



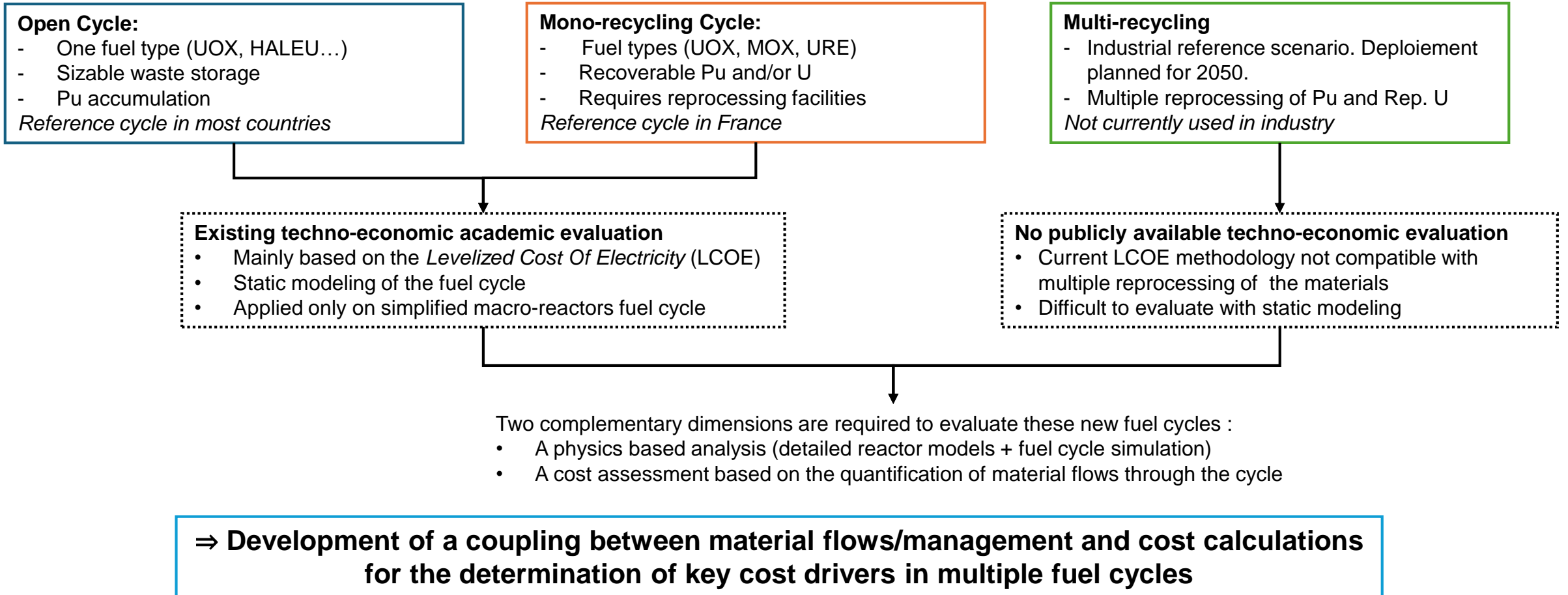
Technical and economic assessment of Pu/U recycling strategies in the French nuclear fuel Cycle

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CONTEXT – TECHNO-ECONOMIC ANALYSIS OF FUEL CYCLES



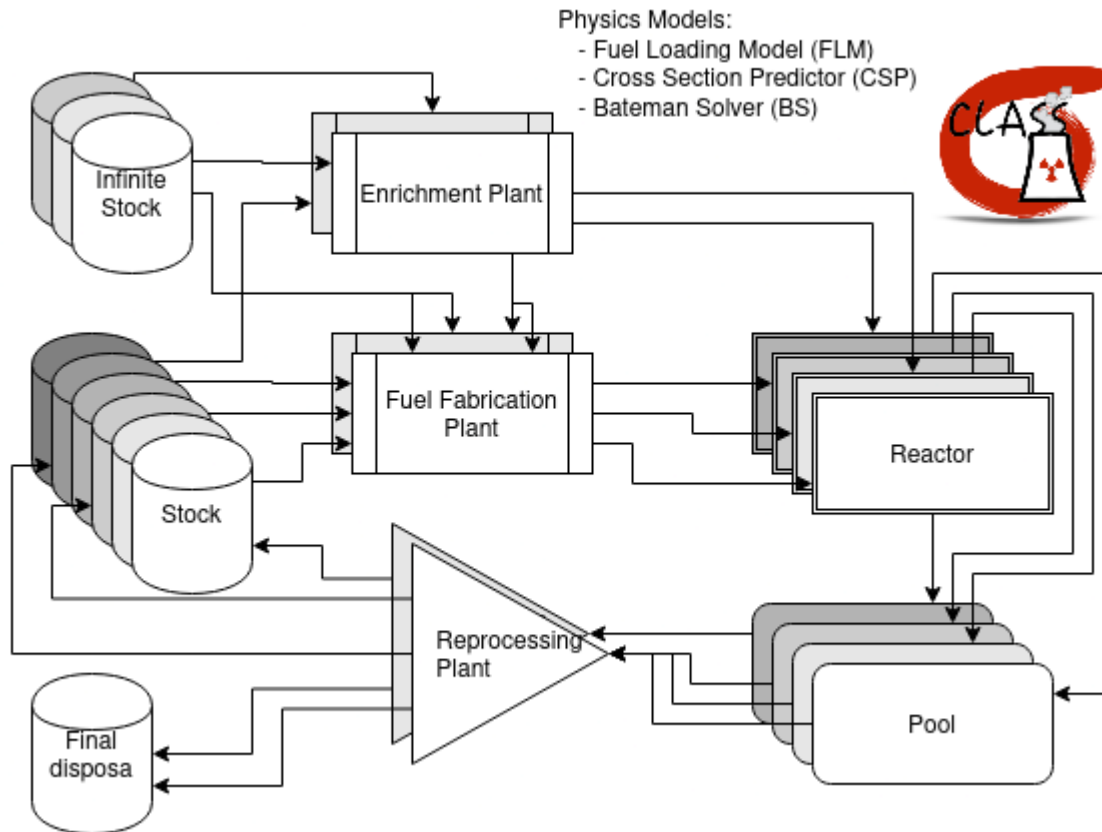
References

1. D'Haeseleer, W. D. Synthesis on the Economics of Nuclear Energy. Study for the European Commission (2013).
2. De Roo, G. & Parsons, J. E. A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling. *Energy Economics* 33, 826-839 (2011).
3. NEA. The Economics of the Back End of the Nuclear Fuel Cycle. *Nuclear Development* 2013 (2013).

ECONOMIC INTEGRATION IN CLASS

CLASS – A DYNAMIC FUEL CYCLE SIMULATOR

Fig. 1: Example of a fuel cycle in the CLASS model



⇒ The CLASS simulator assesses U and Pu multi-recycling from a physics standpoint but needs economic modelling

- Developed since 2010
- Historical collaboration CNRS & IRSN
- Academic scenario code

Context



- Definition of scenario assumptions
- Dynamic modeling of the fuel cycle
 - Reactor models
 - Evolution of fuel cycle facilities
- Generation and analysis of outputs
 - Fuel cycle isotopic inventories evolution
 - Individual isotopic inventories evolution

Approach

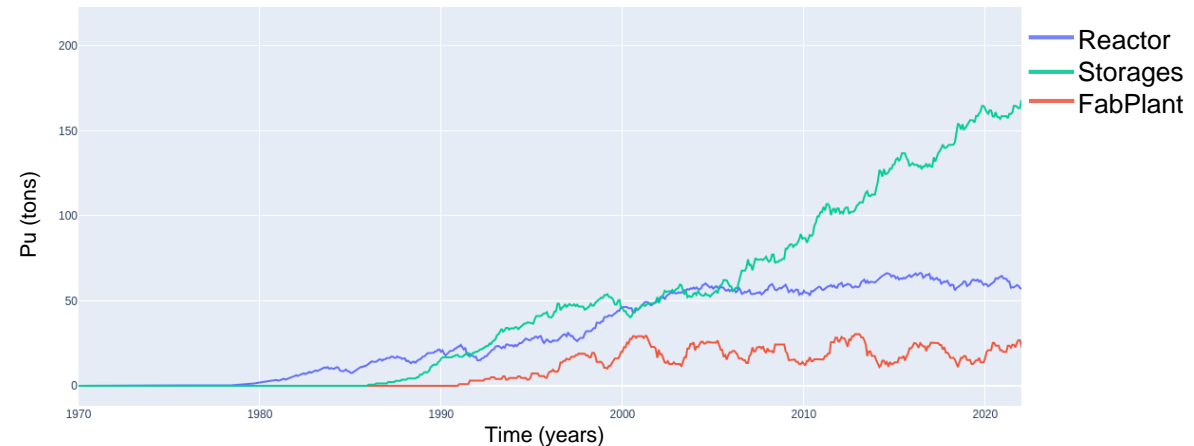


Fig. 2: Output for a French fleet simulation with recycling starting in 1991

ECONOMIC INTEGRATION IN CLASS

HANDLING ECONOMIC FLOWS IN CLASS

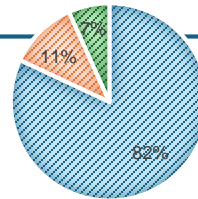
OBJECTIVE

Comparison of **several nuclear fuel cycle** evolution strategies with a **common metric**

