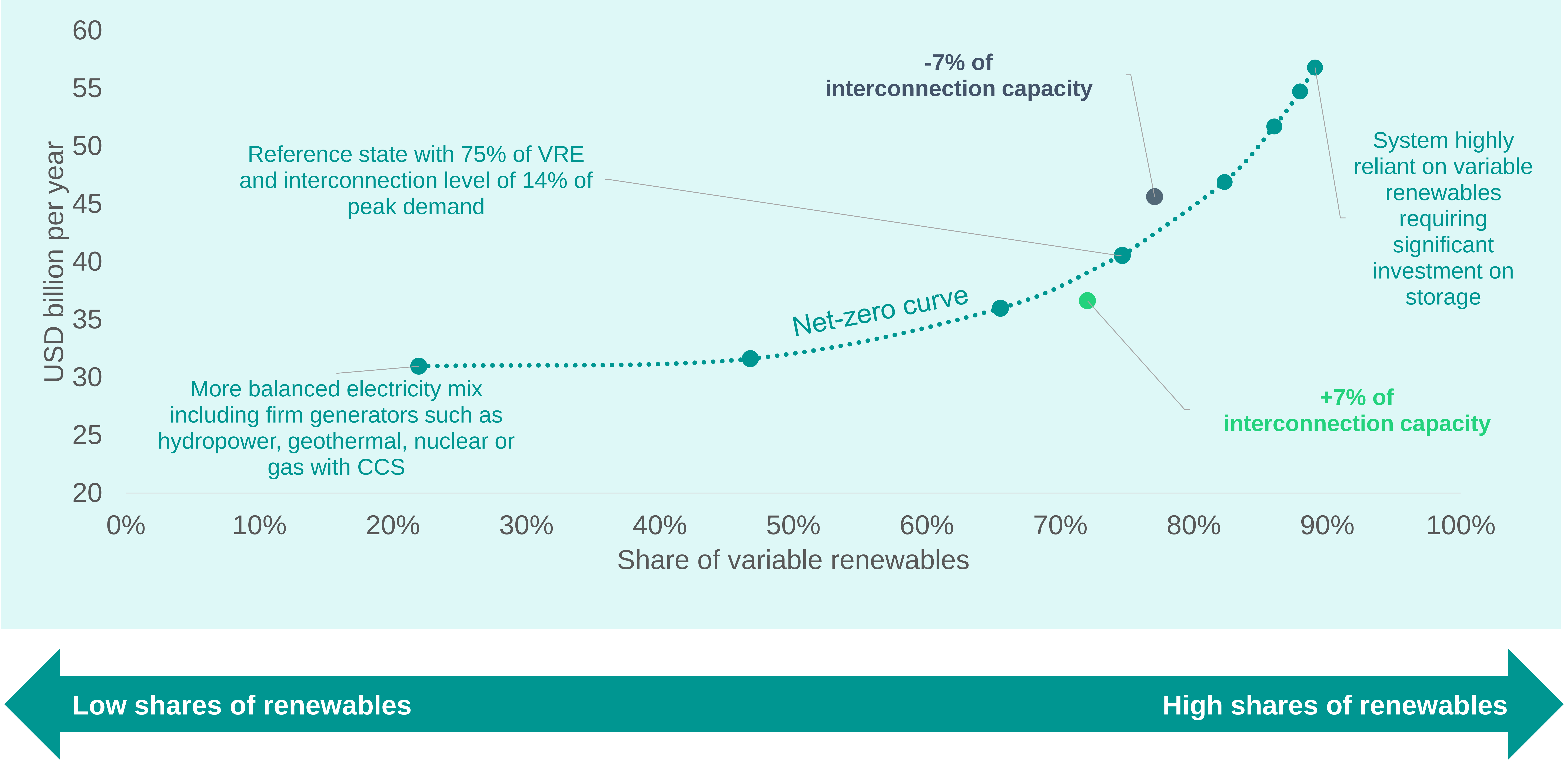
1. Estimated from the modelling performed in AFRY (2023)

Figure 12: Cumulative additional investment induced by the nuclear phaseout in Spain

Source: LucidCatalyst based on AFRY (2023) Note: The additional investment costs are derived by comparing “Cierre nuclear” and “Prorroga nuclear” in the scenarios modelled in AFRY (2023)

Achieving net-zero emissions primarily with variable renewables can be expensive

Figure 13: System costs at net zero as a function of the share of variable renewables and interconnection level

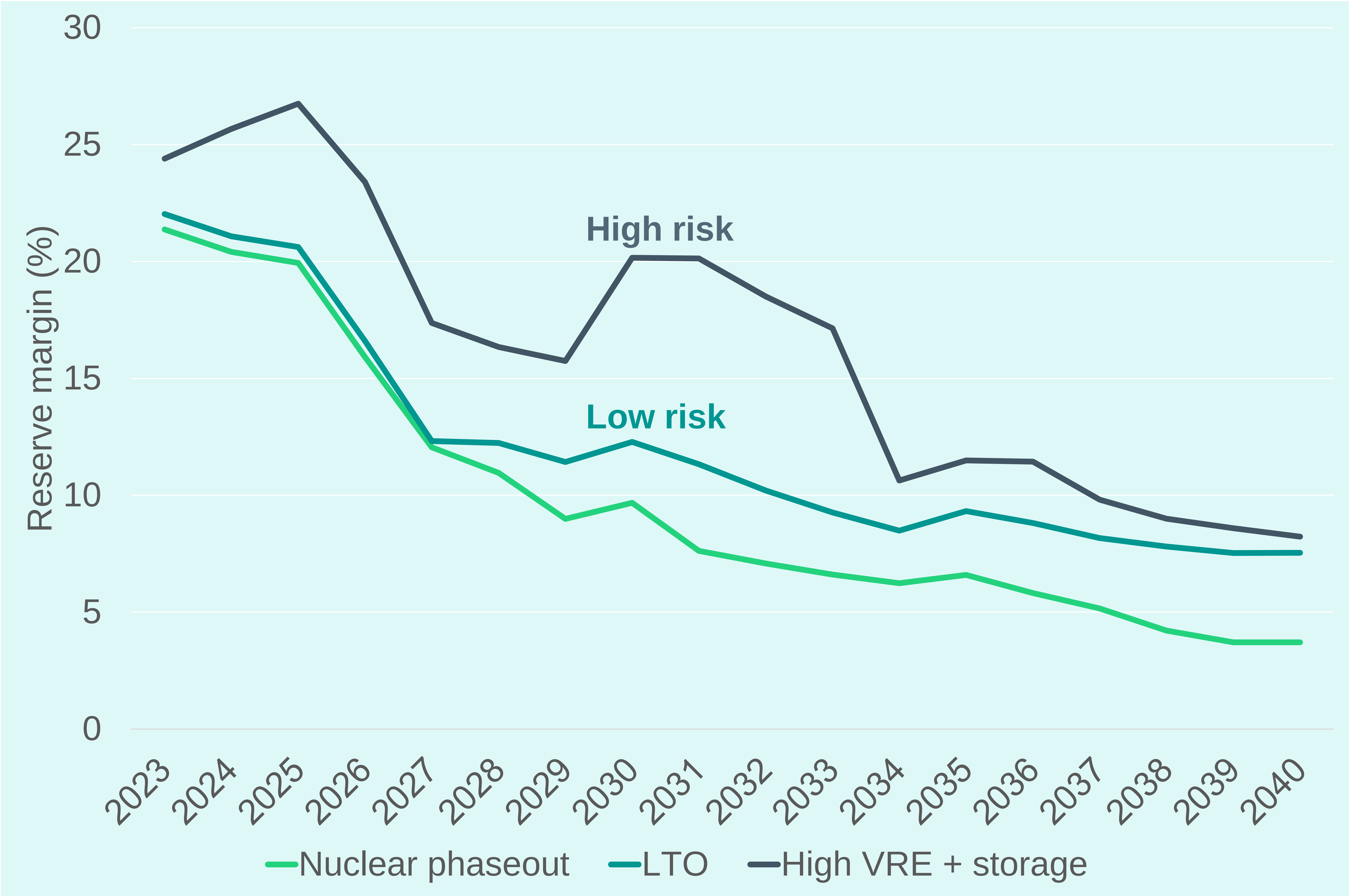


Note: VRE = variable renewable energy. CCS = carbon capture and storage. This is an illustrative example for explanatory purposes computed with a capacity expansion model with hourly resolution. Reference system of an average demand of 50 GW and a peak demand of 83 GW. Interconnection level is defined as a percentage of peak demand. The total economic system costs account for the physical costs (CapEx and OpEx) minus net export revenues. Balancing costs, connection costs and transmission and distribution costs are not considered.

