DEL CARBÓN A LA ENERGÍA NUCLEAR EN COLOMBIA

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Átomos para la Vida

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¿DÓNDE ESTAMOS?

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Comparación regional del sector nuclear

INDICATORS	Colombia	Brazil	México	Perú	Argentina	Chile
Research reactors	1	4	2	2	5	1
Power (MW)	0.1	5.1	1.0	10	10.5	5.0
State of nuclear sector development	Limited capacities. The power does not allow the production of radioisotopes.	Capacity in energy generation and broad research capabilities.	Capacity in energy generation, in formation, activation and radioisotope production.	Broad research capabilities, including radioisotope production.	Has its own nuclear technology. It is self-sufficient in radioisotope production.	Research capacities focused mainly on medicine and mining.
Radioisótopes	○	◑	◑	◔	◑	◔
Education and training	◔	◔	◑	◔	◔	◔
Neutron activation analysis	◔	◔	◔	◔	◔	◔
Geochronology	◔	◔	○	◔	○	○
Other applications	◔	◑	○	◔	◑	◕
Cyclotrons	6	14	8	2	9	2
Maximum power (MeV)	16	30	18	17	42	18
Radioisotope production potential in cyclotron	F-18; O-15; C-11; N-13; Na-22 and V-48	F-18O-15;C-11; N-13; Na-22; V-48 and other 5 radiopharmaceuticals	F-18O-15;C-11; N-13; Na-22;V-48 and other 7 radiopharmaceuticals	F-18O-15;C-11; N-13; Na-22;V-48 and other radiopharmaceuticals	F-18O-15;C-11; N-13; Na-22; V-48 and other 5 radiopharmaceuticals	F-18O-15;C-11; N-13; Na-22;V-48 and other 5 radiopharmaceuticals

● Broad capacity ◑ Partial capacity ○ No significant capacity

MW: Megawatts | MeV: Megaelectronvolts

Fuente: IAEA (2019), Minminas (2019)

SMR

Potencia y prototipos

IAEA, 2022[a]; Vinova, 2023; Schaffrath, 2021; Wormald, 2021

Ventajas de la modularización

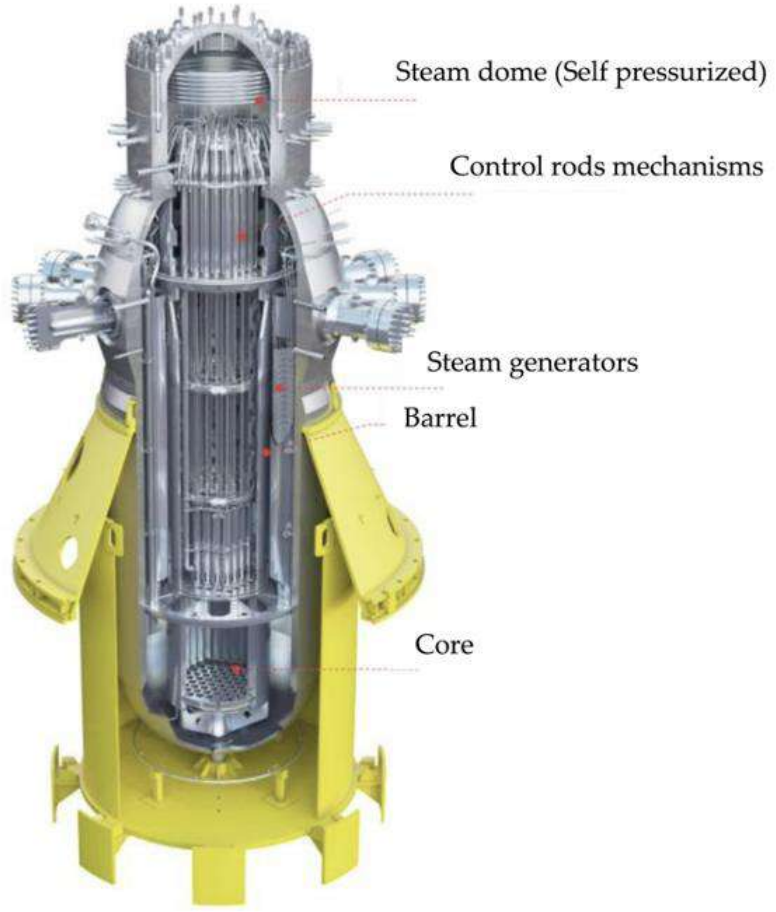
Ingersoll, 2020; Locatelli et al., 2013; Sam et al., 2023

Seguridad y protección radiológica

Hussein, 2021; Lee, 2024; Carter, 1963; Riznic, 2017; Hussein, 2020; IAEA, 2019[a]