STRATEGY

- Determine the **levelized cashflow** over the trajectory
- Output a new metric, the **Cost of the Electro-Nuclear System (CENS, €/MWh)**
- Output a **detailed cost breakdown**

- Reactor
- Front-end
- Back-end



METHODOLOGICAL FEATURES

- Integration of plant **technical constraints**
- Representation of system **dynamic capacity**
- **Endogenous** modelling of **upstream and downstream production costs**

$$CENS = \frac{\sum_{i=1}^n \sum_{t=T_i}^{T_f} (C_f(i, t) + C_v(i, t)) \cdot (1+r)^{-t}}{\sum_{t=T_i}^{T_f} E(t) \cdot (1+r)^{-t}}$$

⇒ **Dynamic coupling provides both the CENS value and detailed cost breakdown across the entire fuel cycle**

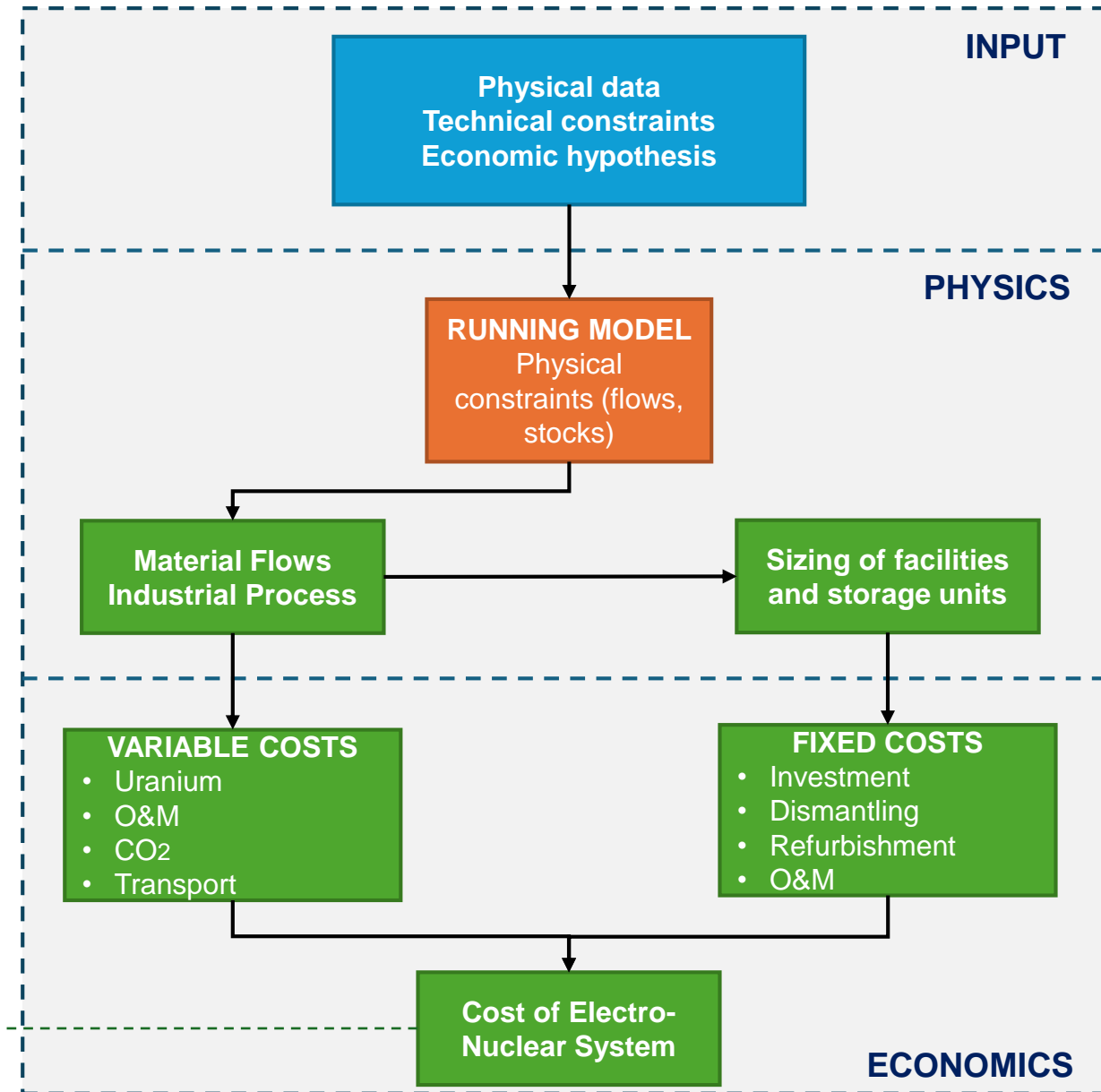


Fig. 3: Workflow for the Cost of the Electro-Nuclear System assessment within the CLASS framework

ECONOMIC INTEGRATION IN CLASS

Input file : a model for defining each cost economic behavior

STATIC ANNUITIES

Use case CAPEX – Fixed Capacity

Inputs OCC (€/Capacity)
Construction Time T_c
Lifetime L_t
Discount rate r

Model TIC (Total Investment Cost)

$$TIC = \frac{OCC}{T_c} \cdot \left(\frac{1+r}{r}\right) \cdot \left((1+r)^{T_c} - 1\right)$$

Construction Annuity

$$A_c = TIC \cdot \left[\frac{r \cdot (1+r)^{L_t}}{(1+r)^{L_t} - 1}\right]$$

Output Constant annuity (€/metric/year)

Examples Fabrication plant CAPEX
Enrichment plant CAPEX

PROVISIONS

Use case Dismantling costs

Inputs ODC (€/Capacity)
Construction Time T_c
Lifetime L_t
Discount rate r

Model Dismantling Annuity

$$A_D = ODC \cdot \frac{r}{(1+r)^{L_t} - 1}$$

Output Constant annuity (€/metric/year)

Examples Reactor dismantling
Conversion plant dismantling

⇒ Five methodologies implemented: default, static annuities, HLW cashflows, provisions, dynamic annuities

GLOBAL SENSITIVITY ANALYSIS

OBJECTIVES

- Identify the **key cost factors** in **open-cycle and mono-recycling** scenarios ;
 - Compare the **influence of these factors** between the two scenarios.

SCENARIO PARAMETERS

- **Duration:** 150 years
- **Power output:** 63 GWe (Based on the French Nuclear Fuel Cycle)
- **Reactor lifetime:** 60 years for UOX, 40 years for MOX
- Facilities operate according **economic optimums**
- Not reused material = **waste**, send to a final disposal
- Reusable material send to a final disposal **only after reactor shutdown**

GLOBAL SENSITIVITY ANALYSIS

Understand the input and output relation :

1. Design experiment for input variables
2. Run N simulations
3. Quantify the impact of each input variables on the output variability

REACTORS PARAMETERS

- **Burn-up :** 45 GWd/tHM
- **²³⁵U enrichment in PWR UOX :** 3.81%
- **Pu content in PWR MOX :** 4 – 16%

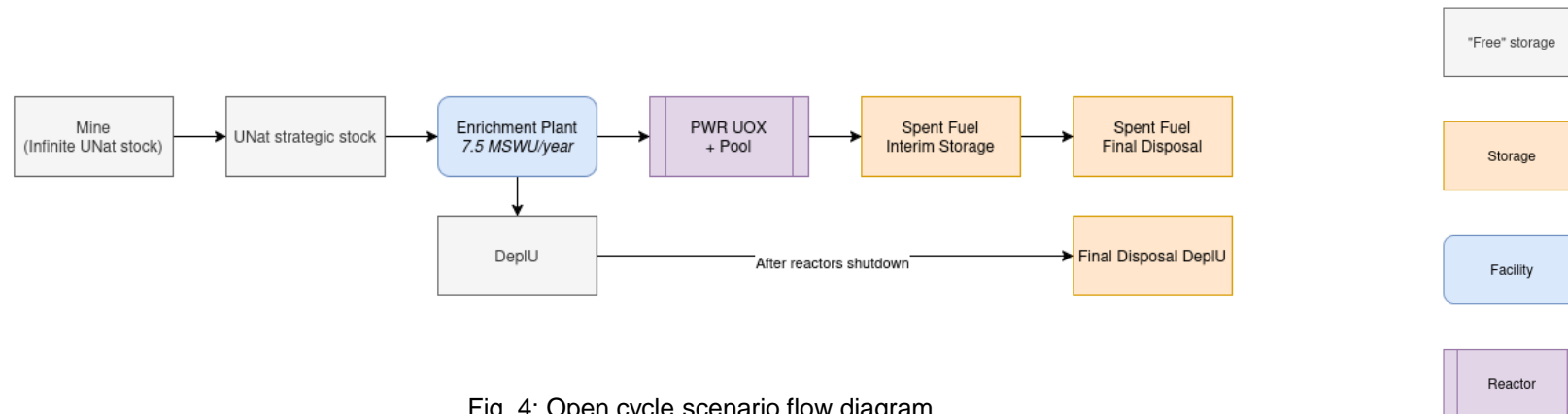


Fig. 4: Open cycle scenario flow diagram

GLOBAL SENSITIVITY ANALYSIS

OBJECTIVES

- Identify the **key cost factors** in **open-cycle and mono-recycling** scenarios ;
- Compare the **influence of these factors** between the two scenarios