LTO enhances electricity security of supply in Spain

- LTO enhances the electricity security of supply in different ways:
  - It displaces gas generation, reducing system exposure to the volatility of fossil fuel prices
  - Automatically increases reserve margins[1] as more capacity is available in hours of peak demand
- While systems with high shares of renewables and storage can show favourable reserve margins, they carry higher deployment risks

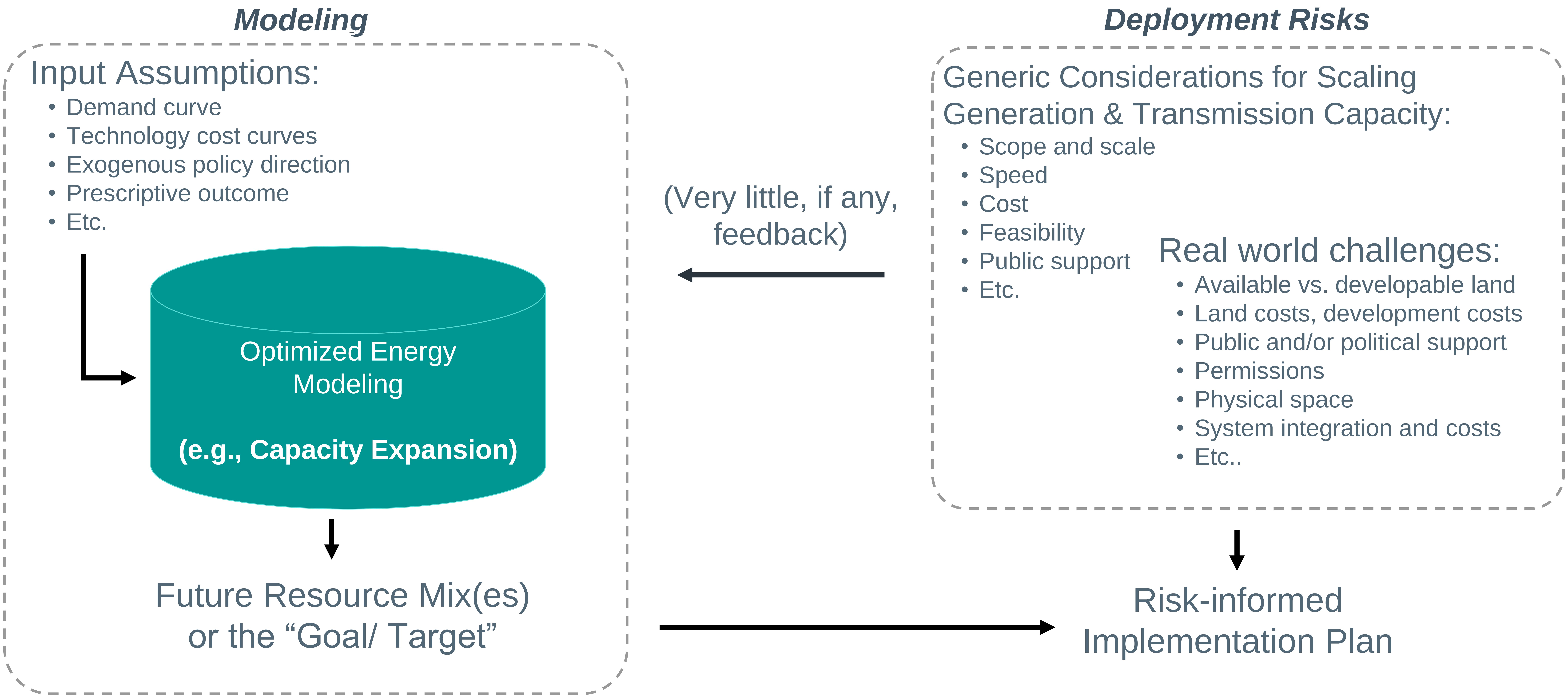
Figure 14: Evolution of reserve margins by selected scenario in Spain



Source: LucidCatalyst based on AFRY (2023)

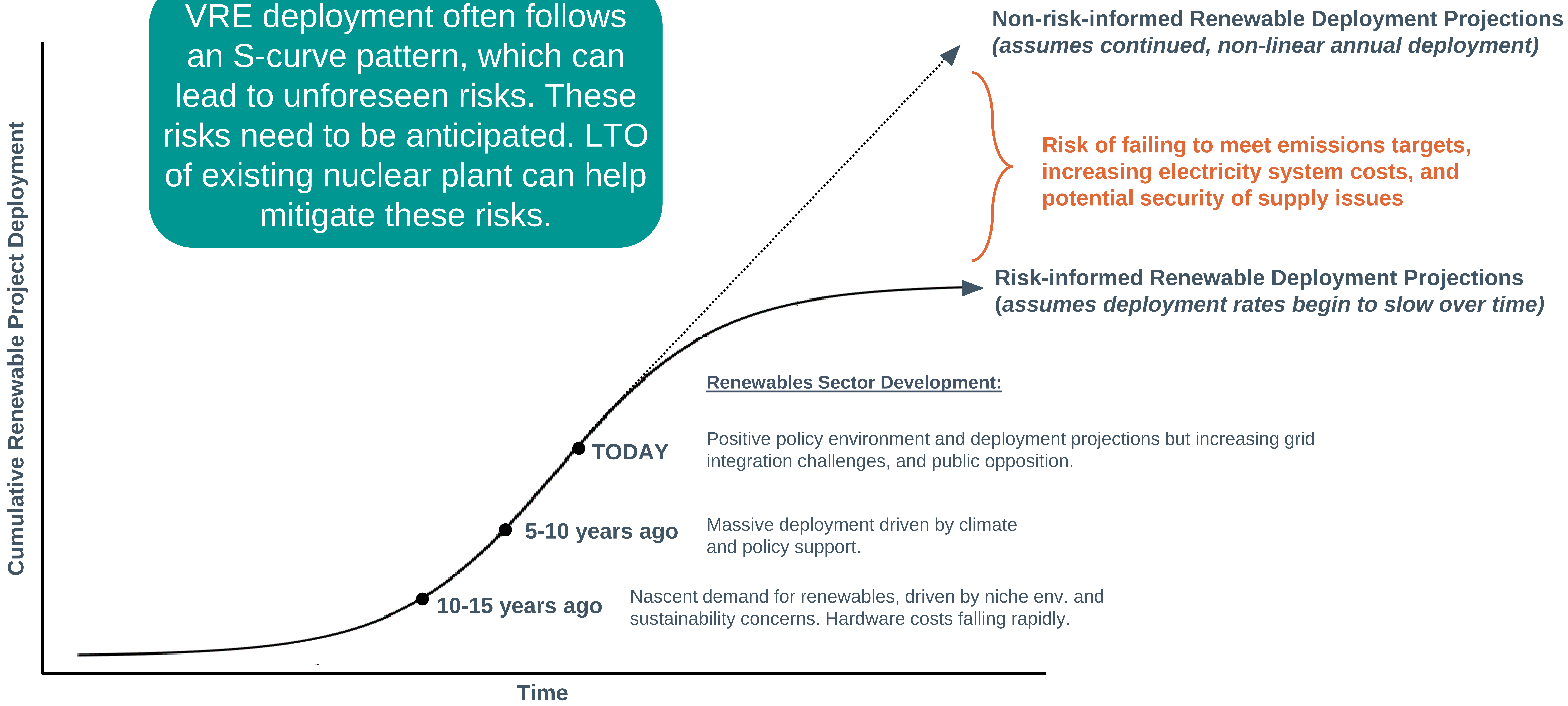
1. Reserve margins are calculated as the percentage difference between total generation capacity and peak demand. It indicates the capacity buffer available to accommodate unexpected demand surges and/or supply shortages

Models are not plans and plans are not projects



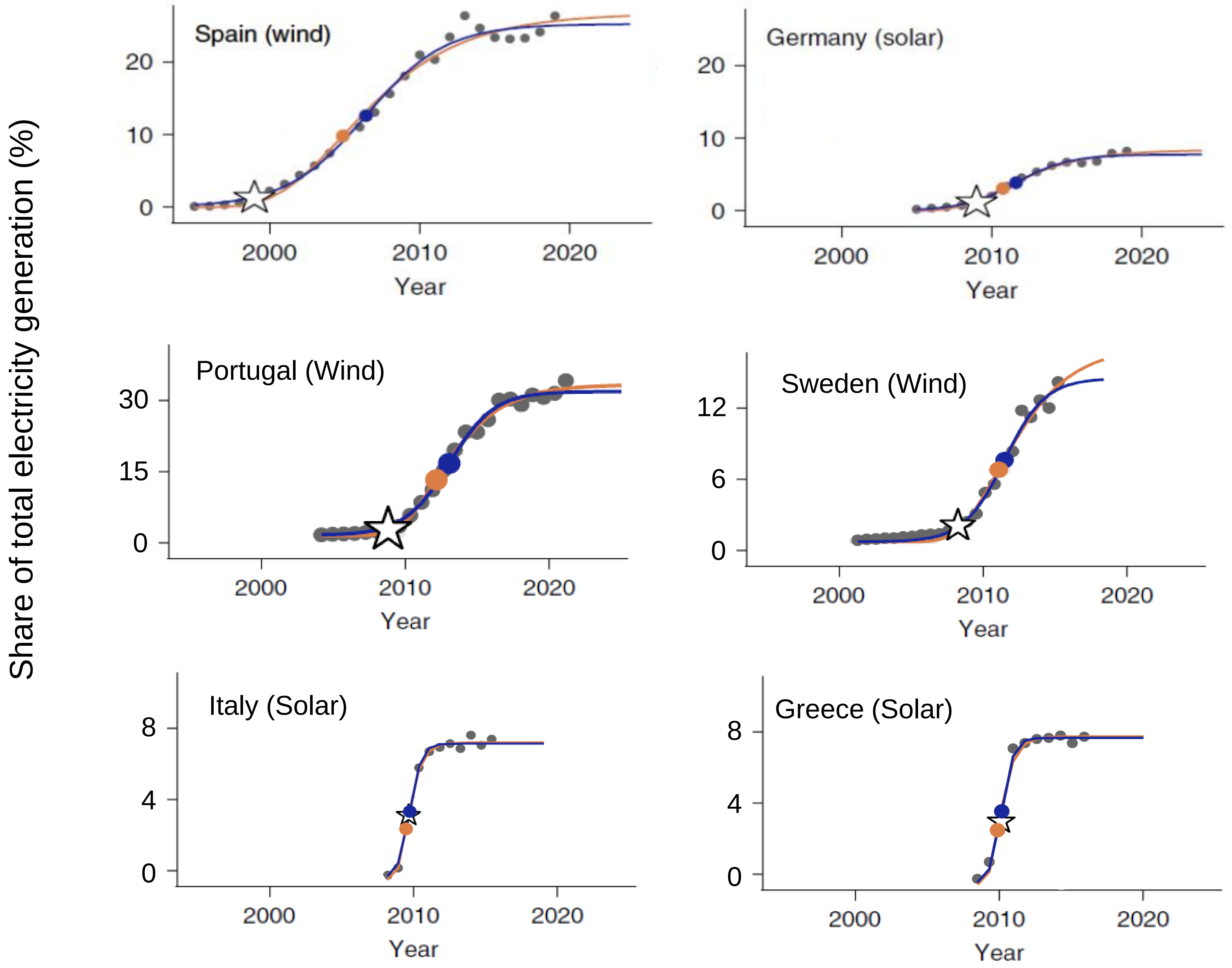
Hedging against VRE deployment risks with LTO