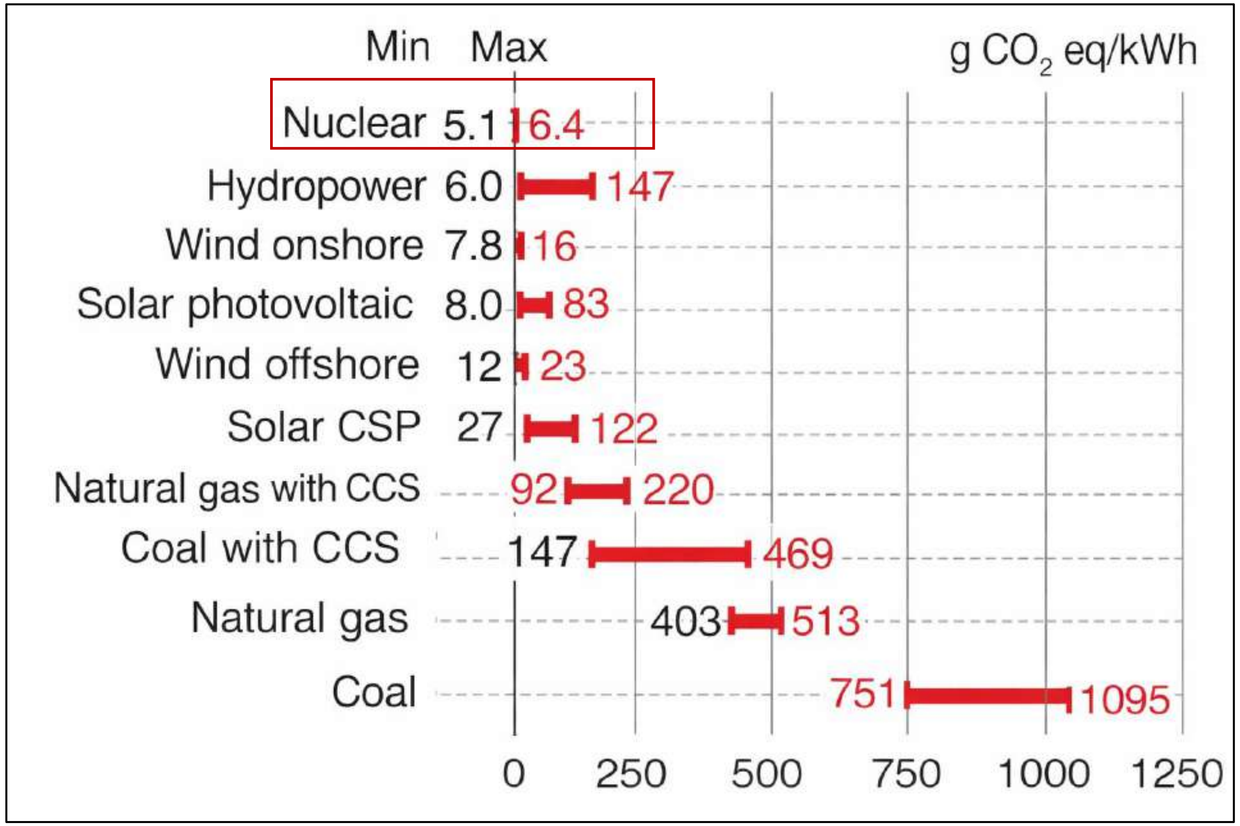
Aplicaciones no eléctricas

Jeong, 2023; Avelar et al., 2020; Assi et al., 2025



Fuente: IAEA, 2022

IMPACTO DE LAS EMISIONES

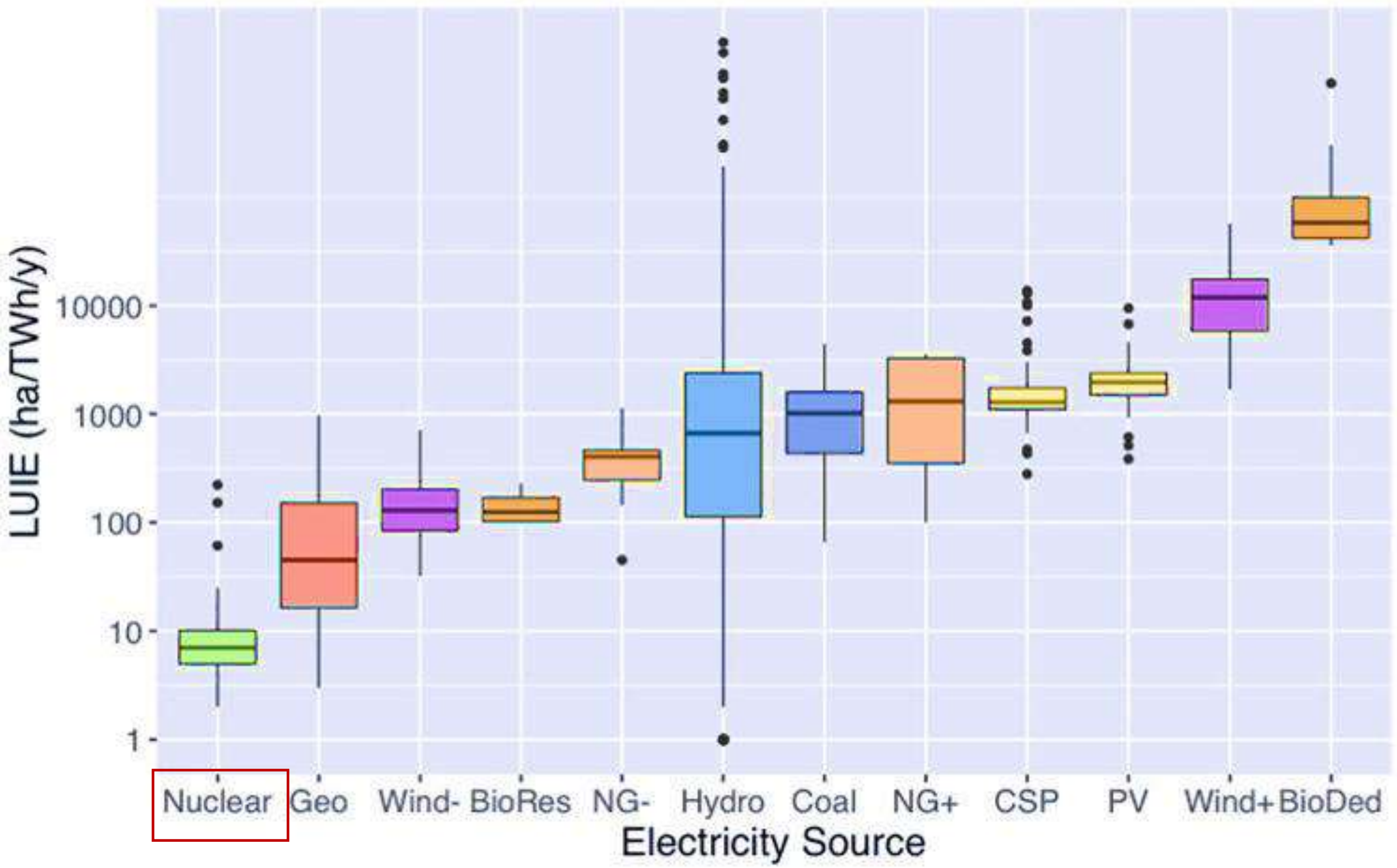


Source: UNECE, 2022, IPCC, 2021; CCS- carbon capture and storage, modified by the author

INTENSIDAD DEL USO DEL SUELO

Total land-use intensity of energy (LUIE)

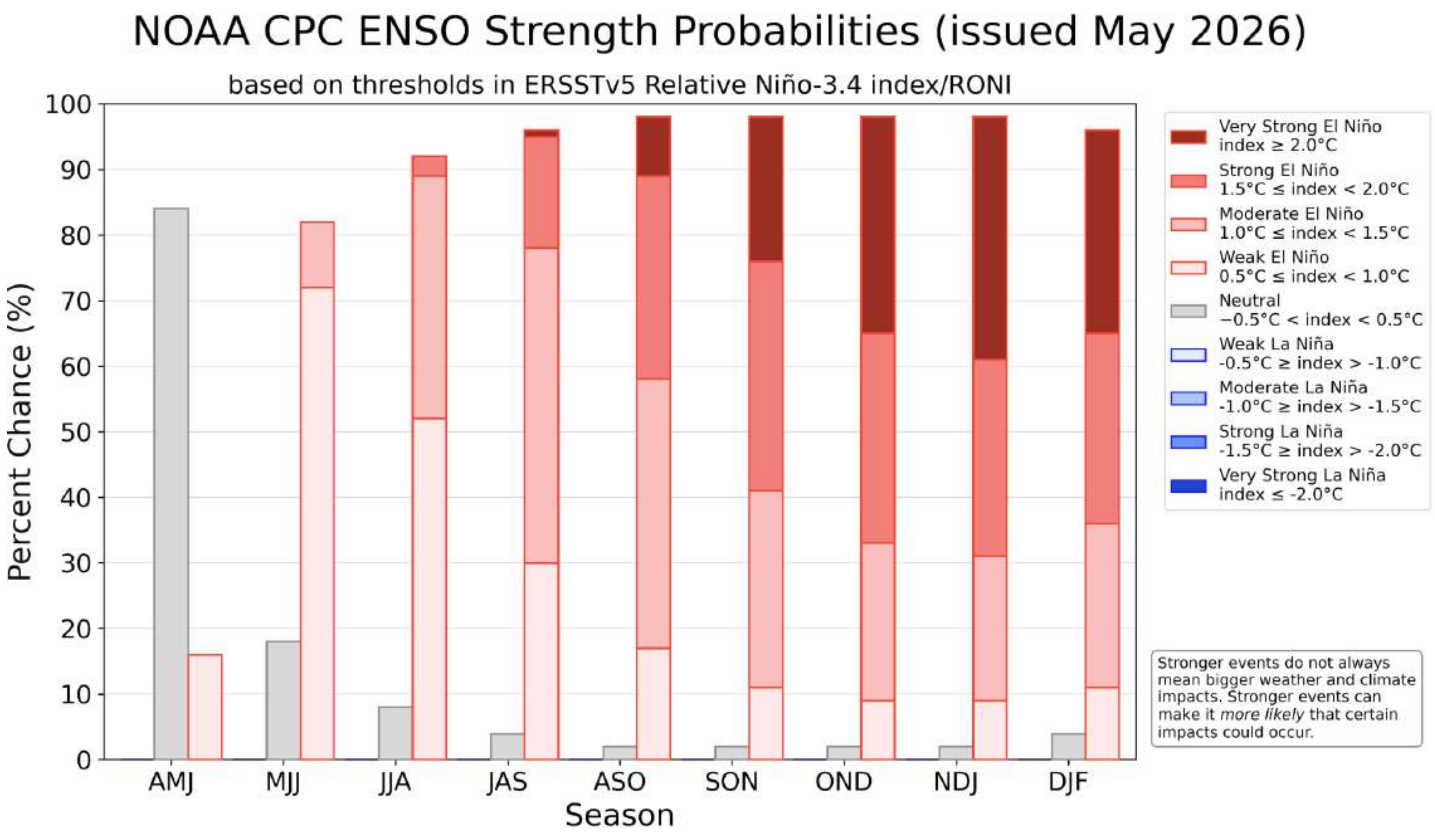
Lovering et al., 2022; IAEA, 2025; Joaqui-Barandica et al., 2025



ENERGÍA EN FIRME

Firm capacity during scarcity

Henao et al., 2020; IEA, 2022; Wei et al., 2025; Stroiny et al., 2023; NOAA, 2026



HERRAMIENTAS DE REDUCCIÓN DE EMISIONES

CUALIDADES DE LA ESTRATEGIA COAL TO NUCLEAR

Reutilización
IAEA, 2022[a]; NEA, 2021; OECD, 2020; WNA, 2021

Balance hídrico
IEA, 2021; AIEA, 2022; DOE, 2020; Burek et al., 2021

Empleo
ILO, 2021; NEA, 2022; IAEA, 2021; NRC, 2020

Polución
WHO; 2021; OECD, 2020; IEA, 2021; EIA, 2020

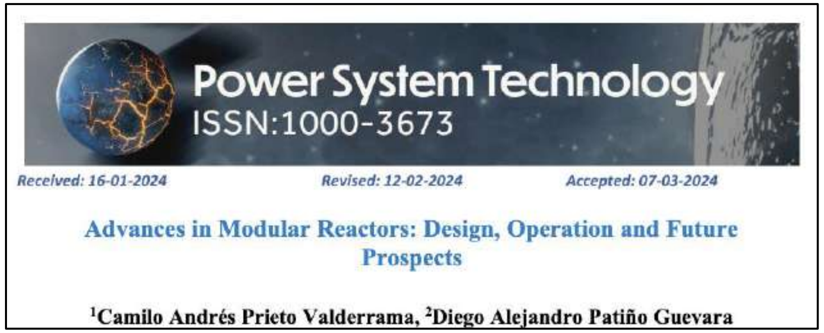
Emisiones evitadas
IPCC, 2021; Jun et al., 2024; IEA, 2020[b]; Mahmood et al., 2020