- Duration
- Power o
- Reactor
- Facilities
- Not reuse
- Reusable

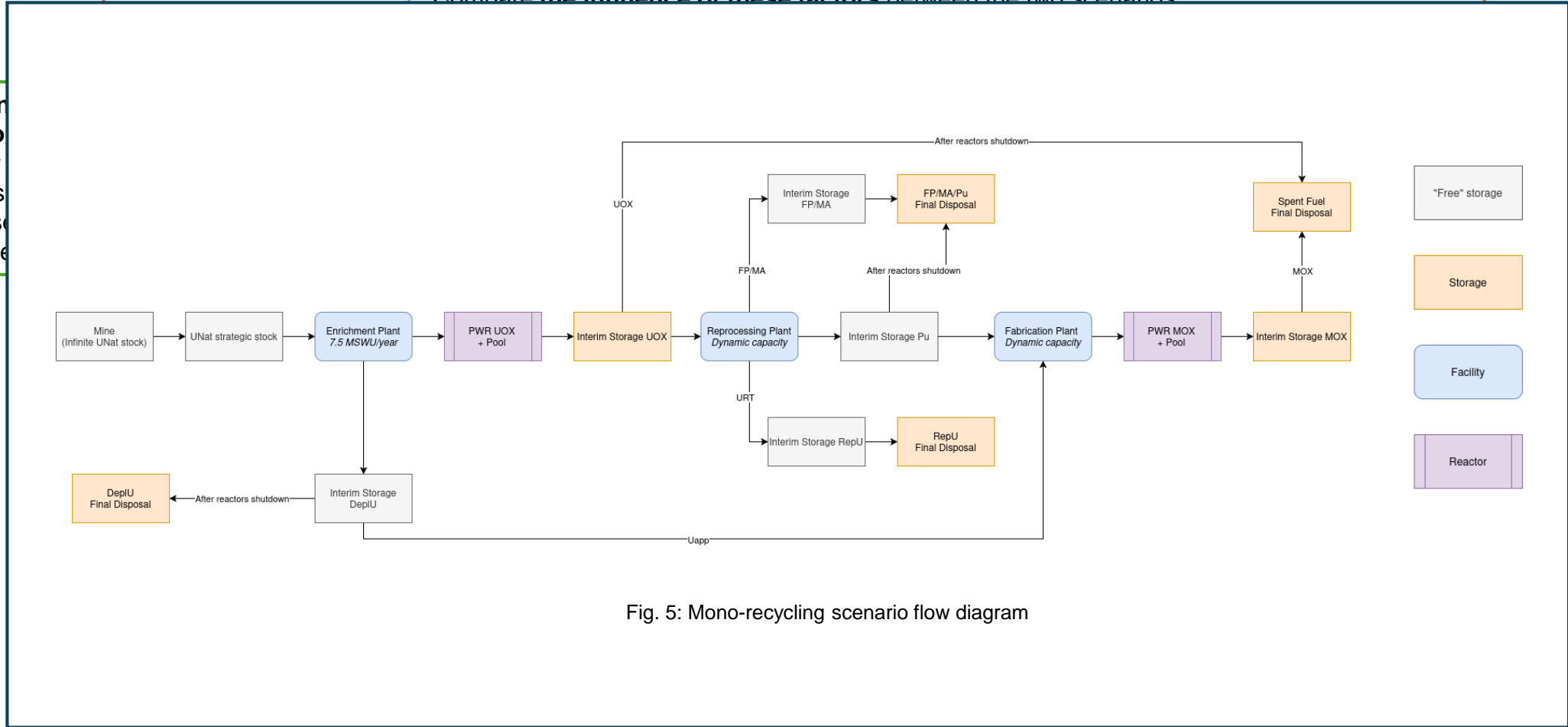


Fig. 5: Mono-recycling scenario flow diagram

GLOBAL SENSITIVITY ANALYSIS - VARIABLES

Approach

- Focus on the back-end of the fuel cycle
- Reactors + front-end CAPEX/OPEX fixed
 - Other costs treated as variables

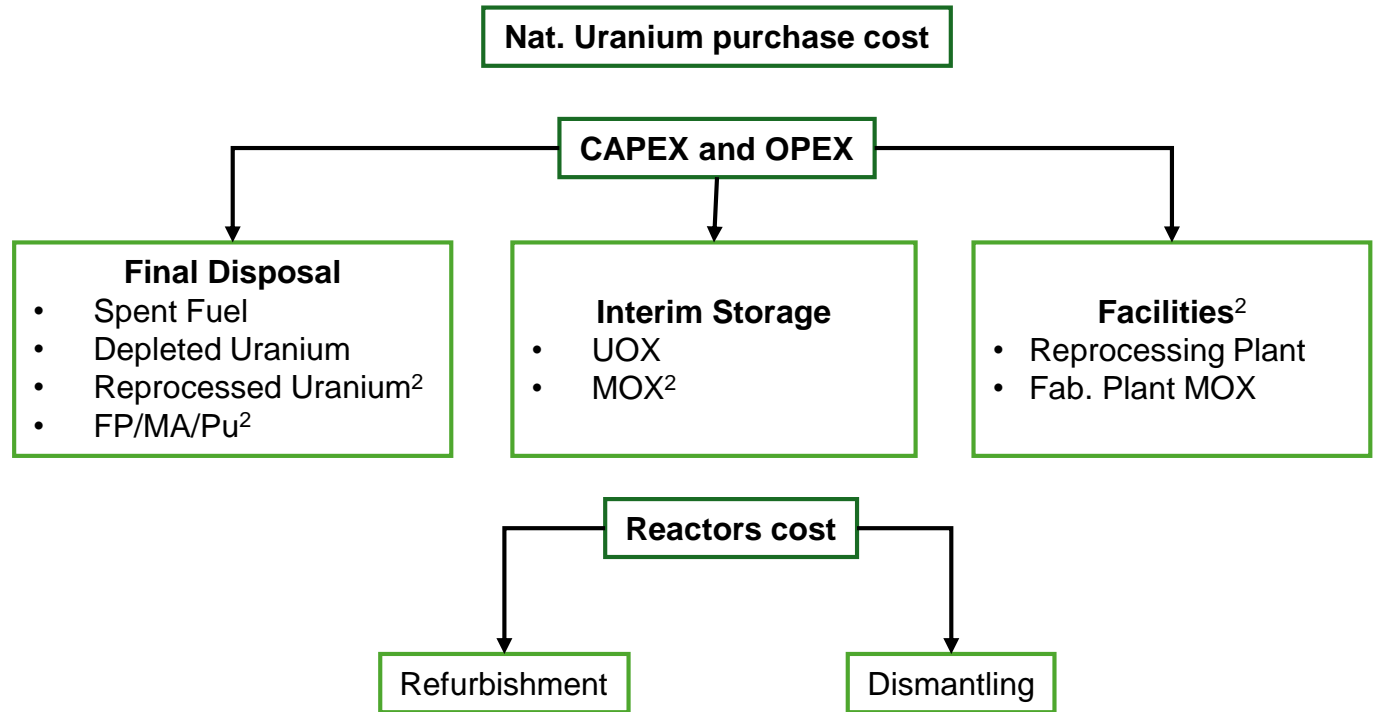
Technical variables

MOX power fraction in the fleet
0.6% - 9,5%

Interim Cooling Time
1 – 60 years

- Depleted Uranium¹
- Reprocessed Uranium²
- UOX¹
- MOX²
- FP/MA/Pu²

Economic variables



¹Open-cycle only

² Mono-recycling cycle only

DATA SELECTION

Reference value :

- Based on a publicly available reference value from historical French nuclear data
- If no historical data available, data taken from international technical economic literature
- Realistic min and max value selected around this reference value for variables

DATA SAMPLING

Global sensibility analysis based on 10 000 simulations with Latin Hypercube sampling for each scenario
Two experimental design : **uniform** and **log-normal** random draw