VRE deployment often follows an S-curve pattern, which can lead to unforeseen risks. These risks need to be anticipated. LTO of existing nuclear plant can help mitigate these risks.



Hedging against VRE deployment risks with LTO

Figure 15: S-curve of VRE development for selected countries



- The best sites are developed first
- Other sites are far from transmission and public opposition progressively grows
- Therefore, sites may increasingly difficult, expensive and risky to develop over time
- At very high shares, grid reliability and stability concerns may limit the development of new projects

Source: Cherp et al (2021), *National growth dynamics of wind and solar power compared to the growth required for global climate targets*

Recent polls show more opposers than supporters to nuclear power in Spain

- There are more opponents than supporters of nuclear power in Spain.
- However, the number of supporters seems to be increasing. This is consistent with most countries where public support for nuclear power is increasing with more supporters than opposers
- Public support trends can vary regionally and locally within a country. Typically, public support around nuclear power plants is high due to the economic benefits they bring

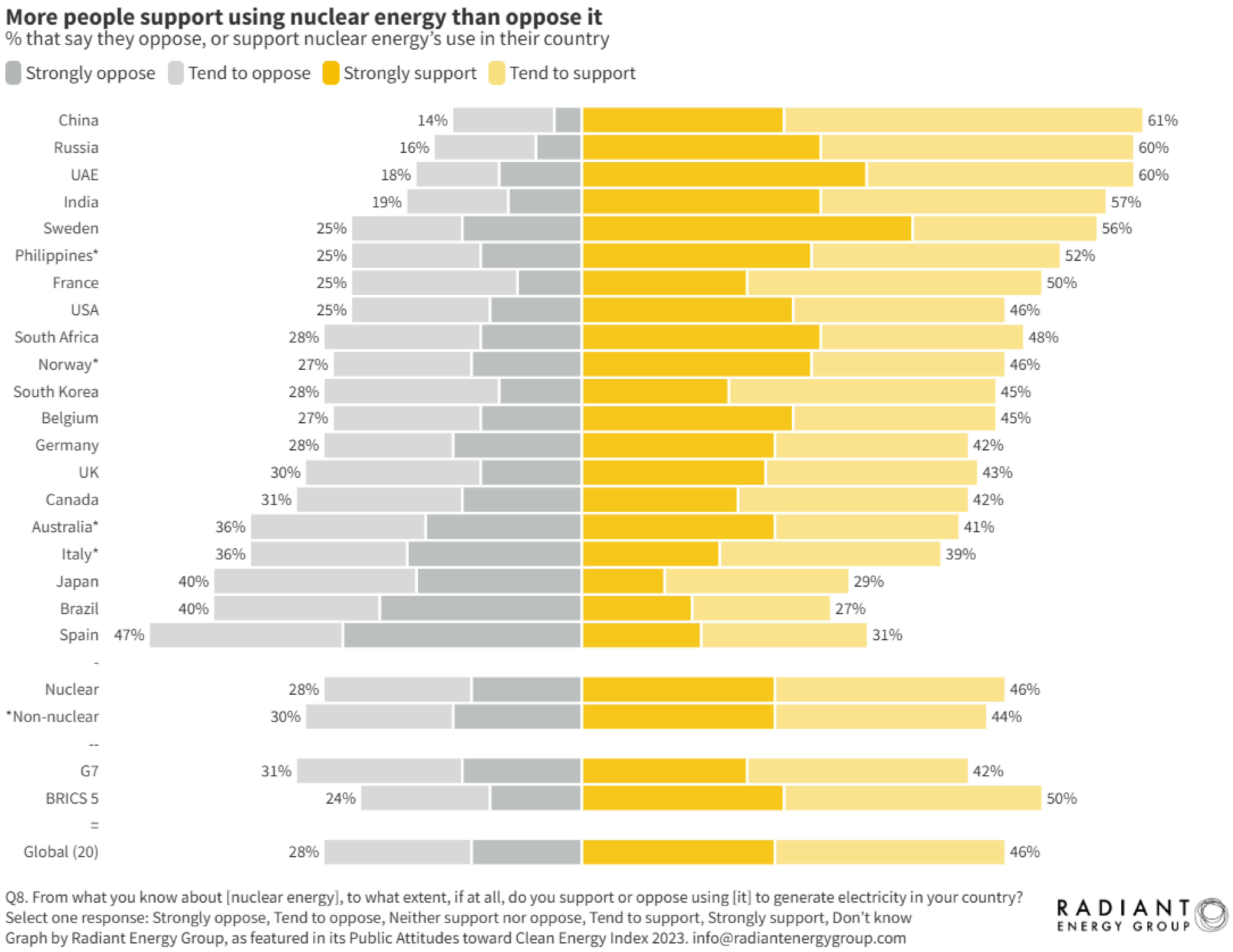


Table 3: Public support trends in Spain

	Damona, 2021	Radiant Energy Group, 2023
Supporters	26%	31%
Opposers	55%	47%

Source: Damona (2021), Radiant Energy Group (2023)

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LTO is highly efficient from a macro-economic perspective

Table 4: Macro-economic impact of the nuclear sector in Spain

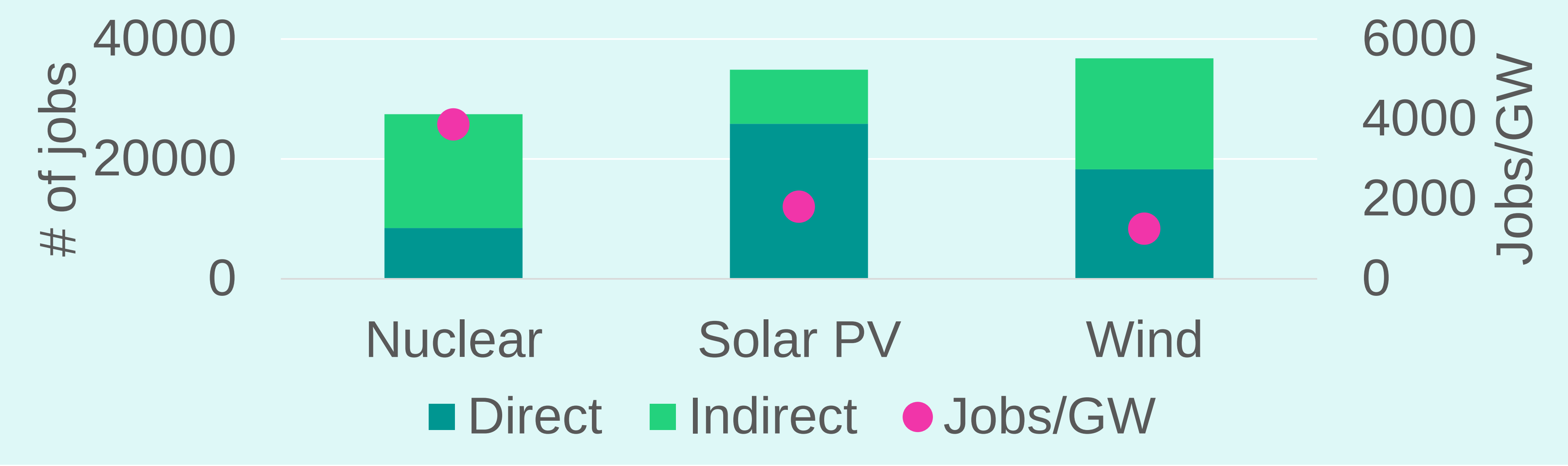
2013 values[1]	
Gross Domestic Product	€2,781 million, representing 0.27% of GDP
Employment	27,466 people (0.16% of total employment), of which 8,472 jobs were generated directly by the nuclear industry
Exports	€238 million, representing 0.10% of total exports
Tax Contribution	€1,141 million, of which 781 million was taxes incurred and 360 million in taxes collected as a result of their business