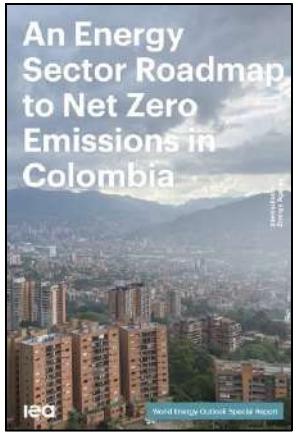
Uso de suelo
UNECE; 2022; Godsey, 2019; Carless y Grifin, 2016

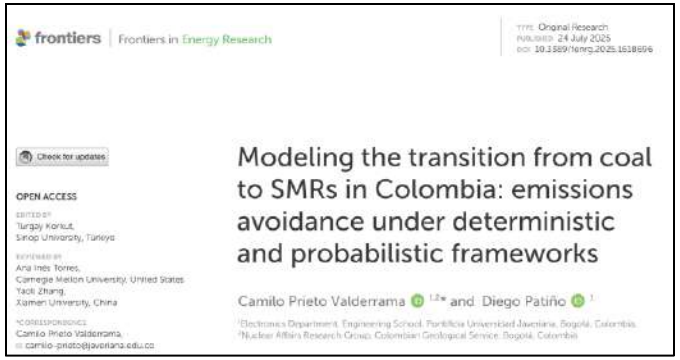
Costo nivelado de energía (LCOE)
IEA, 2023; NEA, 2020; Lazard, 2023; NREL, 2021

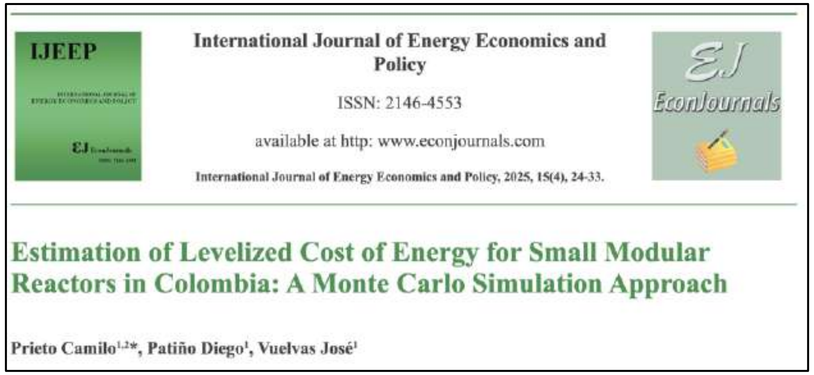
Energía en firme
IEA, 2022; NEA, 2021; NREL, 2021; Gagnon et al., 2020

CONTRIBUCIONES ACADÉMICAS









Modelando la transición del carbón a los SMR en Colombia: emisiones evitadas bajo marcos determinísticos y probabilísticos

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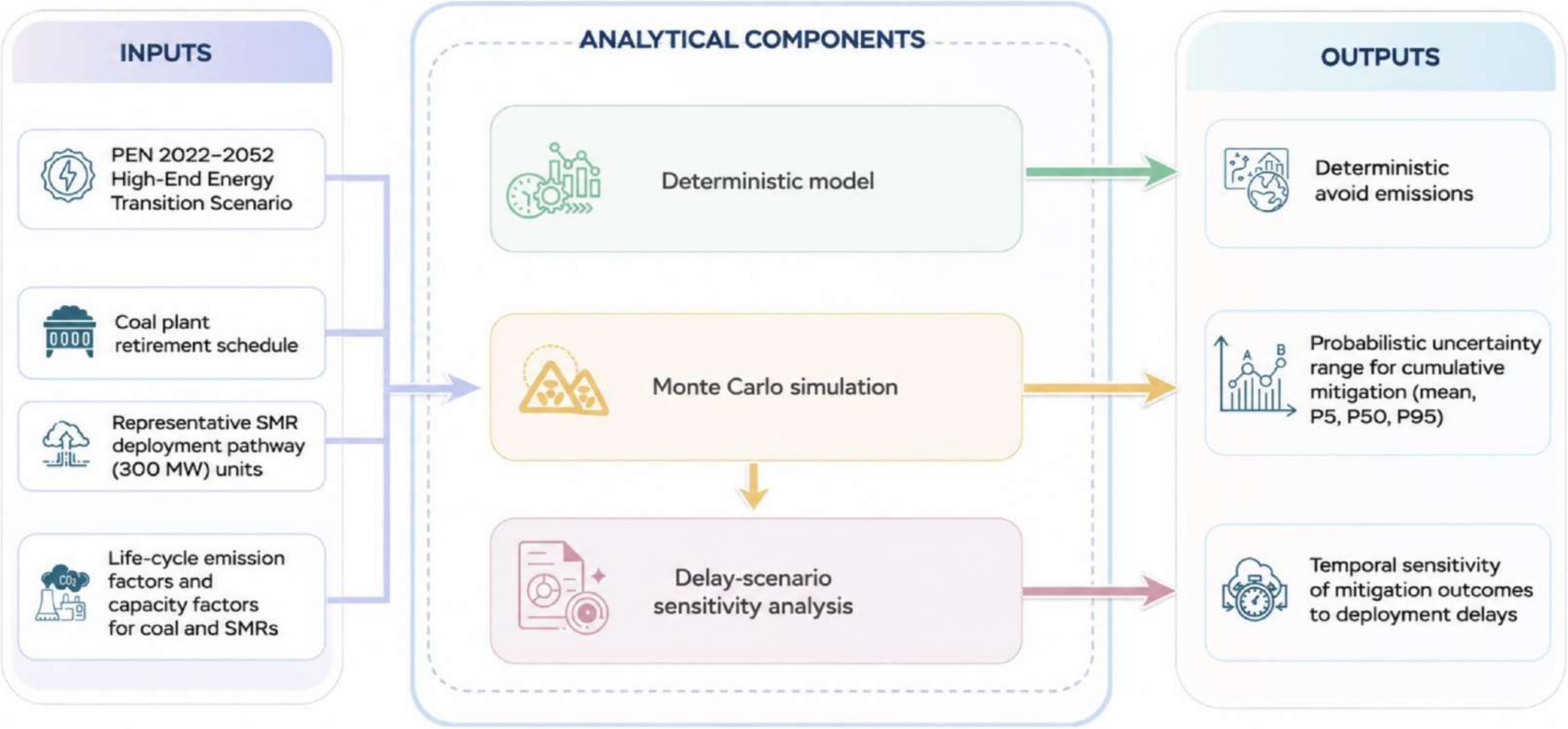
ESTRUCTURA DEL MODELAMIENTO



CALENDARIO DE SALIDA PROPUESTO

Source of Energy	Capacity (MW)	Commission date	Decommission date
PAIPA (4 units)	373	1963	2035
ZIPAEMG (4 units)	227	1964	2039
GUAJIRA (2 units)	324	1983	2043
TASAJERO (2 units)	356	1985	2047
GECELCA 3 (2 units)	491	2015	2051

DEFINICIONES

$$E_{avoided,t} = E_{BAU,t} - E_{nuclear,t}$$

Avoided emissions in year t are the difference between BAU (coal) emissions and nuclear emissions.

$$E_{BAU,t} = G_{coal,t} \times EF_{coal}$$

Emissions in the BAU (coal) scenario in year t.

$$G_{coal,t} = C_{coal,t} \times h_y \times CF_{coal}$$

Generation from coal in year t.

$$E_{nuclear,t} = G_{nuclear,t} \times EF_{nuclear}$$

Emissions in the nuclear scenario in year t.