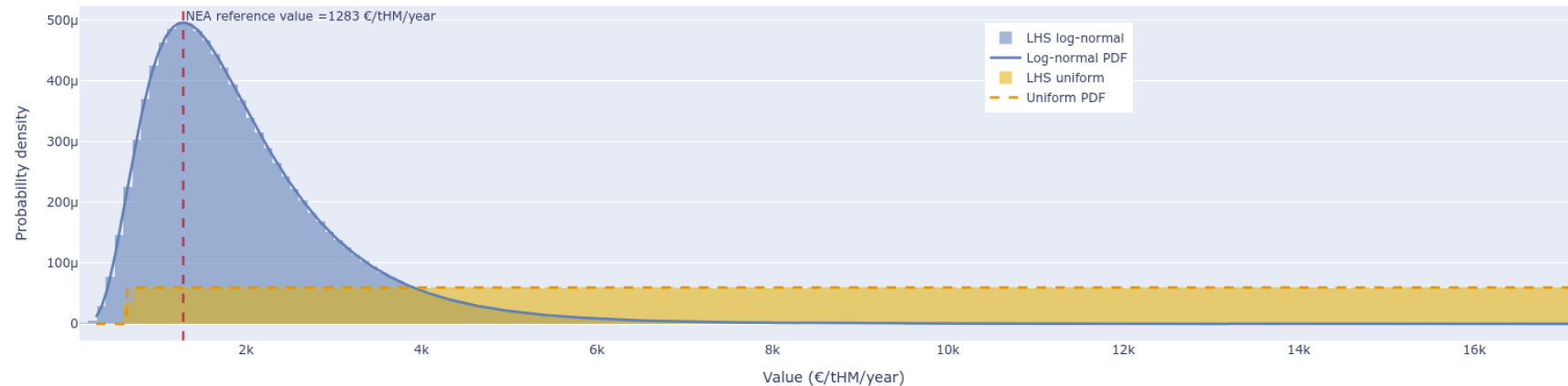


Fig. 6: Spent Fuel Final Disposal OPEX variable uniform and log-normal sampling (€/tHM/year)

⇒ Data sampling is challenging due to limited historical economic data and the absence of defined upper bounds

RESULTS: The difficulties of a variance based approach with economic variables

First approach : elasticity

- Traditional economic approach
- Measures the responsiveness of one economic variable to a change in another

$$\ln CENS = a_0 + \sum_{n=1}^N \epsilon_n \ln x_n$$

$$\epsilon_n = \frac{\partial \ln CENS}{\partial \ln x_n} = \frac{\frac{dCENS}{CENS}}{\frac{dx_n}{x_n}} = \frac{\% \text{ of change in } CENS}{\% \text{ of change in } x}$$

⇒ ϵ determination through a multiple linear regression on $\ln(CENS)$

⇒ **Issue** : obtained coefficients ϵ_n are extremely dependant on the sampling methodology as the relationship between $\ln(CENS)$ and $\ln(x_n)$ is rarely linear.

Dataset
■ mox
■ mox_gauss
■ $\Delta\%$ (mox_gauss vs mox)

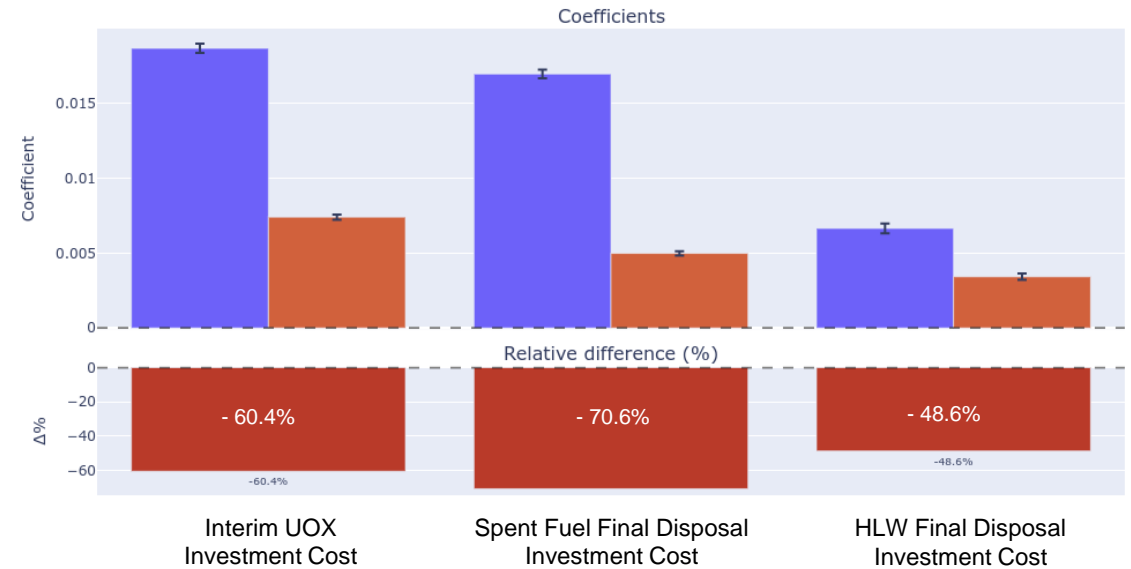


Fig. 7: ϵ_n comparison between the uniform (purple) and log-normal (red) sampling for the MOX scenario

Key cost factors identification



Cost factor comparison between fuel cycle



Independence from the sampling



RESULTS: The difficulties of a variance based approach with economic variables

Second approach : MLR level-level

Simplified approach

- Evaluates the influence of each variable independently from the others
- Enables comparison across scenarios sharing identical variables

$$CENS = a_0 + \sum_{n=1}^N a_n x_n$$

$$a_n = \frac{\Delta CENS}{\Delta x_n}$$

⇒ a_n determination through a multiple linear regression on CENS

⇒ **Issue** : obtained coefficients a_n are **independent of the sampling method for the economic variables**, but do not permit a key factors identification due to the different scale and unit.

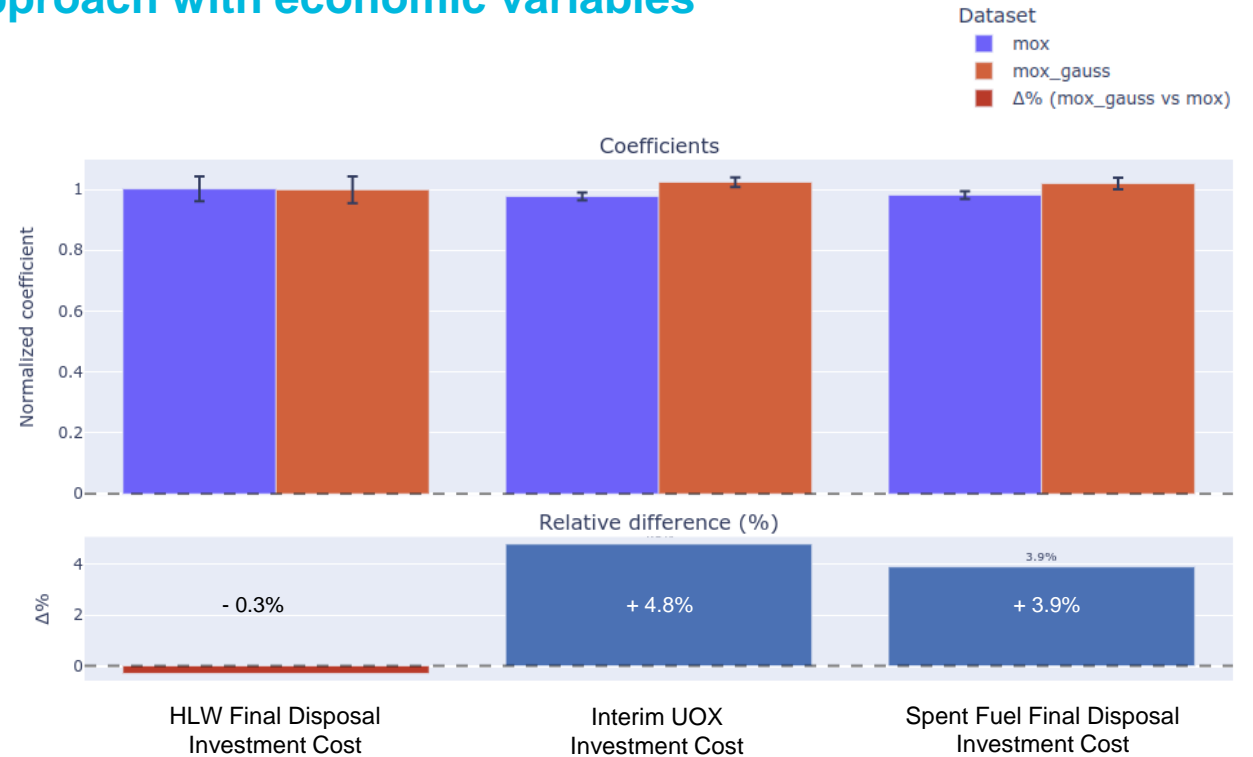


Fig. 8: Normalized a_n comparison between the uniform (purple) and log-normal (red) sampling for the MOX scenario

Key cost factors identification



Cost factor comparison between fuel cycle



Independence from the sampling



RESULTS: Mono-recycling, more resilient but still more expensive

Reactors costs : identical \pm uncertainties as independant from the strategy

Storage of Depl. U : huge decrease (74.6%)

- Final Disposal Depl. U can only open after MOX Fab. Plant closing
- Less enrichment needed due to MOX fuel

Storage of UOX costs decreasing

- Interim UOX with less capacity due to the reprocessing
- Quantity of spent fuel greatly reduced

However

New cashflows (Repro. Plant, HLW storage...) **compensate entirely** these costs reduction :

$\Rightarrow a_{\text{MOX_fraction}}$ is positive for both sampling ; the CENS increases with the mox power fraction.