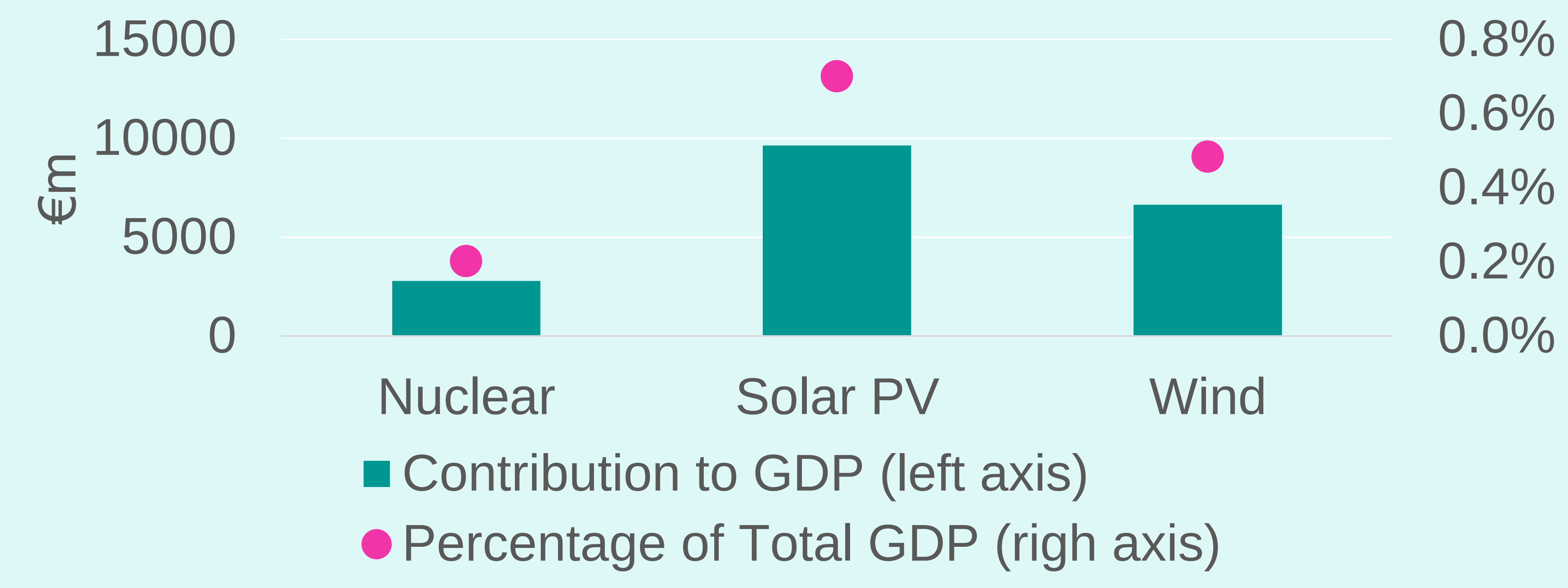
Source: Foro Nuclear (2015)

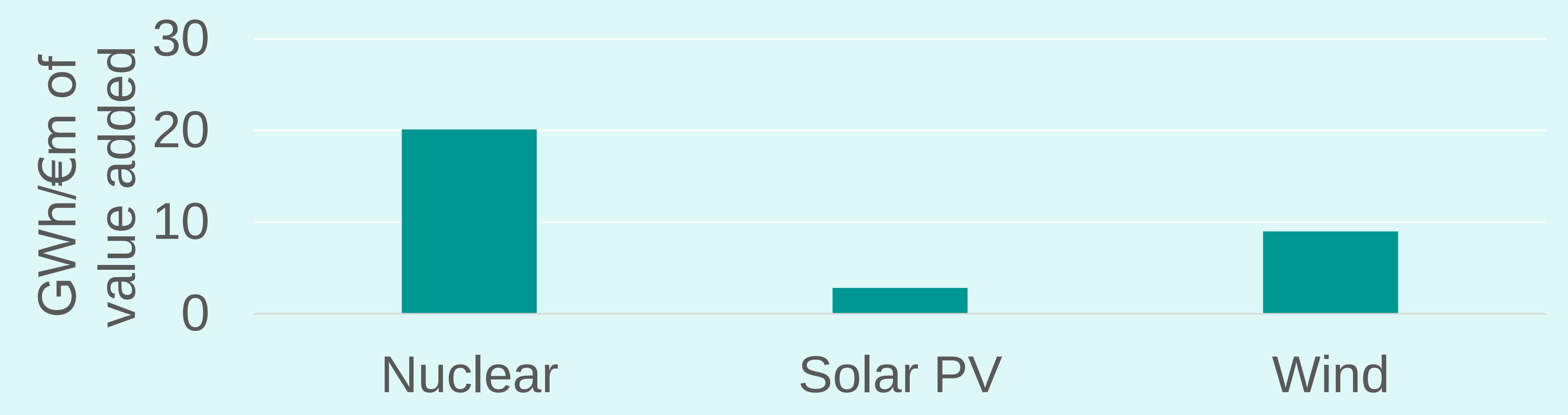
1. Except for tax contribution, it is assumed that the nuclear sector has experience limited growth over the last 10 years so these numbers may be applicable today.

- Nuclear is highly-economically efficient generating more jobs per GW and GWh per million euro of value added than other technologies
- The nuclear and wind sectors have high number of indirect jobs indicating wide-reaching economic impacts
- Other relevant dimensions for employment include: wages, quality and contract duration. Typically, nuclear power brings high-paying, long-term jobs to the local economy

Figure 16: Comparison of macro-economic metrics across energy sectors in Spain, 2022







Source: LucidCatalyst based on Foro Nuclear (2015), Deloitte (2022), Red Electrica (2022)

More waste management funds can be generated during the LTO period

- Decommissioning costs are fairly independent of the lifetime
- The LTO period will lead to additional amount of spent fuel that has to be managed:
  - If the infrastructure is there, it can be considered as a sunk cost
  - If not, these investments (e.g. interim storage) must be accounted in the LTO LCOE
- The additional returns/fee reductions enabled by LTO can be considered as a financial benefit

Figure 17: Evolution of the decommissioning fund as a function of the LTO period and the discount rate

Source: NEA (2021)
Note: The decommissioning costs allocated to the fund are assumed to be disbursed five years after the last operational year, for a duration of decommissioning work lasting ten years

Proposed Analytical Framework

1. Is LTO a commercially-viable solution?
- International trends and reasons for recent closures
- Technical feasibility and aging mechanisms
- Safety and performance with aging
- Regulatory frameworks

2. Is LTO an asset for the energy transition?
- Emissions reductions
- Displacement of fossil fuels
- Economics and profitability
- Security of supply
- VRE deployment risks
- Public acceptance

3. Any additional benefits from LTO?
- GDP
- Employment
- Tax contribution
- Waste management funds

4. Is Spain capable of undertaking LTO projects?
- Supply chain capabilities
- Workforce adequacy
- Waste management infrastructure
- Utilities' willingness to invest
- Availability of investment funds

Spain has a robust supply chain with previous experience in undertaking LTO projects

- The Spanish nuclear industry comprises companies capable of planning and executing LTO projects from end to end. This includes nuclear operators, fuel fabrication, engineering services, and suppliers of nuclear systems and components. There also nuclear training programmes in the best universities of the country
- The industry, including regulators, has successfully implemented similar projects as part of the decennial, periodic safety reviews
- Companies may need to plan generational workforce replacement and face difficulties in attracting new talent

Table 4: Overview of the Spanish nuclear industry

Main companies of the Spanish nuclear industry	
Owners	EDP, Endesa, Iberdrola, Naturgy
Operators	ANAV, CNAT, Iberdrola Confrentes
Fuel fabrication	ENUSA
Engineering services	Amphos 21, Empresarios Agrupados, Enwesa, GD Energy Services, Geotecnia y Cimientos, S.A., Grupo Eulen, IDOM, PROINSA, Westinghouse Electric Spain, Framatome, VIRLAB
Suppliers of nuclear systems	GE-Hitachi, Westinghouse Electric Spain, Framatome, CEN solutions, Coapsa Control, ENSA, Konecranes, Newtesol, Nusim, Ringo Valvulas, Taim Weser
Waste management	ENRESA

Source: LucidCatalyst based on Foro Nuclear (2021)

There is enough nuclear waste storage capacity for LTO

- According to the 7th General Radioactive Waste Plan[1], the centralized storage solution was abandoned in favor of individual interim storage facilities at each nuclear site. The additional cost of this approach led to a reevaluation of the waste management fee
- Low and medium level waste is stored at el Cabril:
  - Capacity as of 2024: 82%[2]
  - Additional capacity needed by 2028, with engineering work for capacity expansion ongoing[3]
- Spent fuel is stored in the pools and in dry casks in the interim storage facilities:
  - Pool capacity as of 2022: 86%[4]
  - Interim storage capacity as of 2022: 52%[4]