$$G_{nuclear,t} = C_{SMR,t} \times h_y \times CF_{SMR}$$

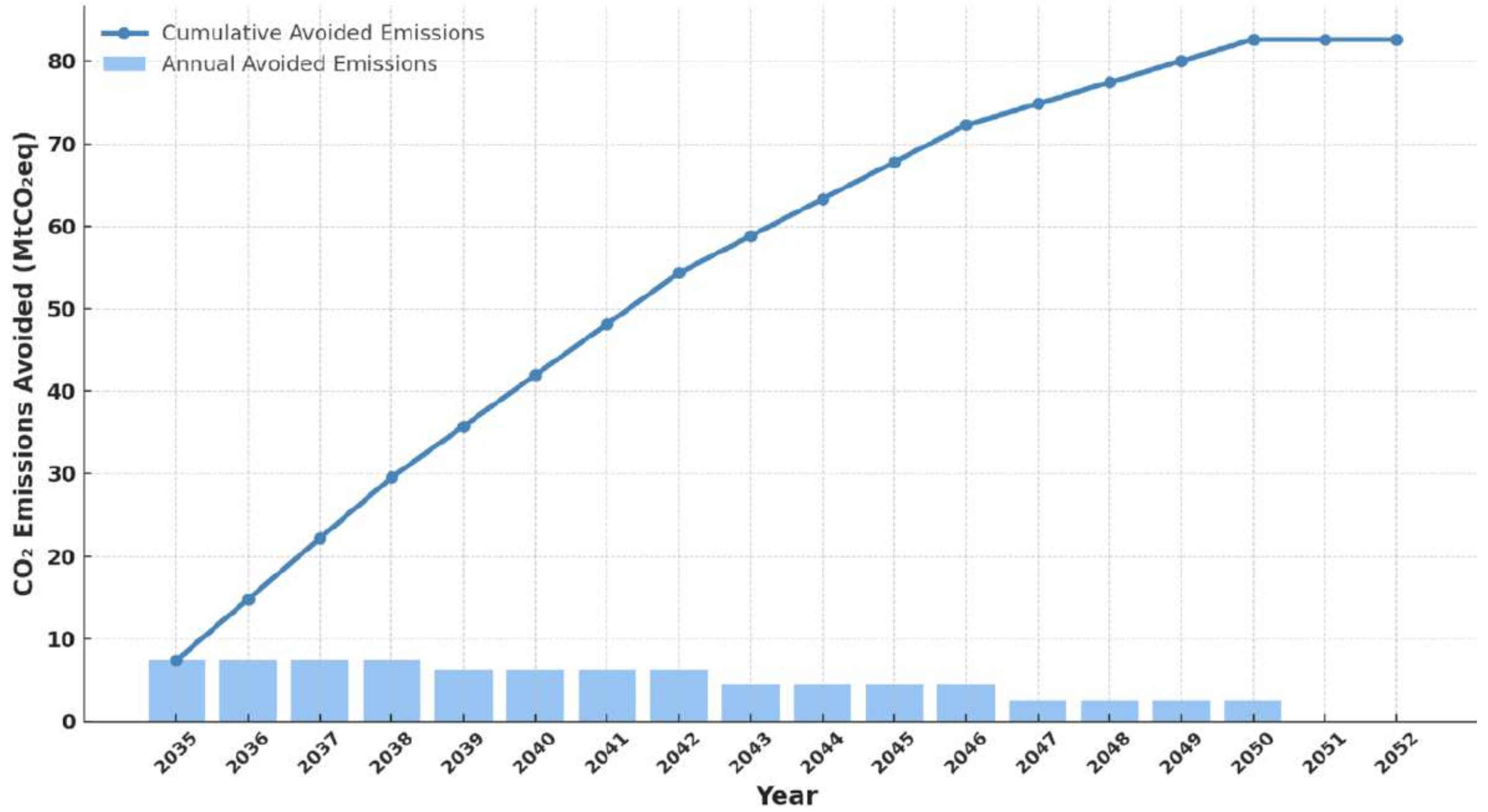
Generation from SMRs in year t.

CUMULATIVE AVOIDED EMISSIONS (2035–2052)

$$E_{\text{avoided, cumulative}} = \sum_{t=2035}^{2052} E_{\text{avoided},t}$$

MODELO DETERMINÍSTICO

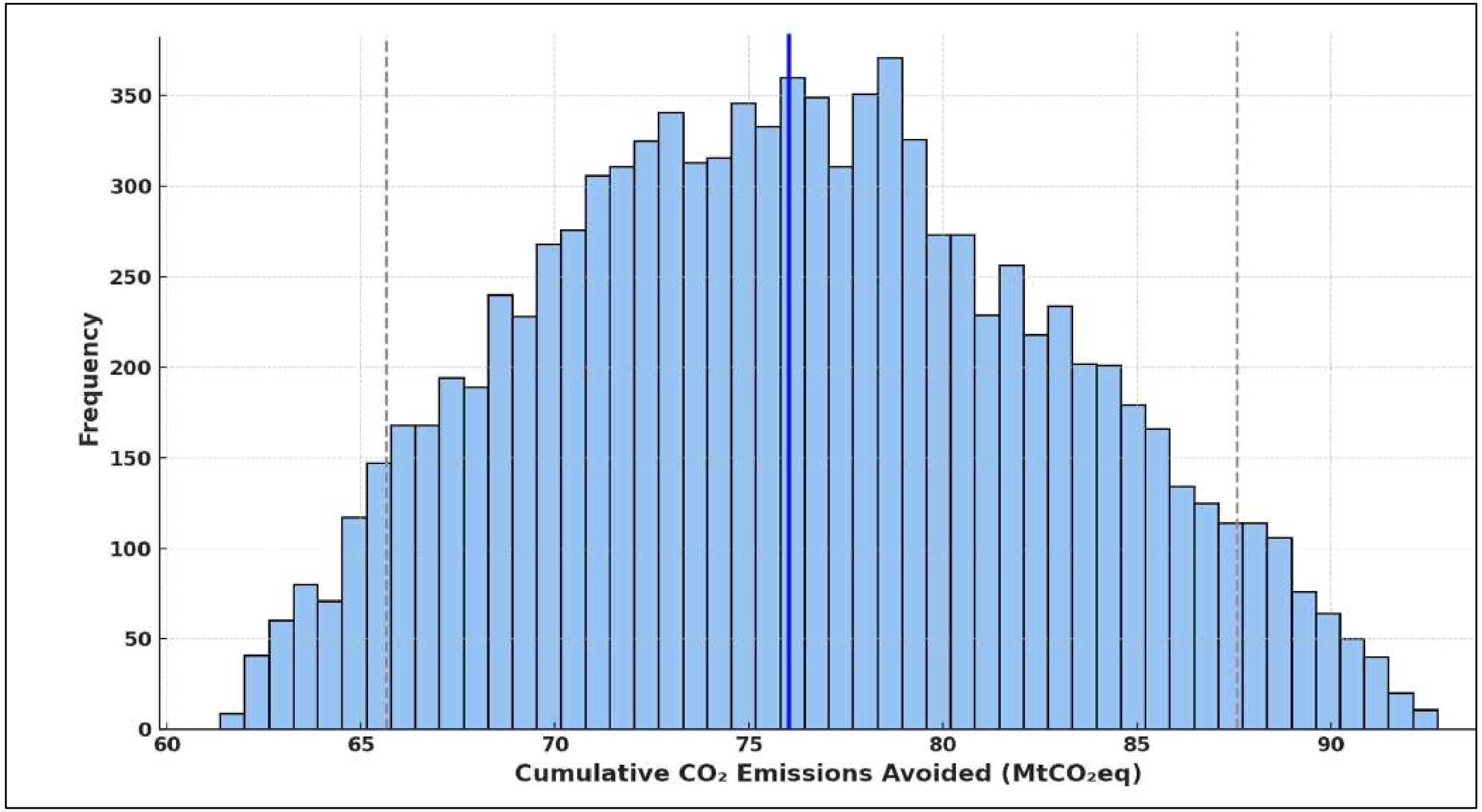
Fig. 3.4: Trajectory of CO_2eq Emissions Avoided in Colombia (2035-2052)