\Rightarrow A Pu mono-recycling fuel cycle with 10% MOX is **1 - 3 €/MWh more expensive** than an open-cycle one.

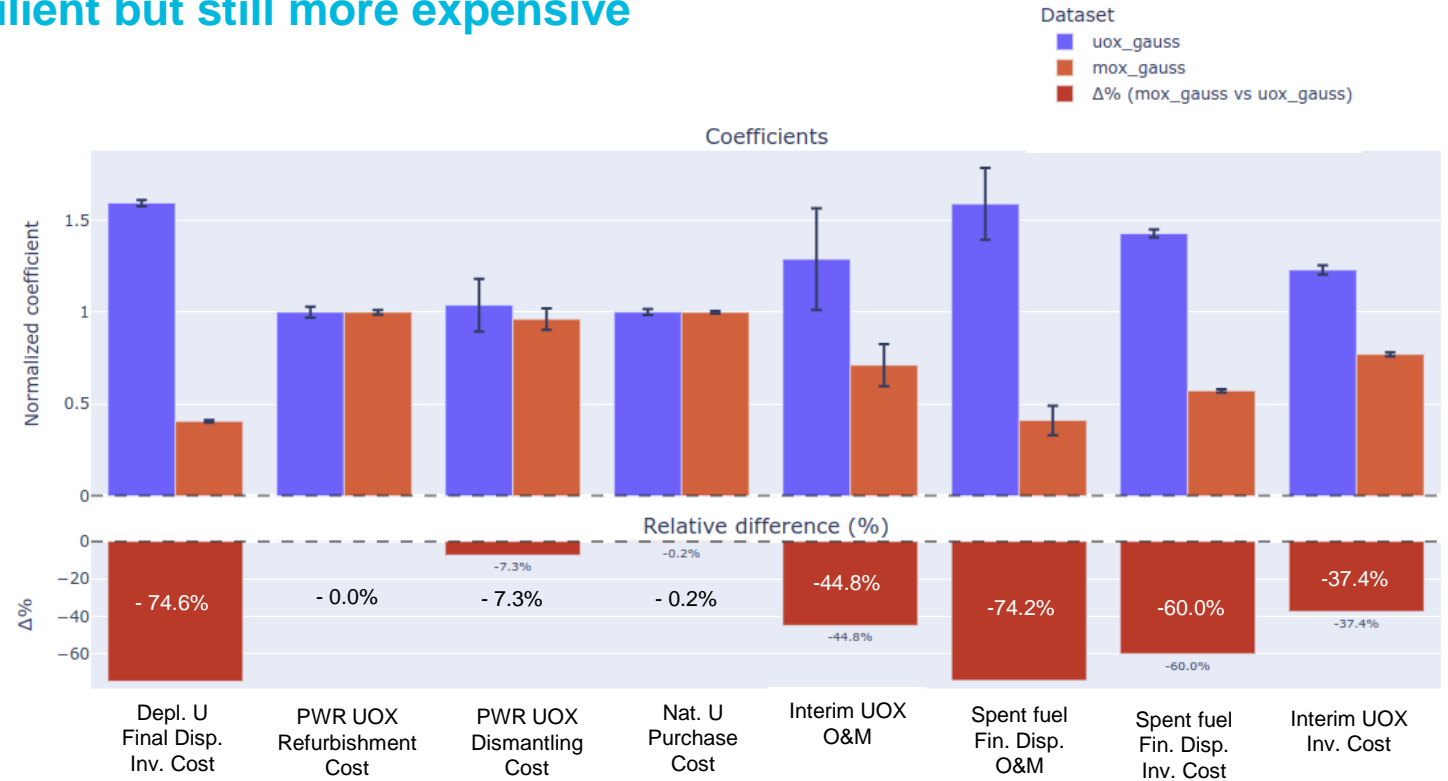


Fig. 9: Normalized a_n comparison between UOX and MOX scenario with log-normal sampling
Only the variables in common are represented on this graph.

\Rightarrow These first conclusions are perfectly coherent with the literature

CONCLUSION

- A conclusive methodology has been developed for the evaluation of complex nuclear fuel cycle strategies
- Enables the generation of multiple economic scenario analyses through dynamic technical-economic coupling

- Tested on a Global Sensitivity Analysis for the comparison of an open cycle and a mono-recycling scenario
- Results coherent with the literature, but no fulfilling metric has been found for a complete results analysis

Prospects:

- Pursue the search for a satisfying methodology for analysing outputs
- Broaden the scope to include U+Pu mono- and multirecycling analysis
- Apply the methodology to the historical French Nuclear Fleet with individual reactors



THANK YOU

Baptiste METIVIER



Input file methodologies

Methodology	Basic	Static annuities	Provision on costs	Dynamic annuities
Main use	Default	CAPEX – Fixed capacity	Dismantling	CAPEX – Evolving capacity
User Input	Yearly cost value (€/metric)	Overnight Construction Cost OCC (€/capacity) Construction time T _c (years) Lifetime Lt (years) Discount rate r	Overnight Dismantling Cost (ODC) (€/capacity) Lifetime Lt (years) Discount rate r	Base Cost B _c (€) Construction Cost CC (€/metric) Initial Capacity C _i (metric) Construction Time T _c (years) Discount rate r
Model computation	None	Total Investment cost : $TIC = \frac{OCC}{T_c} \cdot \left(\frac{1+r}{r}\right) \cdot \left((1+r)^{T_c} - 1\right)$ Annuities : $A_c = TIC \cdot \left[\frac{r \cdot (1+r)^{Lt}}{(1+r)^{Lt} - 1}\right]$	Dismantling annuity A _D : $A_D = ODC \cdot \frac{r}{(1+r)^{Lt} - 1}$	First years annuity : $A_c = \left(\frac{B_c + CC}{T_c}\right) \cdot \left(\frac{1+r}{r}\right) \cdot \left((1+r)^{T_c} - 1\right)$ When new capacity (C _N) is deployed : $A_c = \left(\frac{CC}{T_c}\right) \cdot \left(\frac{1+r}{r}\right) \cdot \left((1+r)^{T_c} - 1\right)$
Model final input	Yearly cost value (€/metric/year) Evolving with time	Annuities (€/metric/year) Same every year	Dismantling annuity (€/year) Same every year	Annuities(€/year) Evolving with time Applied for T _c years before each new capacity extension
Examples	Natural uranium purchase (€/kg) Reactor operational cost (€/W/year)	Fabrication Plant CAPEX (€/tHM) Enrichment Plant CAPEX (€/SWU)	Reactors dismantling (€/W) Conversion Plant dismantling (€/tU)	Interim Storage Construction(€/tHM) Pool construction (€/tHM)

Variables

Variable	Name	Min.	Reference	Max	Unit (2025)	Source
MOX fraction	MOX_fraction	6,00 %	-	9,50 %	-	Between the minimal computable value and the equilibrium
Final Disposal Overnight Construction Cost	finDisp_invCost	4,12E+04	8,84E+04	2,89E+06	€/tHM	Between min and 10x max (NEA, 2013) values
Final Disposal O&M Cost	finDisp_OM	1,28E+03	1,22E+03	1,73E+04	€/tHM/year	Between min and 10x max (NEA, 2013) values
Interim UOX Overnight Construction Cost	int_uox_invCost	6,56E+04	1,38E+05	2,24E+06	€/tHM	Between min and 10x max (NEA, 2013) values
Interim UOX O&M Cost	int_uox_OM	2,62E+02	5,80E+02	1,16E+04	€/tHM/year	Between min and 10x max (NEA, 2013) values
Interim MOX Overnight Construction Cost	int_mox_invCost	1,64E+05	3,45E+05	5,60E+06	€/tHM	Between min and 10x max (NEA, 2013) values
Interim MOX O&M Cost	int_mox_OM	6,55E+02	1,45E+03	2,89E+04	€/tHM/year	Between min and 10x max (NEA, 2013) values
Final Disposal Rep. U + Depl. U cost factor	u_def_cost	4,49E+04	8,98E+04	2,69E+05	€/tHM	Between 0.5 and 3x times EDF estimation (CDC, 2012)
Final Disposal FP/MA cost factor	pfma_def_factor	7,50E+09	2,50E+10	2,50E+11	€	Between 0.3 and 10x times the CIGEO cost analysis (ANDRA, 2020)
PWR Overnight Dismantling Cost	uox_odc	0,33	0,45	1,12	€/W	Between 300 M€ and 1 B€ for a 900 MW PWR
PWR Overnight Refurbishing Cost	uox_orc	0,79	1,59	3,18	€/W	Between 50 B€ and 200 B€ for the 63 GW fleet
Front-end Plant Overnight Dismantling Cost	front_odc	0,33	1	3	-	Between a third and three times the base cost of the French facilities (NEA 2013, AREVA 2004)
Reprocessing Plant cost factor	rp_factor	0,33	1	3	-	Between a third and three times the base cost of the French facilities (CDC, 2014)
Fabrication Plant MOX cost factor	fp_factor	0,33	1	3	-	Between a third and three times the base cost of the French facilities (De Roo et al., 2011)
Interim Cooling Cycletime (all)	name_cycletime	0	-	60	-	Realistic waiting schedule before geological repository opening
Uranium Cost		0	12	250	€/kg	Log-normal calibrated on the historical spot price of natural uranium

References

1. NEA. The Economics of the Back End of the Nuclear Fuel Cycle. Nuclear Development 2013 (2013).
2. Cour des comptes. Les coûts de la filière électronucléaire. (2012).
3. ANDRA. Évaluation socioéconomique du projet global Cigéo. (2020).
4. AREVA, Projet Georges Besse II – Dossier du maître d’ouvrage. (2004)
5. Cour des comptes. Le Coût de Production de l’électricité Nucléaire. (2014).
6. De Roo, G. & Parsons, J. E. A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling. Energy Economics 33, 826–839 (2011).