Table 5: Status of spent fuel storage capacity in Spain, 2022

Nuclear facility	Type of storage	Authorized storage capacity	Stored spent fuel (occupancy rate)
Almaraz	Pool unit 1	1804	1604 (98%)
Almaraz	Pool unit 2	1804	1536 (95%)
Almaraz	Interim storage	640	192 (30%)
Asco	Pool unit 1	1421	1160 (94%)
Asco	Pool unit 2	1421	1132 (91%)
Asco	Interim storage	1024	832 (81%)
Cofrentes	Pool	5404	4704 (98%)
Cofrentes	Interim storage	1248	260 (21%)
Trillo	Pool	805	568 (92%)
Trillo	Interim storage	2208	800 (36%)
Vandellos II	Piscina	1802	1392 (77%)

Source: LucidCatalyst based on CSN Alfa (2022)

1. Septimo Plan General de Gestion de Residuos Radioactivos
2. EFE (2024)
3. IEA (2021)
4. CSN Alfa (2022)

The owners can largely cover LTO investments

- The existing nuclear fleet is co-owned by Iberdrola, Endesa, Naturgy, and EDP, with Iberdrola and Endesa owning 90% of the fleet
- The total investment cost for a 10-year lifetime extension of the entire nuclear fleet can be conservatively estimated at around $5.4 billion[1]
- Each of the owners could theoretically—largely in some cases—cover their part with one year's worth of their annual investments. In practice, such investments would be carried out over several years, further increasing the availability of funding.

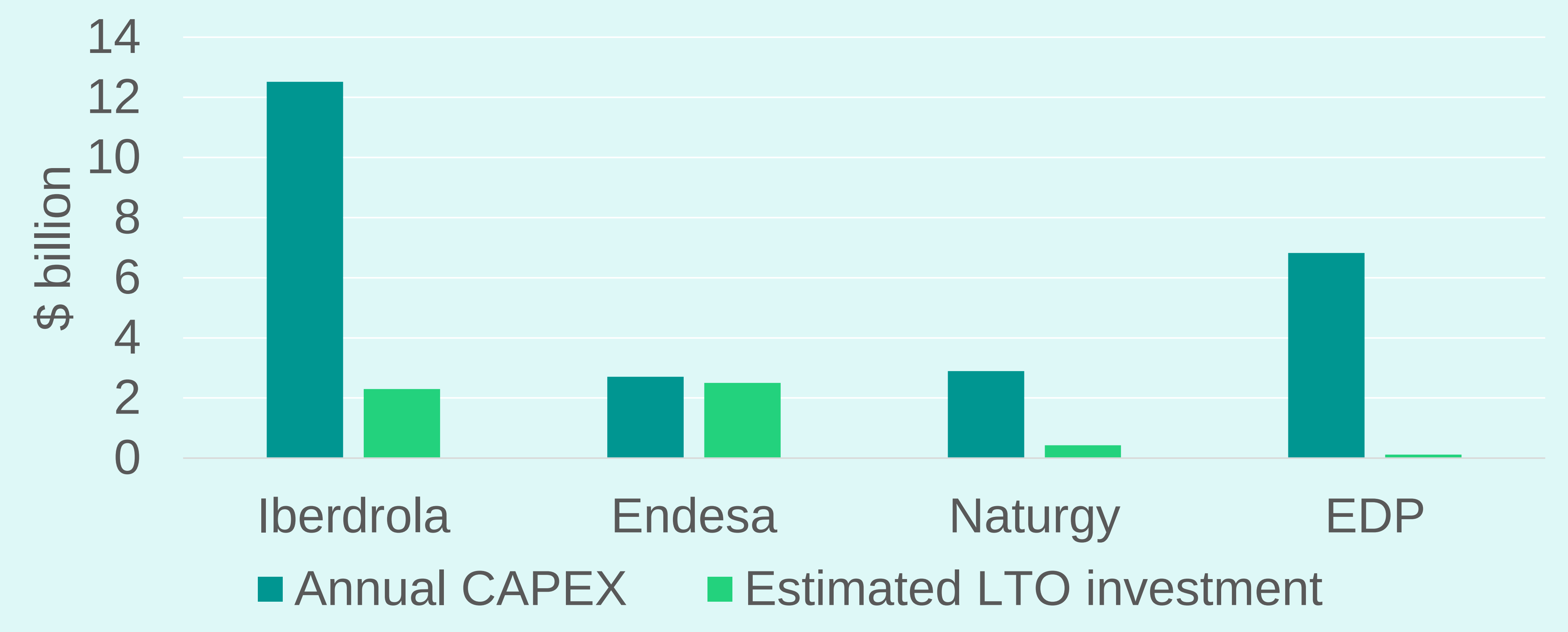
1. LTO cost can be estimated at $750/kWe. For a fleet of 7121 MWe, this yields $5.4 billion. AFRY (2023) estimates the additional investment of the “Prorroga Nuclear” scenario at $3.5 billion

Table 6: Ownership of the Spanish nuclear fleet

Iberdrola	Endesa	Naturgy	EDP
43%	47%	8%	2%

Source: LucidCatalyst based on IEA (2021)

Figure 18: Comparison of annual CAPEX of owners and estimated LTO investment



Source: LucidCatalyst based on Iberdrola (2023), Endesa (2023), Naturgy (2023), EDP (2023) Note: The estimated LTO investment of $5.4 billion is distributed among companies prorata to their ownership stake

The main owners are willing to undertake LTO investments if they are economically attractive

- Owners have historically complained about the excessive tax burden on nuclear assets, which could lead to operating at a loss when wholesale prices are low[1]
- **CEO of Iberdrola Galan**: *"No hay ninguna razón para que no podamos alargar su ciclo de vida como está haciendo Estados Unidos", "La parte económica debe ser atractiva", "Técnicamente es posible"*[2]
- **CEO of Endesa Bogas**: *"Creo que habría que dejar más tiempo las nucleares, y se lo propondremos al Gobierno. A ver si somos capaces de convencerlo, trataremos de hacerlo al menos desde Endesa"*[3]
- With appropriate policy support and tax reductions, getting the owners onboard for LTO should not pose significant challenges.

1. NucNet (2021)
2. La Vanguardia (2024)
3. El Periodico de España (2024)

Recommendations and Next Steps

Recommendations

- **Recommendations for the client:** “We would recommend considering extending the operations of existing nuclear reactors in Spain for the following reasons:

  1. **Technical feasibility**: It is a technically proven option that is being actively pursued in other countries.
  2. **Plant and electricity system economics**: The economics are sound from both a plant-level and system perspective. However, the plan would benefit from a reduction in the tax burden and waste management fees, as extended operation provides more time to secure necessary funds. These adjustments would facilitate getting the owners on board.
  3. **Macro-economics benefits**: In macroeconomic terms, nuclear sector’s contribution is similar to renewables but more efficient in terms of employment and energy production.
  4. **Industrial capabilities**: The country has a robust supply chain with experience in supporting such projects. Low or very limited investment in waste management infrastructure would be needed, and owners have the ability to undertake the investment with low risk exposure”

Recommendations

- **Challenges:** “The decision may face the following challenges:
  1. **Owners' alignment**: Their visions about the future of nuclear energy may diverge. Economic incentives (e.g., tax reductions) will play a primary role in aligning the owners.
  2. **Political costs**: The decision may carry some political cost, as there are currently more opponents than supporters of nuclear power in Spain. This cost could be mitigated with a well-designed communication strategy.
  3. **Timelines for regulatory review**: The deadline for licensing the LTO of some units may have already passed. However, the Belgian case demonstrates that it's possible to refocus the LTO licensing scope without compromising safety to accommodate new government decisions”
- The Belgian case can serve as an excellent example of how owners and government can reach an agreement after a shift in nuclear strategy. It may offer valuable lessons for the Spanish case.