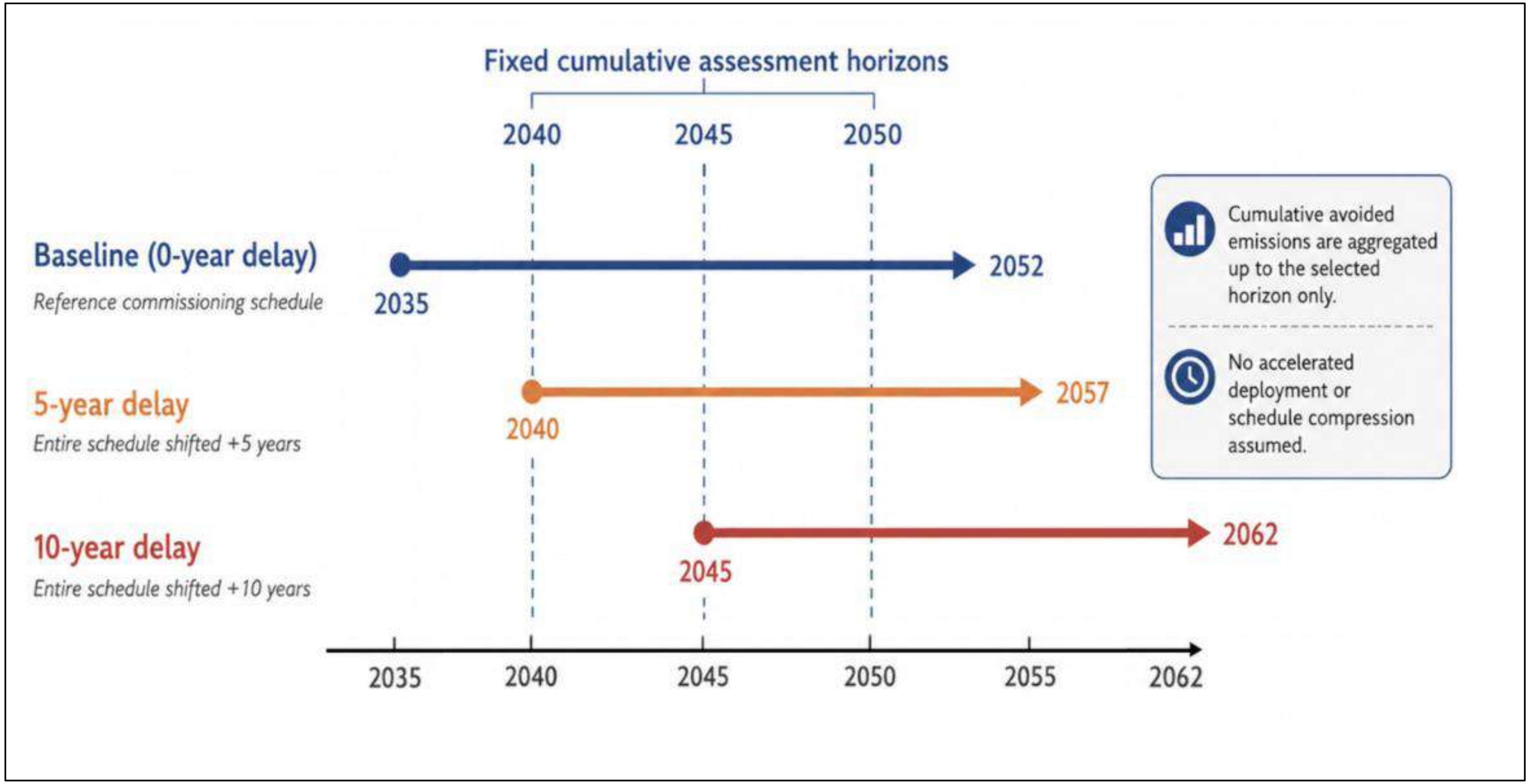
82.6 $MtCO_2eq$

MODELO PROBABILÍSTICO

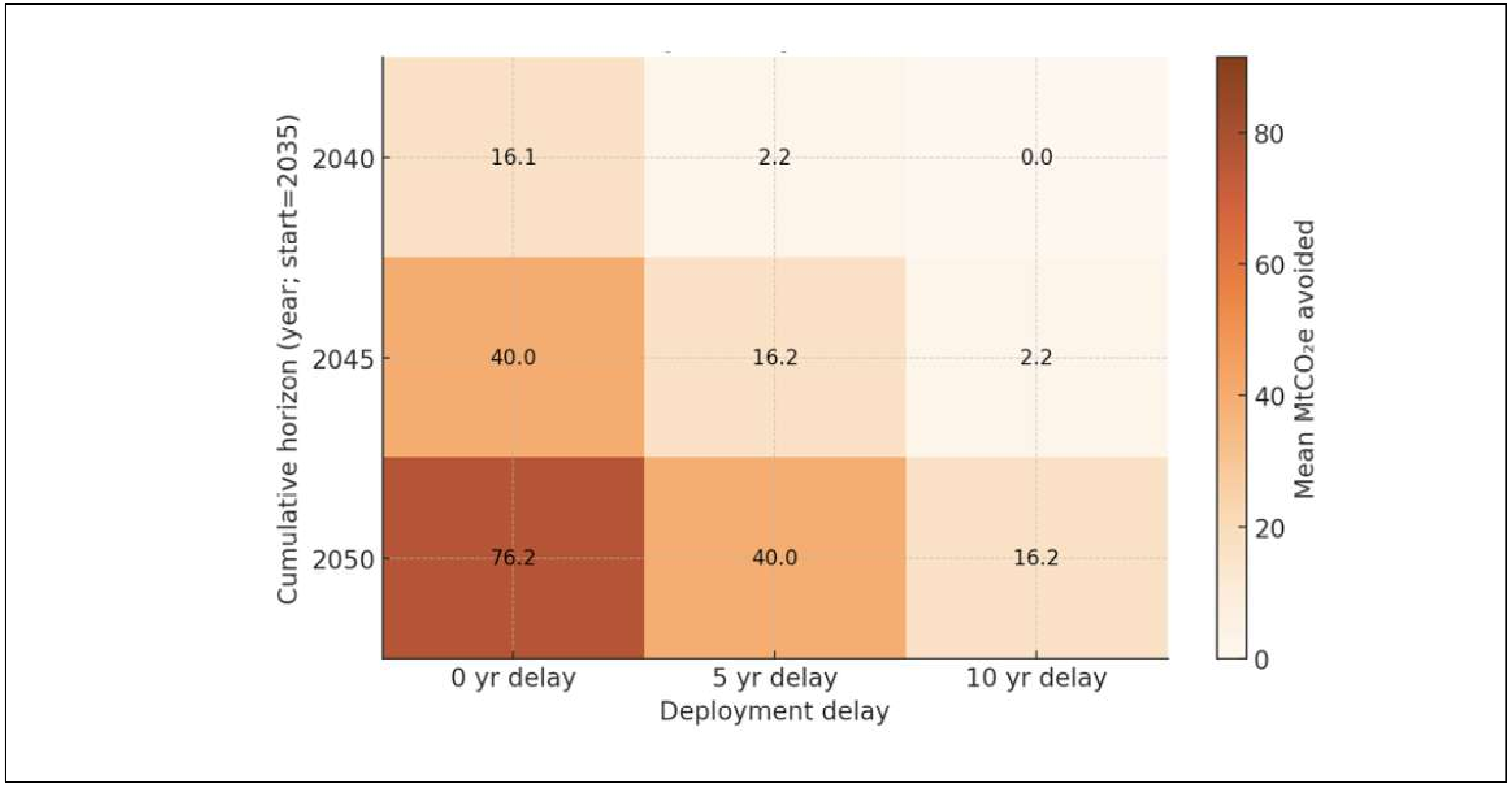
P(50) 76.3 $MtCO_2eq$



ESCENARIOS DE RETRASO



ANÁLISIS DE SENSIBILIDAD



Evaluando la eficiencia en el uso del suelo en los SMR

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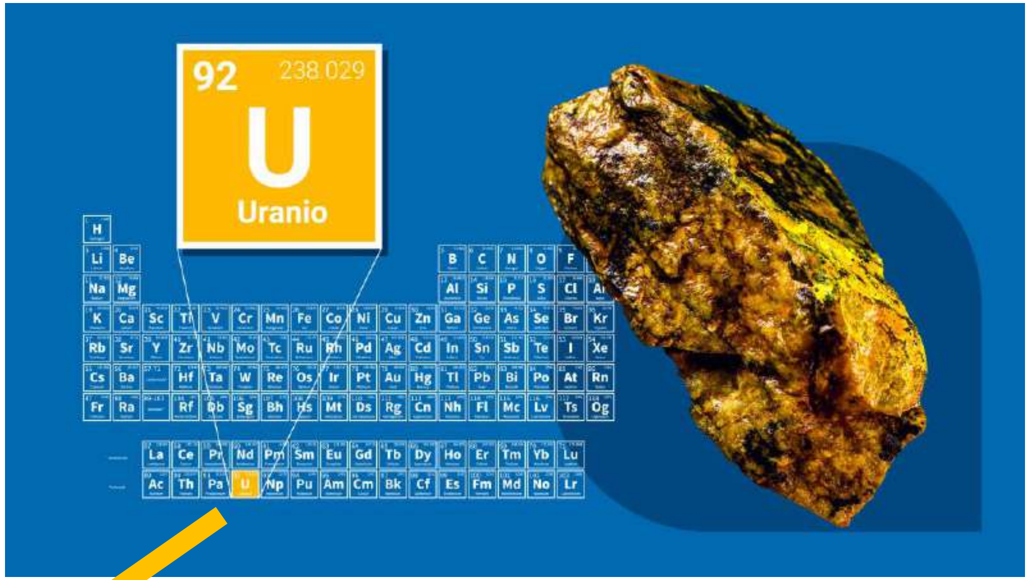
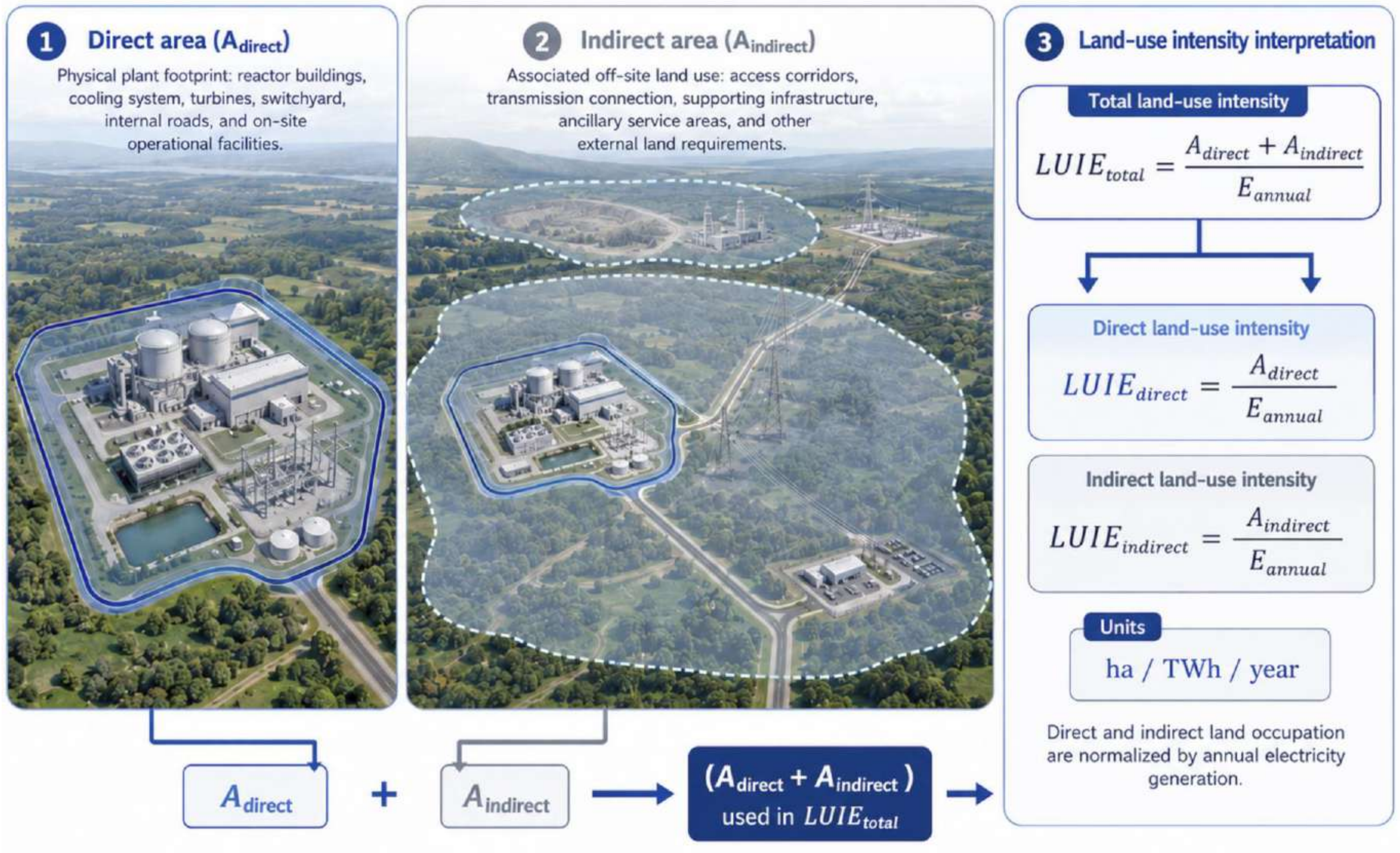
INTENSIDAD DEL USO DEL SUELO

Total LUIE	$LUIE_{total} = \frac{A_{direct} + A_{indirect}}{E_{annual}} \left[\frac{ha}{TWh/y}\right]$
Direct LUIE	$LUIE_{direct} = \frac{A_{direct}}{E_{annual}} \left[\frac{ha}{TWh/y}\right]$