Facilities costs

Facility	OCC	O&M	Unit	Source
Conversion Plant	193	3	€/SWU	NEA, 2013
Enrichment Plant	533	11	€/SWU	Areva, 2004
Fabrication Plant UOX	852	104	€/SWU	NEA, 2013
Reprocessing Plant	1,55E+07	4,08E+05	€/tHM	CDC, 2014
Fabrication Plant MOX	3,75E+07	835	€/tHM	De Roo et al., 2011
Pressurized Water Reactor	3,45	18	€/W	CDC, 2012

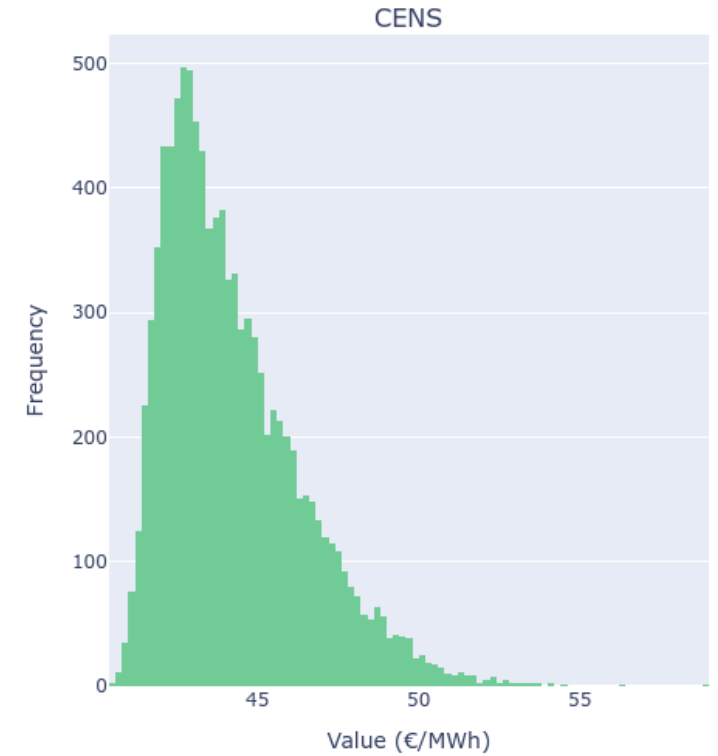
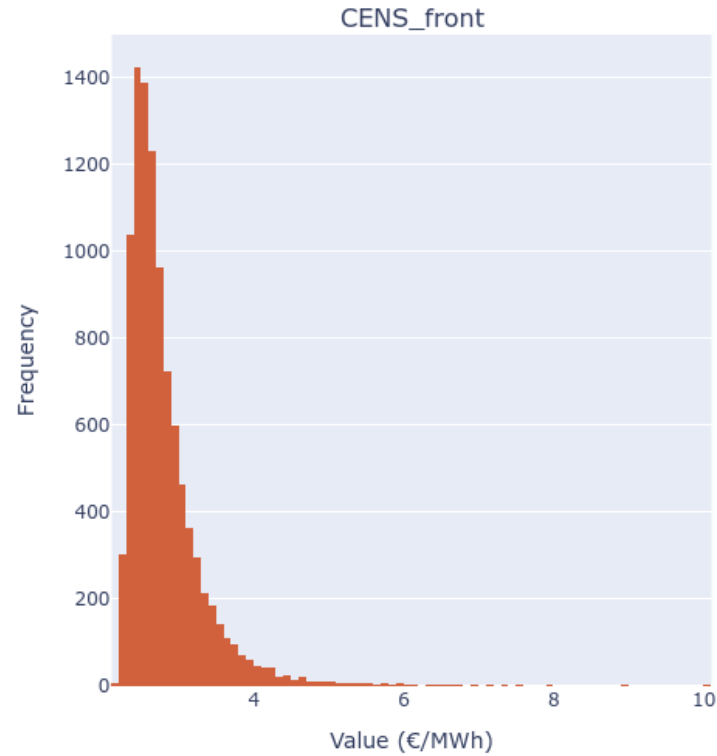
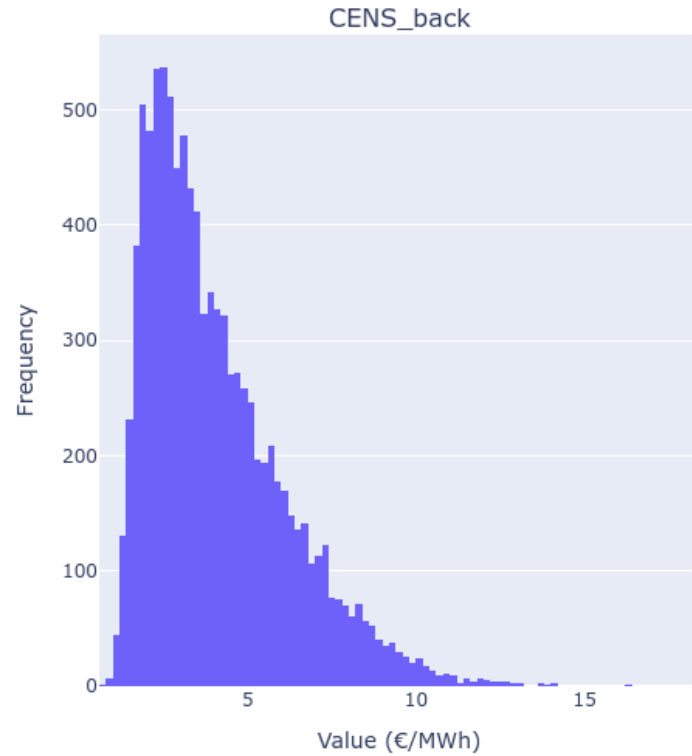
O&M costs were determined from the capital annuities using the 70/30 methodology (Patarin, 2002). Assuming a load factor of 1, capital annuities make up 70% of the annual costs and operation and maintenance make up the remaining 30%.

References

1. NEA. The Economics of the Back End of the Nuclear Fuel Cycle. Nuclear Development 2013 (2013).
2. AREVA, Projet Georges Besse II – Dossier du maître d'ouvrage. (2004)
3. Cour des comptes. Le Coût de Production de l'électricité Nucléaire. (2014).
4. De Roo, G. & Parsons, J. E. A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling. Energy Economics 33, 826–839 (2011).
5. Cour des comptes. Les coûts de la filière électronucléaire. (2012).
6. Patarin, L., Baron, P., Fournier, P. & Ochem, D. Le cycle du combustible nucléaire. (EDP sciences, Paris, 2002).