Next Steps

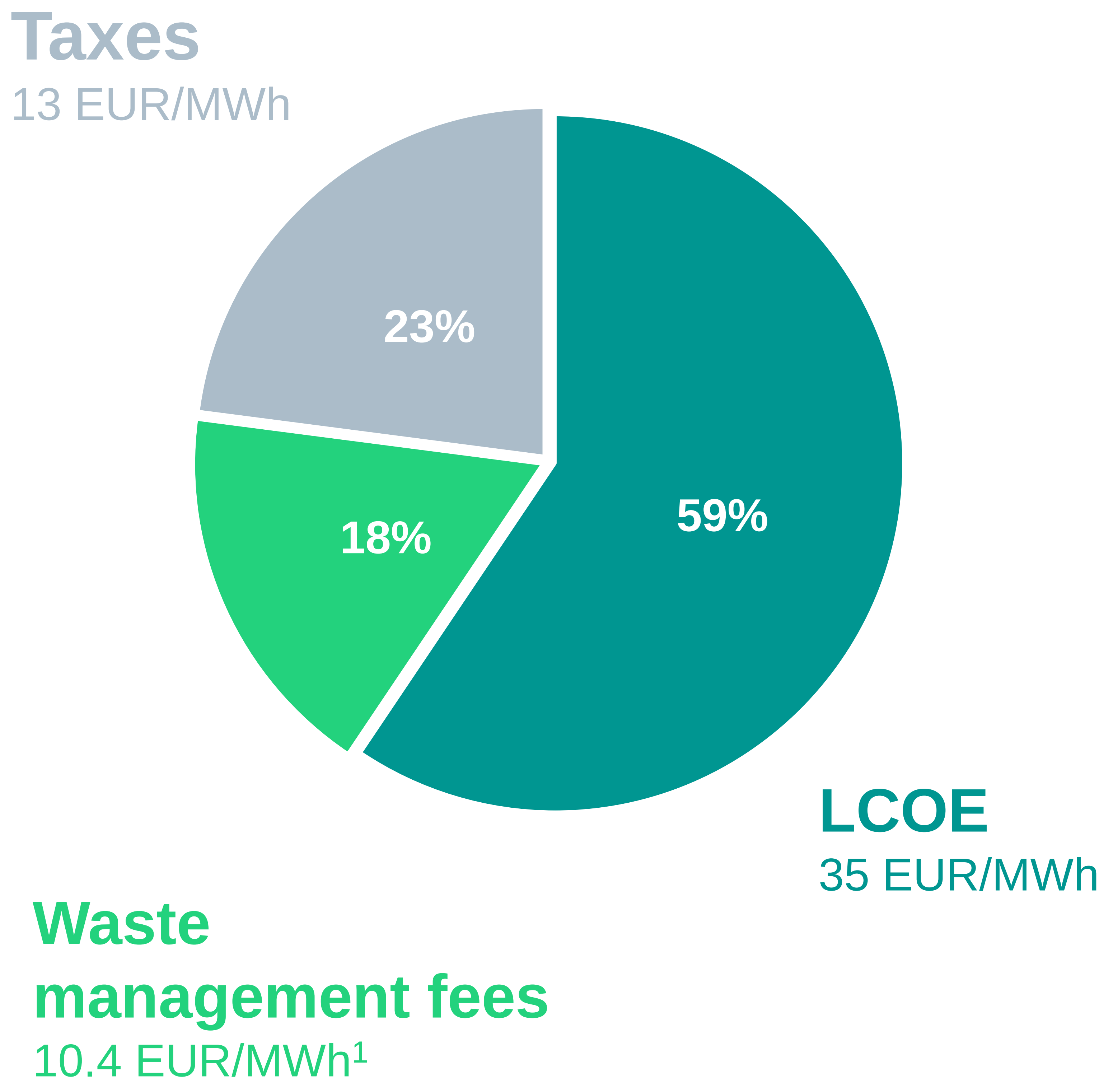
- **Next steps:** “Assuming that the Spanish government is willing to reconsider its stance against LTO, the following actions should be pursued in priority:
    1. Meet with key stakeholders, particularly owners, to communicate government plans for extending nuclear operations and understand their views and terms
    2. Reach an agreement with owners on an LTO plan.
    3. Develop a national LTO strategy and update relevant legislation. Support this with positive communication and initiatives to increase public support and sector's attractiveness for young professionals”

Annex slides

The cost structure of Endesa's nuclear power generation assets, Spain

	EUR/MWh
Variable operating cost	**14.0**
Fuel expenses	5.3
Electricity purchases and generation tolls	0.7
Nuclear waste fees*	8.0
Fixed operating costs and recurring costs	**17.6**
Fixed operating costs	13.1
Investments	4.5
Tax Law 15/2012 and autonomous communities	**13.4**
Electricity generation tax (7%)*	3.2
Nuclear fuel tax*	5.2
Autonomous communities' nuclear tax	5.0
Capital cost	**11.1**
Total generation cost	**56.1**
(Taxes and nuclear waste fees)	(21.4)

Source: Based on IEA (2021)



1. Since July 2024, the new waste management fee is €10.4/MWh

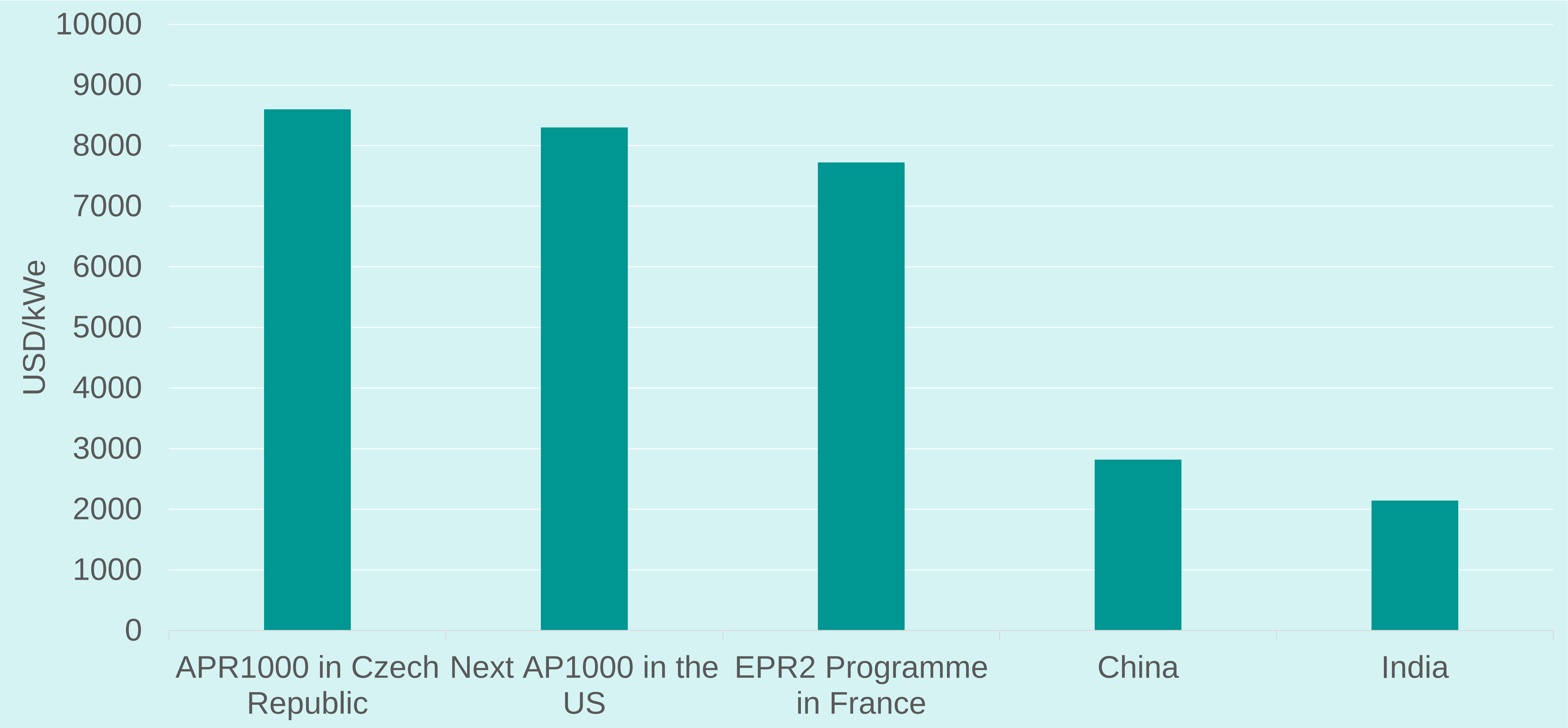
Taxes and levies for nuclear power in Spain

Tax/Levy	Value in 2025 (EUR/MWh)	Justification and potential limitations
Tasa Enresa	10.36	Finances the future dismantling of nuclear power plants and the management of radioactive waste (a task assigned to Enresa). It is generally considered necessary; most countries with nuclear power have similar mechanisms
IVPEE	4.85	Applies a 7% tax on the value of all electricity generated in Spain, regardless of the technology (Law 15/2012).
Impuesto de produccion combustible nuclear gastado	5.17	Specifically taxes spent nuclear fuel (also under Law 15/2012) with the purpose of charging the operator for the specific costs and impacts generated by the management of that fuel. There is some overlap with the Tasa Enresa (which already covers management and dismantling). Depending on how it is applied and where the funds go, it could be seen as double taxation on the same issue (waste)
Ecotasas autonomicas	4.77	These are justified on environmental grounds and are collected by regional governments. Their legitimacy depends on whether they actually finance control, protection, or environmental restoration measures around the plant. If there is no clear traceability, they may be seen as “duplicated” charges compared to other taxes with environmental goals
Other (IBI, IAE, tasas Guardia Civil, Consejo de Seguridad Nuclear, etc.)	3.07	These are general taxes or fees (for example, the IBI is the property tax paid by any facility) or specific fees for oversight and safety (Guardia Civil, CSN…). As long as there are effective control and oversight services—and because these are fiscal measures of a general nature or a fee for a very specific service—they are generally considered necessary

Source: LucidCatalyst based on PwC (2024)