Indirect LUIE	$LUIE_{indirect} = \frac{A_{indirect}}{E_{annual}} \left[\frac{ha}{TWh/y}\right]$



(Lovering et al., 2022; IAEA, 2024)

METODOLOGÍA DE LOVERING

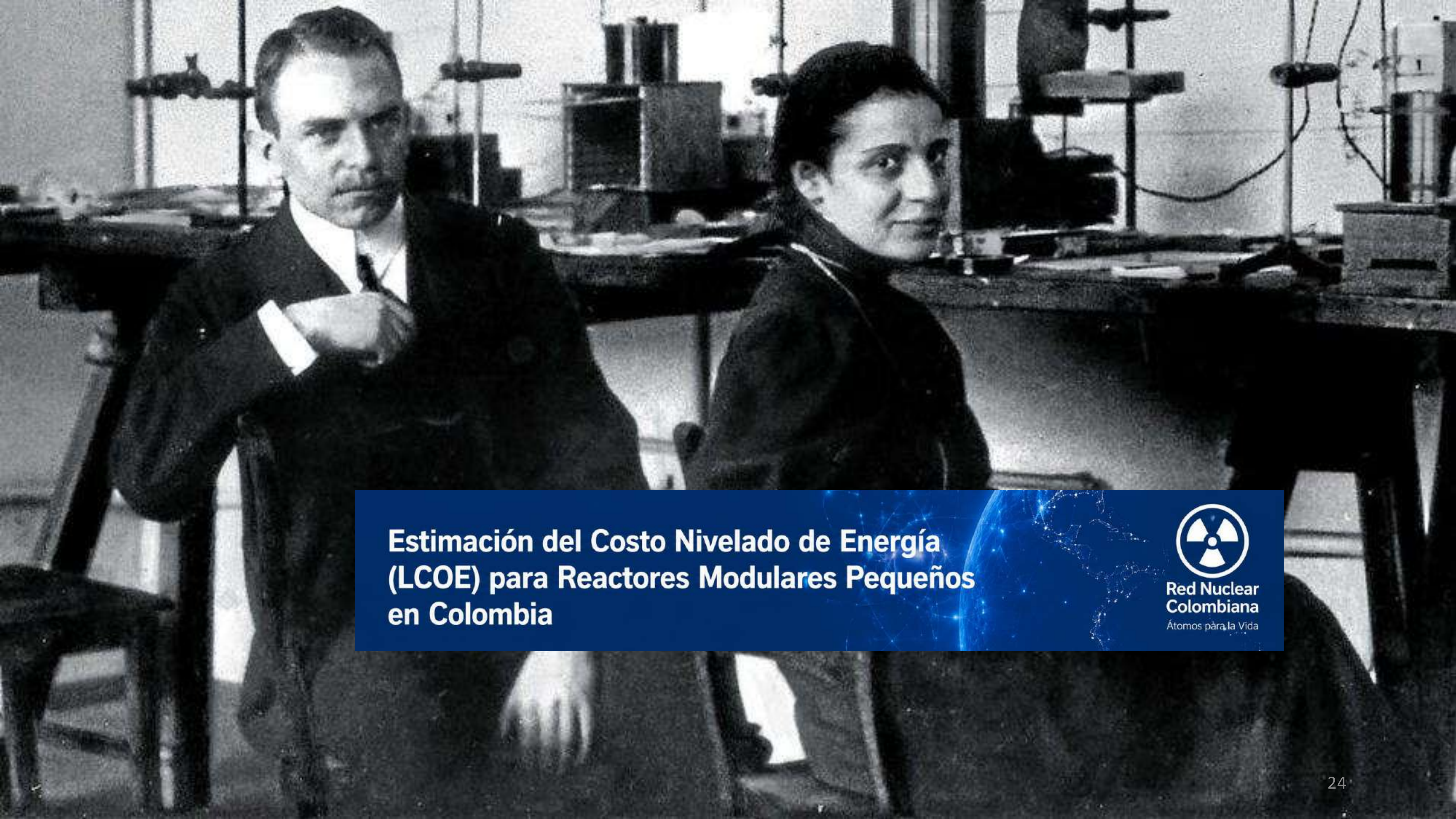


RESULTDOS EN SMRs

SMR Type	ha/TWh/y (CF 95%)	ha/TWh/y (CF 80.2%)	Approximate TRL
Land-Based Water-Cooled SMR	5	5	TRL 8-9
Marine-Based Water-Cooled SMR	8	10	TRL 8-9
Fast-Spectrum SMR	4	4	TRL 6-8
High-Temperature Gas-Cooled SMR	10	10	TRL 6-7
Molten-Salt SMR	2	3	TRL 3-5
Microreactors	7	9	TRL 4-6
Mean Direct LUIE	**6**	**7**	—