CENS distribution – Open Cycle

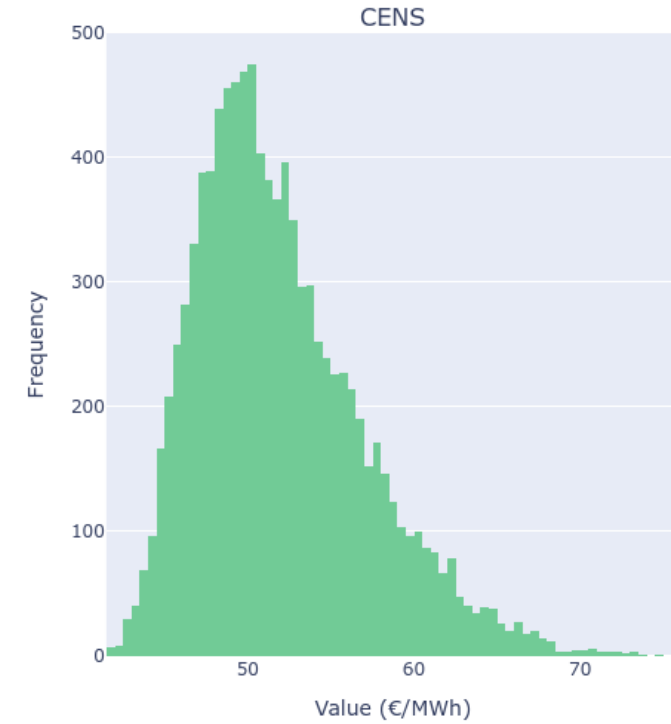
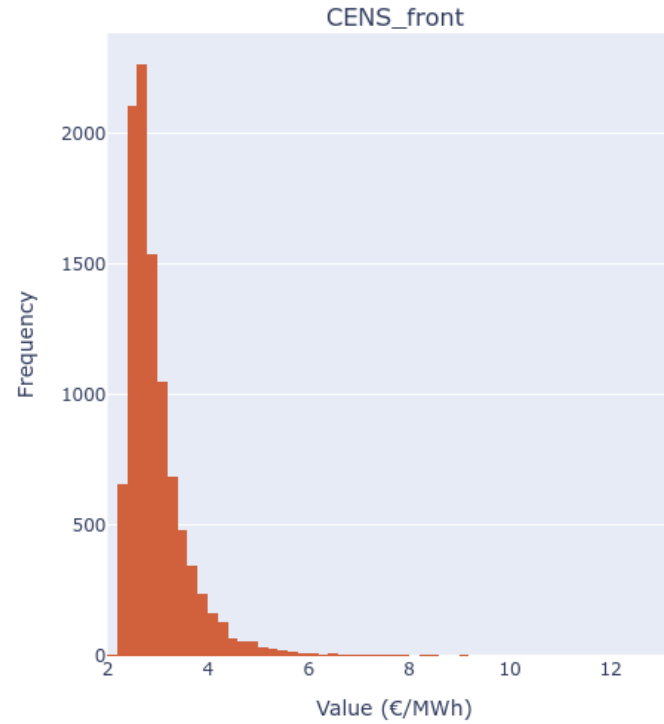
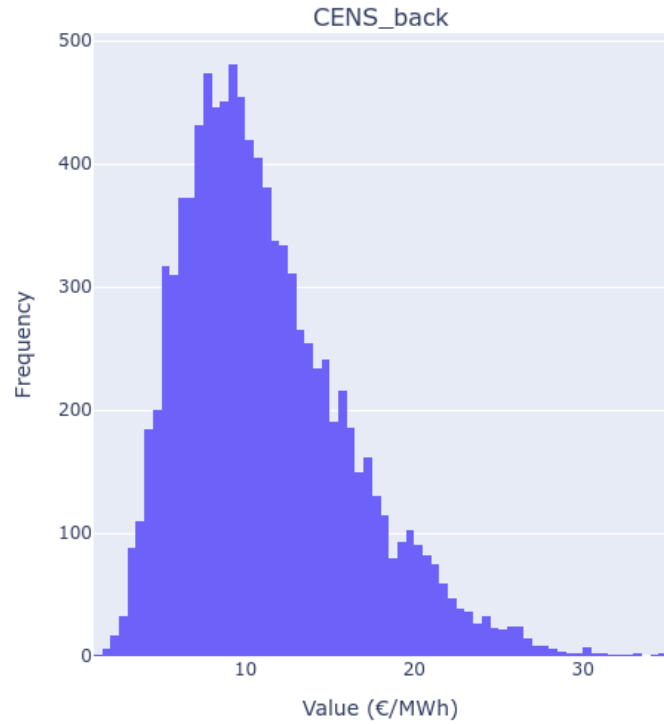
Log-normal distribution



CENS (€/MWh)	Back-end	Front-end	Total
Mean	4.1	2.8	44.2
Variance	4.3	0.3	4.6
St. deviation	2.1	0.5	2.2

CENS distribution – Open Cycle

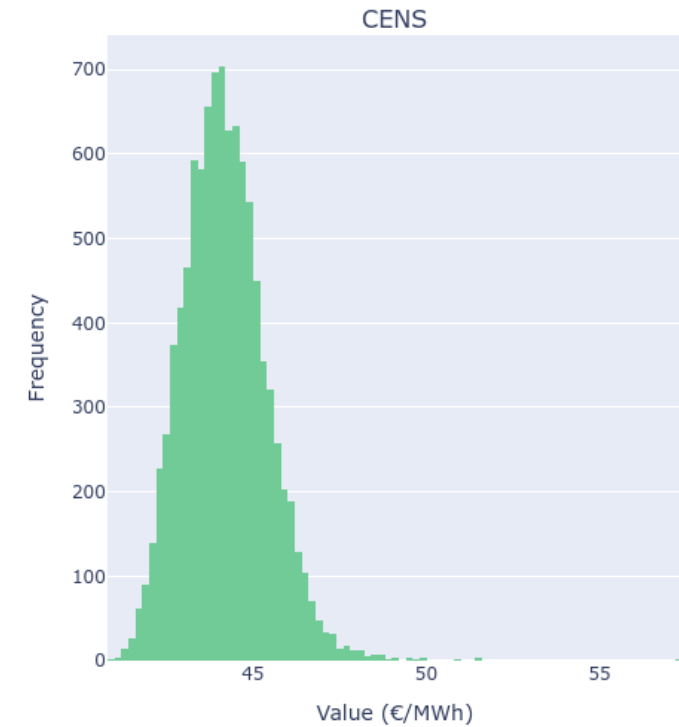
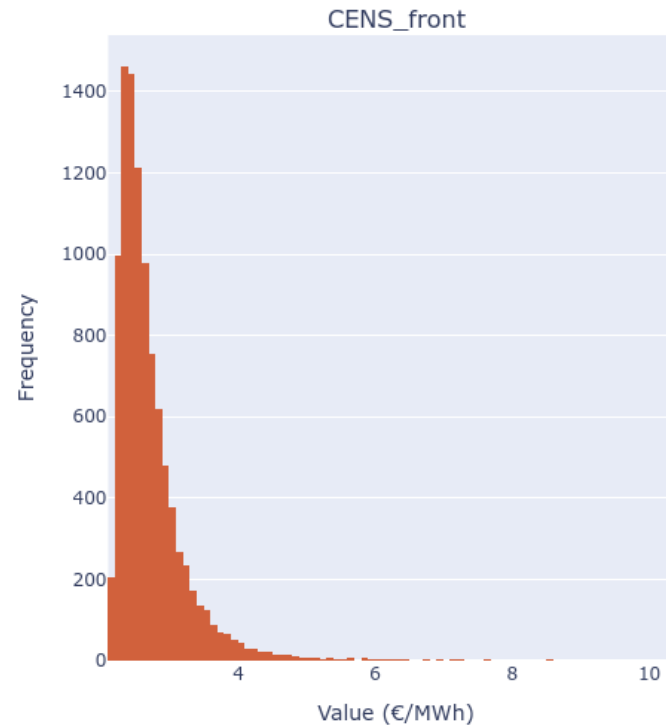
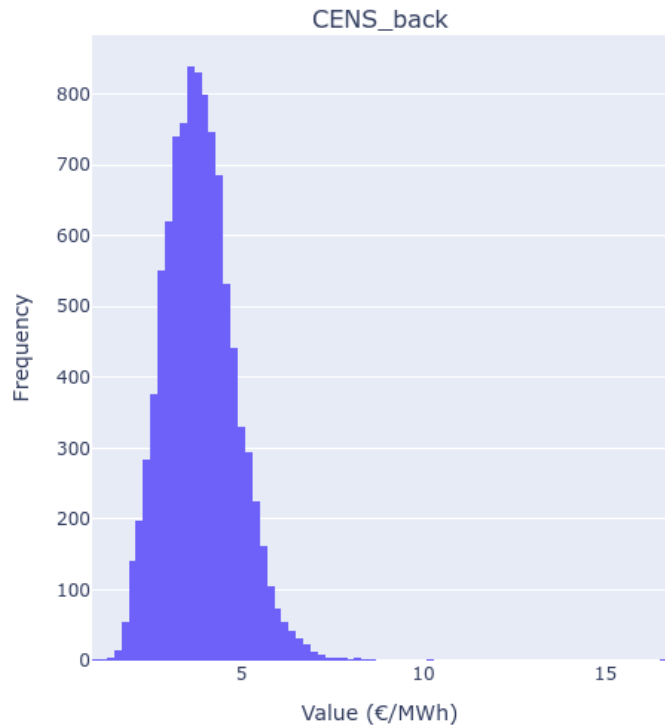
Uniform distribution



CENS (€/MWh)	Back-end	Front-end	Total
Mean	11.2	3.0	52.0
Variance	24.9	0.4	25.7
St. deviation	5.0	0.6	5.1