Large nuclear overnight investment costs in 2024 across regions

Figure 19: Overnight investment cost for large nuclear projects, 2024

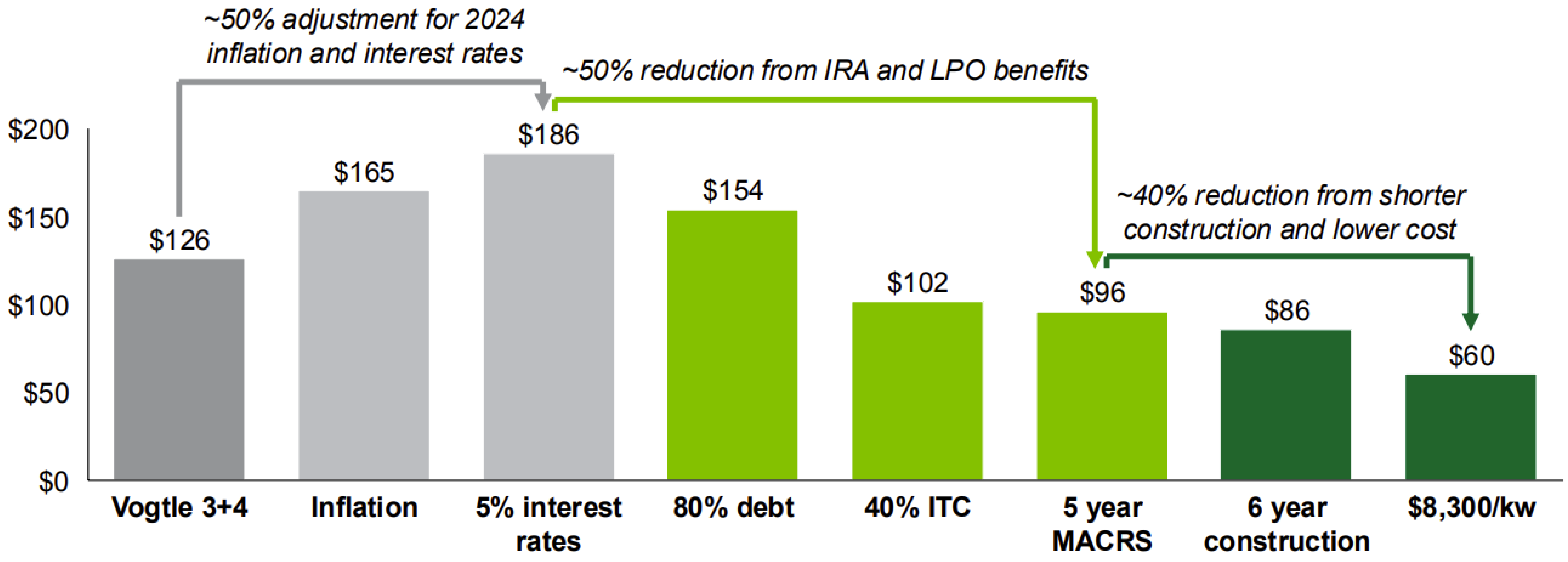


Source: LucidCatalyst based on ANS (2024), DOE (2024), Montel News (2024), Powermag (2024), Business Today (2024)

- The difference between Europe, US and the rest of the world can be explained by differences in the supply chain capabilities
- China and India are in more advanced stages in the large nuclear learning curve due to continuous construction and a long-term nuclear expansion programme.

Large nuclear could reach $60/MWh with government support and a programmatic approach

LCOE using NREL model, 2024 $/MWh



Overnight capital cost	$11,000	$15,000	$15,000	$15,000	$15,000	$15,000	$15,000	$8,300
Construction time	11 years	11 years	11 years	11 years	11 years	11 years	6 years	6 years
Interest rate on debt	3.5%	3.5%	5%	5%	5%	5%	5%	5%
Debt fraction	60%	60%	60%	80%	80%	80%	80%	80%
Tax credit	PTC (old)	PTC (old)	PTC (old)	PTC (old)	40% ITC	40% ITC	40% ITC	40% ITC
Depreciation	15 years	15 years	15 years	15 years	15 years	5 years	5 years	5 years

Source: DOE (2024).

2023 European Electricity Market Reform

- The 2023 European electricity market reform introduces market mechanisms to provide long-term price stability and encourage investment in low-carbon energy sources. They are applicable to new and existing nuclear.
  - **Contract for difference (CfD)**: CfDs are agreements where a public entity and an energy producer agree on a fixed "strike price" for electricity. If the market price falls below this strike price, the producer receives a payment to cover the difference; if the market price exceeds the strike price, the producer pays back the excess.
  - **Power purchase agreements (PPAs)**: PPAs are long-term contracts between electricity producers and purchasers, such as utilities or large consumers, specifying the price and terms for electricity supply.
- These mechanisms can be considered forms of state aid under EU law, depending on their structure and the involvement of public resources. In such cases, they are subject to EU state aid rules and require notification to, and approval by, the European Commission's Directorate-General for Competition (DG COMP)[1,2]

1. European Council (2024)
2. SFEN (2023)

Understanding the cost of the electricity provision

PLANT-LEVEL

Generation Costs

Levelized Cost of Electricity

+

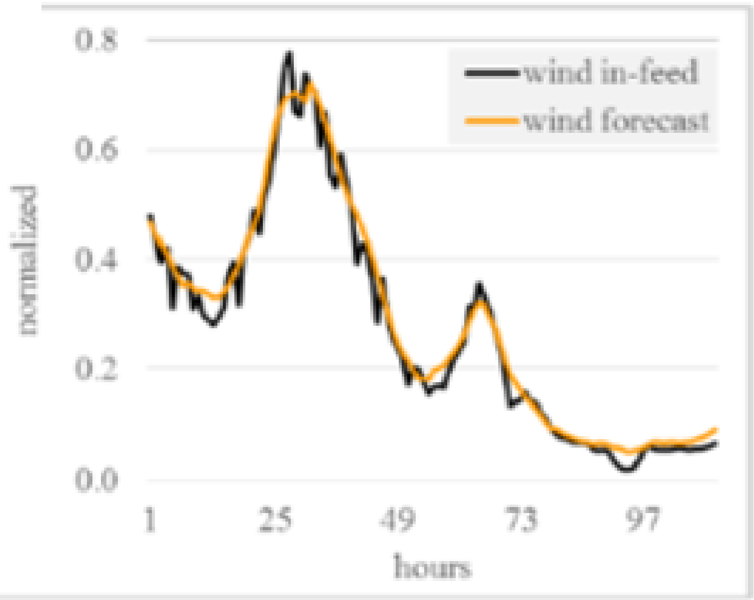
GRID-LEVEL

Connection, Transmission and Distribution Costs

Costs of delivering electricity from distributed power generation to customers

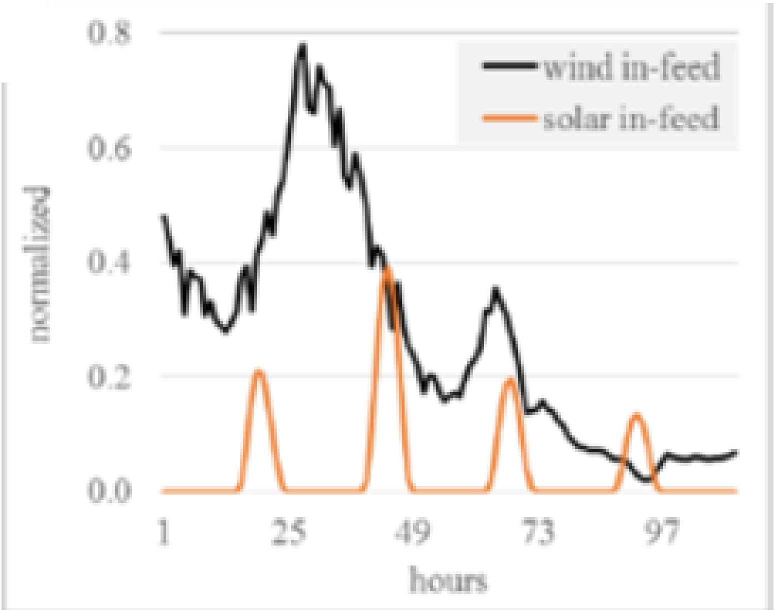
Balancing costs

Grid-level costs imposed by uncertainty in generation



Profile costs

Grid-level costs imposed by Variability or intermittency



Source: NEA (2019)

VRE S-curves in Spain

Figure 20: Share of wind power as a percentage of total electricity generation, Spain, 2023