COMPARACIÓN ENTRE DIFERENTES FUENTES

Source of Energy	LUIE Total (ha/TWh/y) Mean
Hydroelectric	15,000
Ground-mounted PV	2,100
Natural gas	410
Wind	170
Nuclear LR	15
SMR	**8**



Estimación del Costo Nivelado de Energía (LCOE) para Reactores Modulares Pequeños en Colombia

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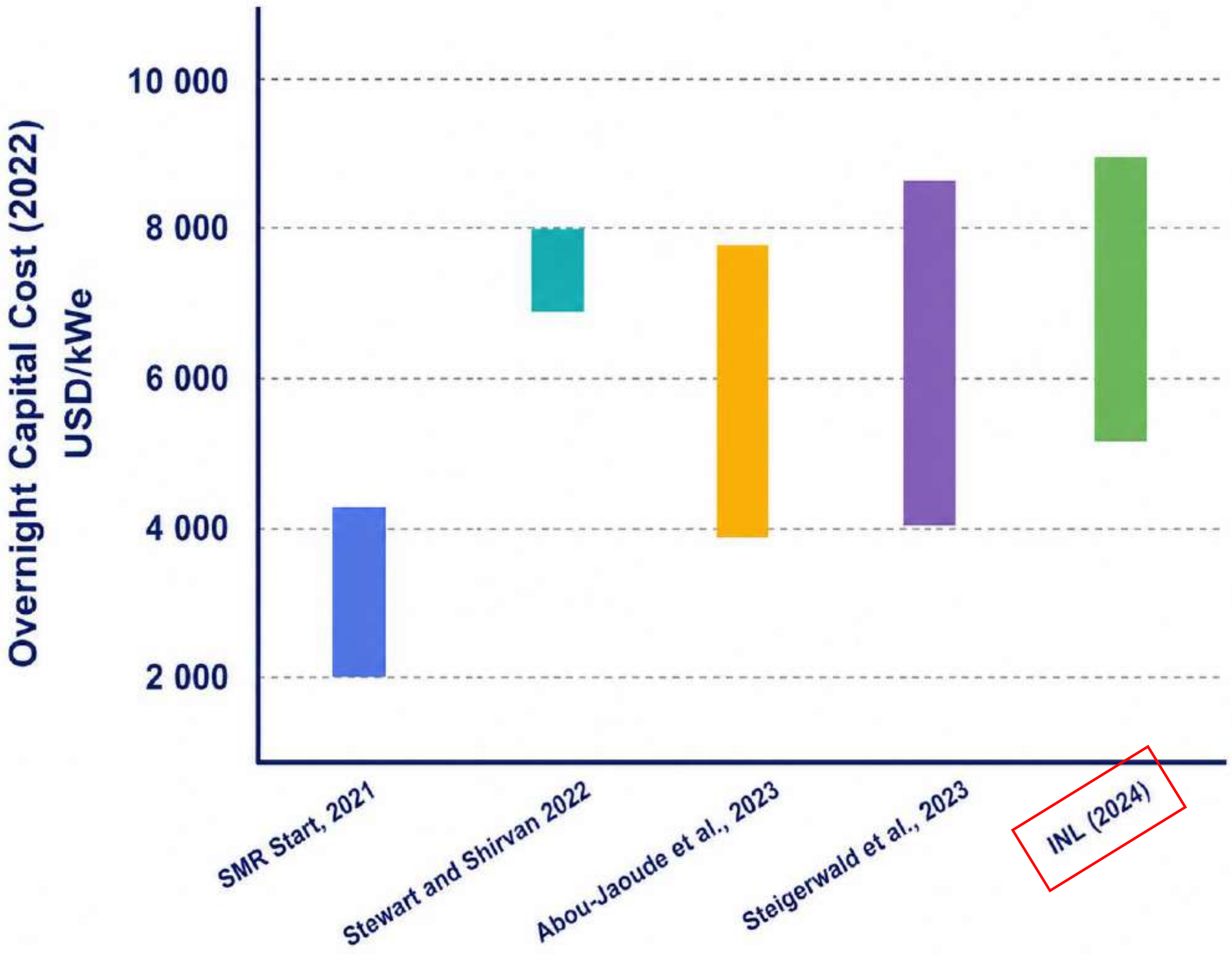
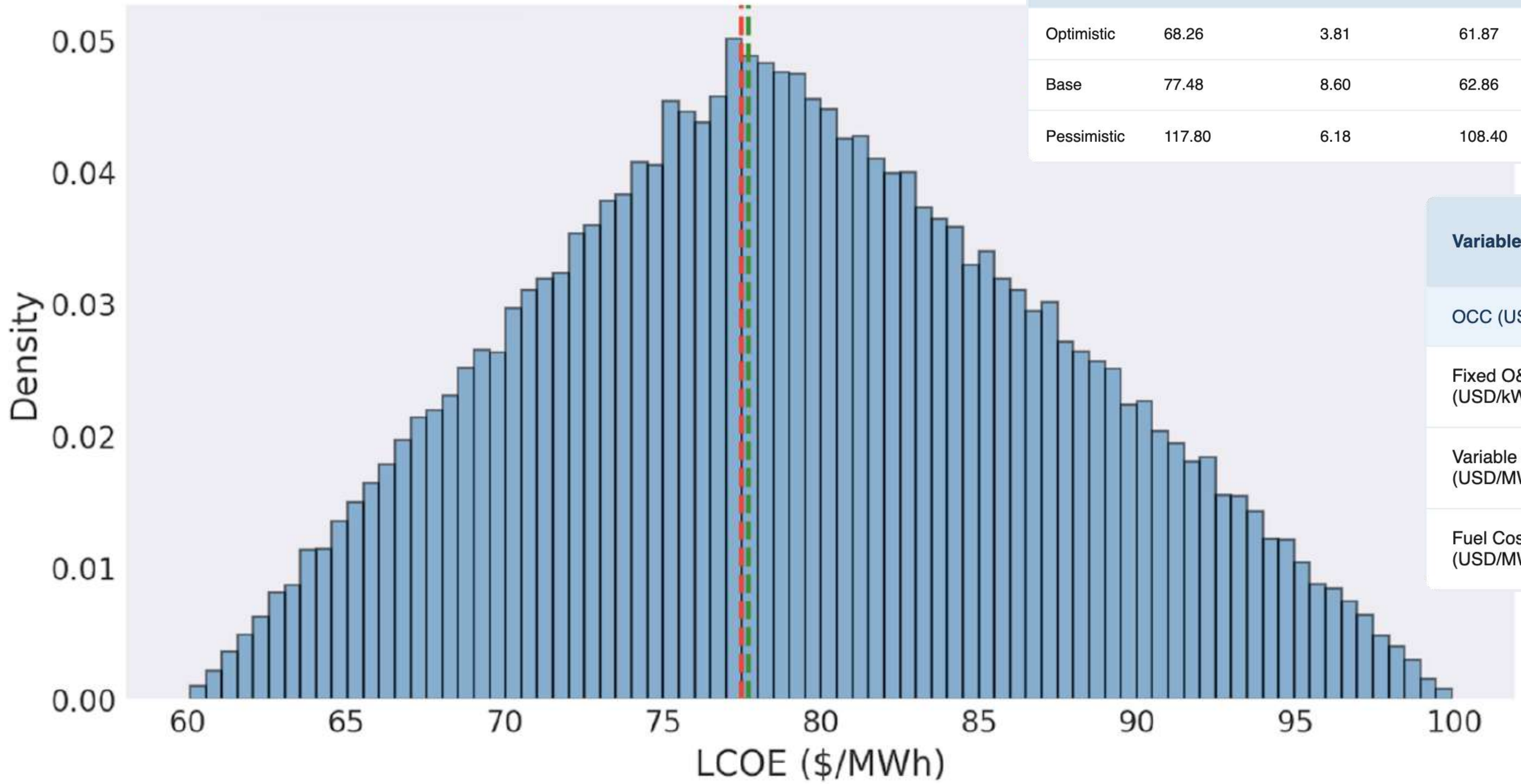
CÁLCULOS DE LCOE EN COLOMBIA

Source	UPME LCOE (USD/MWh)	IEA Median LCOE (USD/MWh) (2020–2025)
Onshore wind	224.07 (Guajira)	50
PV	373.13 (Guajira)	56
Coal	93.69 (Cundinamarca)	88
Natural Gas CCGT	97.3 (Guajira)	71
Large Hydro	45.16 (Santander)	72
Geothermal Flash	98.8 (Cauca)	99
Biomass	107.8 (Valle del Cauca)	118
Nuclear	*Not defined*	69

ESTUDIOS FUENTE



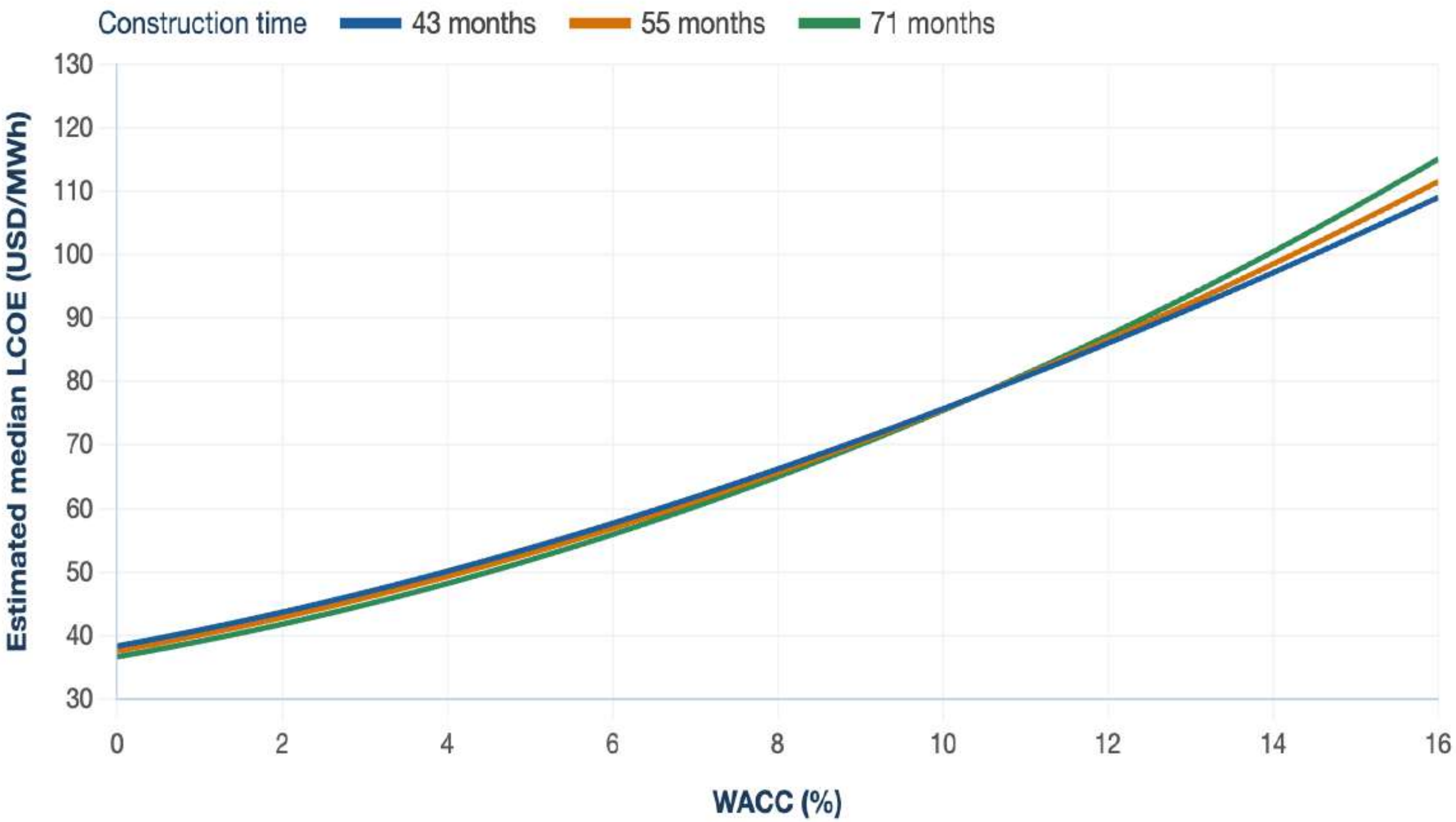
CÁCULO DE LCOE DE SMR PARA COLOMBIA



Scenario	Mean LCOE ($/MWh)	Std Dev ($/MWh)	5th Percentile ($/MWh)	Median ($/MWh)	95th Percentile ($/MWh)
Optimistic	68.26	3.81	61.87	68.27	74.63
Base	77.48	8.60	62.86	77.71	91.63
Pessimistic	117.80	6.18	108.40	117.20	128.86

Variable	Pearson Correlation (Univariable)
OCC (USD/kWe)	0.9986
Fixed O&M (USD/kW-yr)	−0.0014
Variable O&M (USD/MWh)	0.0079
Fuel Cost (USD/MWh)	0.0488

ANÁLISIS DE SENSIBILIDAD DEL WACC



LEVELIZED COST OF ENERGY (LCOE)

$$LCOE(r,T) = LCOE_{non-capital} + LCOE_{capital,base}\left[\frac{CRF(r,n)}{CRF(r_0,n)}\right]\left[\frac{M(r,T)}{M(r_0,T)}\right]$$

CAPITAL RECOVERY FACTOR

$$CRF(r,n) = \frac{r(1+r)^n}{(1+r)^n - 1}$$

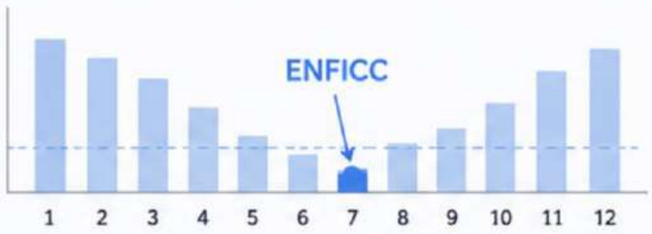
WHERE THE CONSTRUCTION-PERIOD FINANCING MULTIPLIER IS DEFINED AS:

$$M(r,T) = \frac{(1+r)^T - 1}{rT}$$

MÉTODOLOGÍA PARA CÁCULO DE ENFICC

ENFICC: Definition and Interpretation

$$\text{ENFICC} = \min_{m\in\{1,\dots,12\}} P_{5\%}\left(E_m\right)$$



Where:

E_m:	The monthly energy generated in month m across multiple simulation iterations.
$P_{5\%}\left(E_m\right)$:	Denotes the 5th percentile of monthly energy production for each month.
$ENFICC$:	Is defined as the minimum of these percentiles across the twelve months of the year.

MÉTODOLOGÍA PARA CÁCULO DE ENFICC

Category	Climatic Vulnerability	Proposed Adjustment Factor	Methodological Application
A1: Freshwater-cooled	High	$F_H(m)$: monthly hydrological derating factor	Apply monthly hydrological derating to simulated monthly energy output
A2: Seawater-cooled	Moderate	F_T: fixed thermal correction factor	Apply fixed thermal correction to the monthly percentile-based energy estimate
B: Non-water-cooled	None	None	Use base availability model without climatic derating

MÉTODOLOGÍA PARA CÁCULO DE ENFICC

1. MONTHLY ENERGY

$$E_m^{(i)} = \sum_{t \in m} P_t^{(i)} \, A_t^{(i)} \, \Delta t$$

where $P_t^{(i)}$ is the simulated reactor power output at hour t in Monte Carlo iteration i, $t \in m$ denotes all hourly time steps within month m, and Δt is the simulation time step, expressed in hours.

2. REACTOR GROUPS

GROUP A1
Freshwater-Cooled Reactors

$$E_{m,A1}^{(i)} \rightarrow F_H(m)\, E_{m,A1}^{(i)} \rightarrow Q_{0.05}\left(E_{m,A1}\right) \rightarrow \min_m Q_{0.05}\left(E_{m,A1}\right)$$

GROUP A2
Seawater-Cooled Reactors

$$E_{m,A2}^{(i)} \rightarrow Q_{0.05}\left(E_{m,A2}\right) \rightarrow F_T Q_{0.05}\left(E_{m,A2}\right) \rightarrow \min_m \left(F_T\, Q_{0.05}\left(E_{m,A2}\right)\right)$$

GROUP B
Non-Water-Cooled Reactors

$$E_{m,B}^{(i)} \rightarrow Q_{0.05}\left(E_{m,B}\right) \rightarrow \min_m Q_{0.05}\left(E_{m,B}\right)$$

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