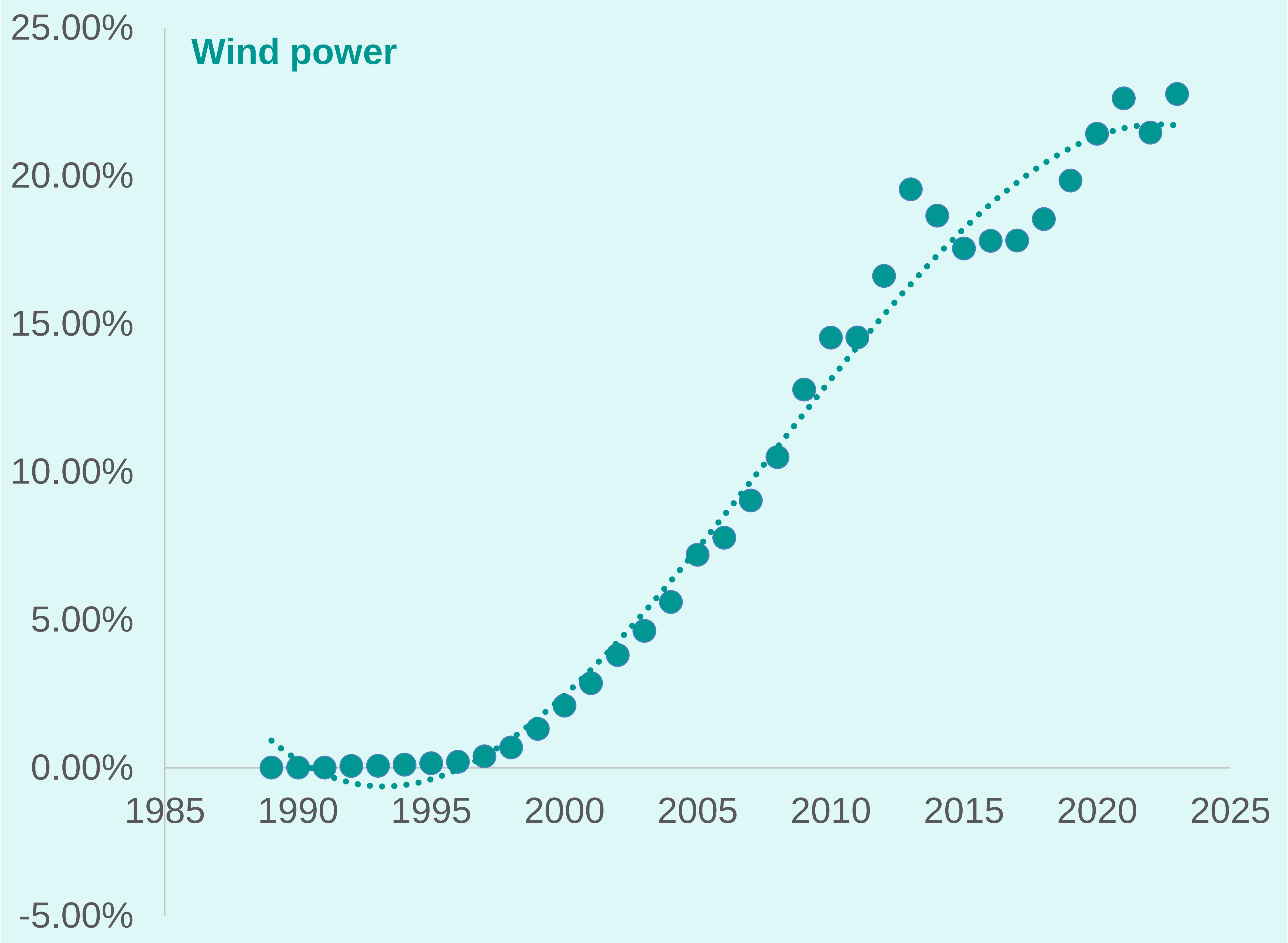
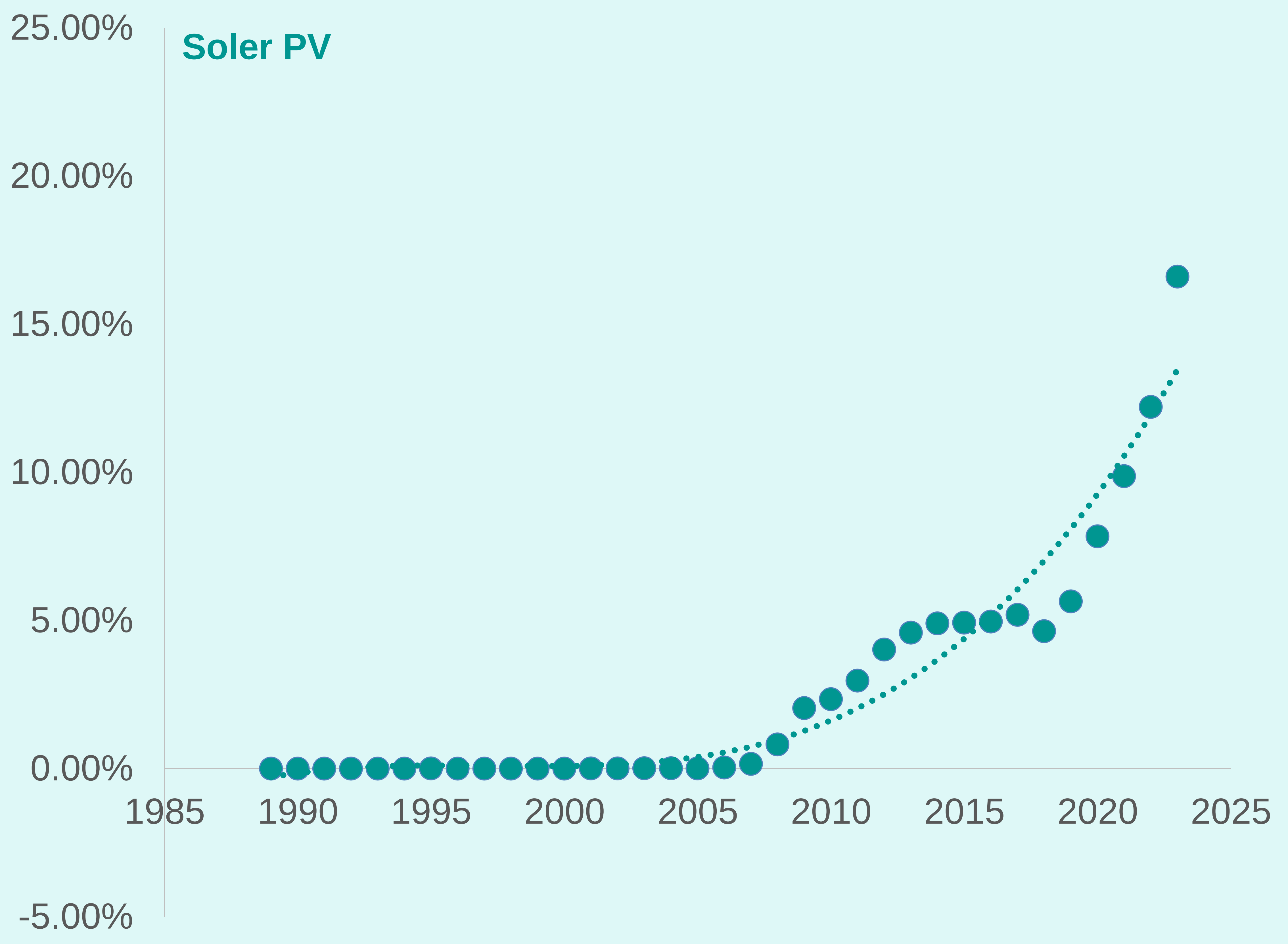


Figure 21: Share of solar PV as a percentage of total electricity generation, Spain, 2023



Source: LucidCatalyst using data from Energy Institute (2024)

Employment across energy sectors in the United States

Table 7: Nuclear provides high paying jobs and the most jobs on site per GW

Generation type	Permanent jobs on site, jobs/GW	Industry wage median, $/hour	Benefits concentrated in local community?
Nuclear	237 / ~500	$56	✓
Coal	107	$49	✓
Natural gas	~30	$49	✓
Wind	80	$37	✗
Solar	~36	$34	✗

Note 237 jobs is an estimate for SMRs; ~500 represents the current operating fleet of large reactors; coal and natural gas are both the value of "Fossil Fuel Electric Power Generation;" when they were measured separately in the 2020 USEER Wage Report, they were within ~5% of each other; hydropower onsite jobs per GW not available, but industry median wage was $51/hour

Source: DOE (2024).

Chronology of the Belgian case

- **2003:** Belgium's federal Law of 31 January 2003 requires the phase-out of all nuclear electricity generation in the country[1]
- **2013-2015:** The law was amended in 2013 and 2015 to provide for the Tihange 1, Doel 1 and 2 reactors to remain operational until 2025[1]
- **2022**: In the context of the 2022 energy crisis and the war in Ukraine, as a measure to reduce Belgium's dependency on fossil fuels and to contribute to security of supply, the Belgian government decided to extend the lifetime of two nuclear reactors (Doel 4 and Tihange 3) for ten years[2]
- **2022:** The Federal Agency for Nuclear Control (FANC) submitted an analysis to the federal government regarding the potential extension of the Doel 4 and Tihange 3 reactors' operations, concluding that such an extension is feasible and acknowledging the possibility to be flexible to meet deadlines[3]

1. IEA (2022)
2. Official Journal of the European Unition (2024)
3. FANC (2022)

Chronology of the Belgian case (cont'd)

- **2023:** On December 13, 2023, Engie and the Belgian government signed a final agreement detailing the terms of the reactors' extension and addressing nuclear waste obligations. Key elements of the agreement included:
  - **Flexible Long-Term Operation** (Flex LTO): Both parties committed to investing between €1.6 billion and €2 billion to restart the reactors by November 2025.
  - **Joint Venture Formation**: A legal entity, BE-NUC, was established, equally owned by the Belgian State and Engie, to oversee the extended operations.
  - **Contract for Difference Mechanism**: This financial arrangement was implemented to ensure balanced risk allocation and stable remuneration for electricity generation.
  - **Nuclear Waste Liability Cap**: Engie's liability for future nuclear waste treatment costs was fixed at €15 billion, providing financial predictability.[1]

1. Engie (2023)

LucidCatalyst delivers strategic thought leadership to enable rapid decarbonization and prosperity for all.

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