CENS distribution – Pu Mono-Recycling

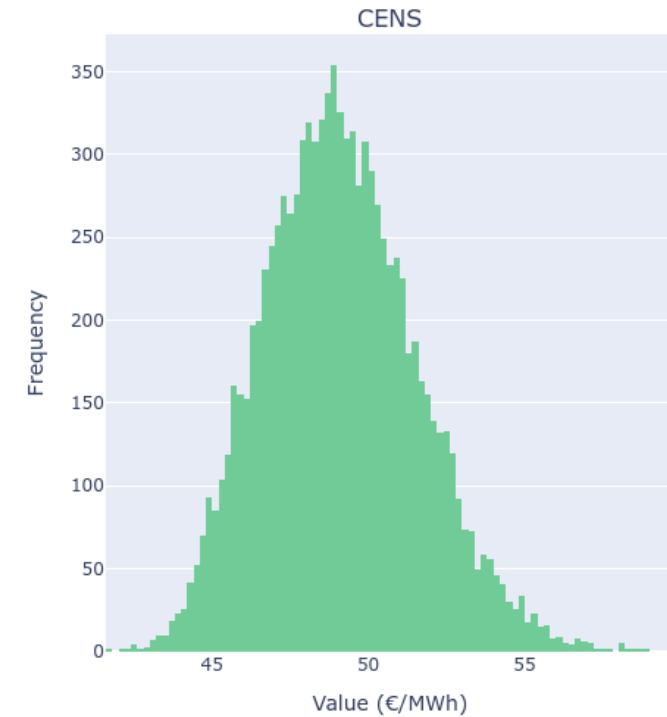
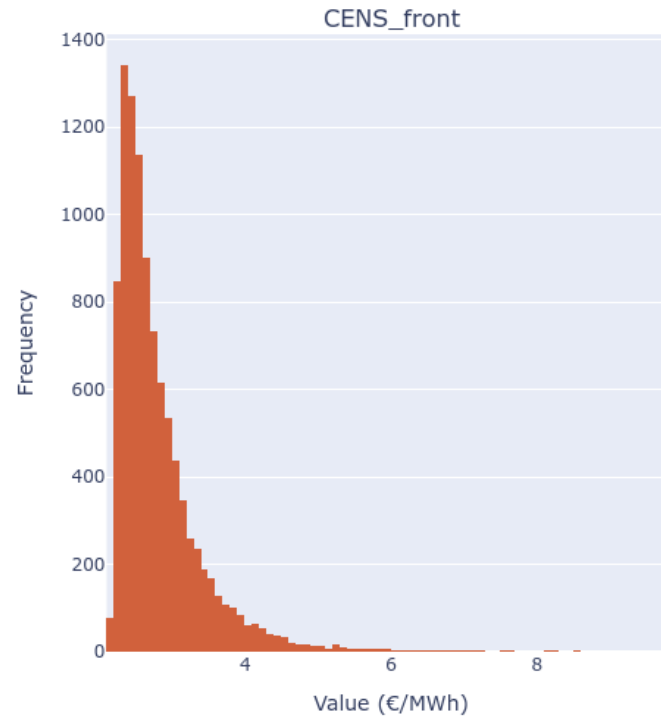
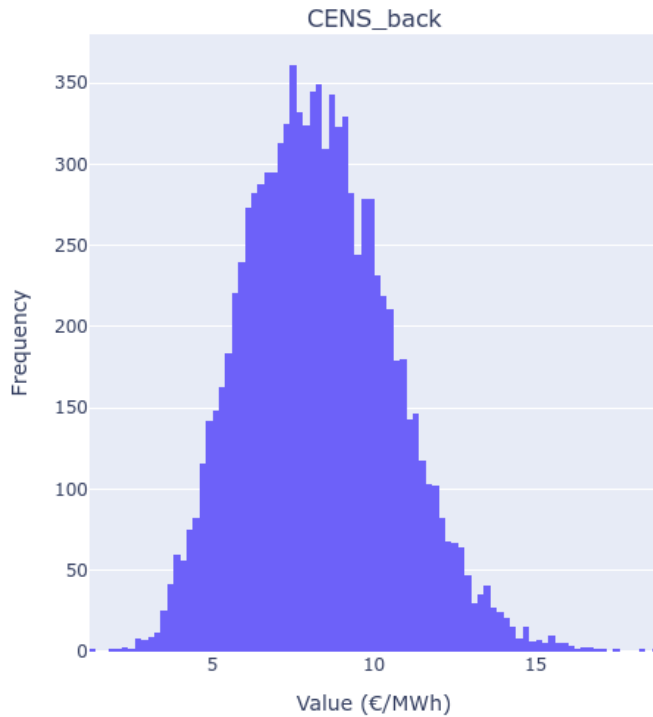
Log-normal distribution



CENS (€/MWh)	Back-end	Front-end	Total
Mean	3.9	2.7	44.2
Variance	1.0	0.2	1.4
St. deviation	1.0	0.5	1.2

CENS distribution – Pu Mono-Recycling

Uniform distribution



CENS (€/MWh)	Back-end	Front-end	Total
Mean	8.3	2.8	49.1
Variance	5.2	0.4	6.0
2.3	5.0	0.6	2.4

RLM level – level – Log-normal distribution

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=====
                    OLS Regression Results
=====
Dep. Variable:          CENS      R-squared:                0.868
Model:                 OLS      Adj. R-squared:           0.868
Method:                Least Squares      F-statistic:              5981.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  14:04:03           Log-Likelihood:          -11725.
No. Observations:     10000             AIC:                     2.347e+04
Df Residuals:         9988              BIC:                     2.356e+04
Df Model:              11
Covariance Type:      nonrobust

=====
                    coef      std err      t      P>|t|      [0.025      0.975]
-----
const                41.3818      0.074      557.705      0.000      41.236      41.527
int_uox_invCost     1.981e-06     4.23e-08     46.779      0.000      1.9e-06     2.06e-06
int_uox_OM          4.275e-05     8.78e-06     4.872      0.000      2.56e-05     6e-05
uox_cycletime       -0.0191      0.000     -42.364      0.000     -0.020     -0.018
finDisp_invCost     2.561e-06     3.95e-08     64.807      0.000      2.48e-06     2.64e-06
finDisp_OM          5.195e-05     5.44e-06     9.552      0.000      4.13e-05     6.26e-05
uox_odc              0.4898      0.069      7.139      0.000      0.355      0.624
front_ODC           0.1286      0.025      5.160      0.000      0.080      0.177
uox_orc              0.8453      0.026     32.300      0.000      0.794      0.897
U_cost              0.0275      0.000     65.567      0.000      0.027      0.028
u_def_cost          2.3098      0.025     92.706      0.000      2.261      2.359
uapp_cycletime      -0.0939      0.000    -207.842      0.000     -0.095     -0.093

=====
Omnibus:              2734.546      Durbin-Watson:           1.980
Prob(Omnibus):        0.000      Jarque-Bera (JB):       11512.567
Skew:                 1.289      Prob(JB):                0.00
Kurtosis:             7.581      Cond. No.:               4.33e+06

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Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
    
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Open Cycle

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=====
                    OLS Regression Results
=====
Dep. Variable:          CENS      R-squared:                0.928
Model:                 OLS      Adj. R-squared:           0.928
Method:                Least Squares      F-statistic:              7545.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  13:55:20           Log-Likelihood:          -2841.9
No. Observations:     10000             AIC:                     5720.
Df Residuals:         9982              BIC:                     5850.
Df Model:              17
Covariance Type:      nonrobust

=====
                    coef      std err      t      P>|t|      [0.025      0.975]
-----
const                37.5148      0.035     1078.939      0.000      37.447      37.583
mox_fraction        28.3425      0.125     226.168      0.000      28.097      28.588
finDisp_invCost     1.095e-06     1.64e-08     66.612      0.000      1.06e-06     1.13e-06
finDisp_OM          1.362e-05     2.66e-06     5.116      0.000      8.4e-06     1.88e-05
int_uox_invCost     1.276e-06     1.74e-08     73.507      0.000      1.24e-06     1.31e-06
int_uox_OM          2.399e-05     3.84e-06     6.255      0.000      1.65e-05     3.15e-05
int_mox_invCost     5.279e-08     7.13e-09     7.406      0.000      3.88e-08     6.68e-08
int_mox_OM          1.06e-06     1.56e-06     0.677      0.498     -2.01e-06     4.13e-06
u_def_cost           0.5895      0.010     57.475      0.000      0.569      0.610
uox_orc              0.8585      0.011     79.743      0.000      0.837      0.880
uox_odc              0.4637      0.028     16.413      0.000      0.408      0.519
rp_factor            1.6781      0.010    163.578      0.000      1.658      1.698
fp_factor            0.2262      0.010     22.058      0.000      0.206      0.246
pfma_def_factor     0.0953      0.004     26.700      0.000      0.088      0.102
mox_cycletime       -0.0099      0.000    -53.104      0.000     -0.010     -0.010
pfma_cycletime      -0.0050      0.000    -27.152      0.000     -0.005     -0.005
urt_cycletime       -0.0058      0.000    -31.447      0.000     -0.006     -0.005
U_cost              0.0267      0.000     154.609      0.000      0.026      0.027

=====
Omnibus:              4727.141      Durbin-Watson:           1.987
Prob(Omnibus):        0.000      Jarque-Bera (JB):       977754.852
Skew:                 1.136      Prob(JB):                0.00
Kurtosis:             51.389      Cond. No.:               3.24e+07

=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
    
```

Pu Mono-Recycling Cycle

RLM level – level – Uniform distribution

OLS Regression Results

```

=====
Dep. Variable:          CENS      R-squared:          0.819
Model:                 OLS       Adj. R-squared:    0.818
Method:                Least Squares  F-statistic:       4098.
Date:                  Fri, 03 Apr 2026  Prob (F-statistic): 0.00
Time:                  14:05:24    Log-Likelihood:   -21891.
No. Observations:     10000      AIC:              4.381e+04
Df Residuals:         9982       BIC:              4.389e+04
Df Model:              11
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	45.8381	0.155	295.941	0.000	45.534	46.142
int_uox_invCost	1.884e-06	3.44e-08	54.696	0.000	1.82e-06	1.95e-06
int_uox_OM	5.074e-05	6.61e-06	7.679	0.000	3.78e-05	6.37e-05
uox_cycletime	-0.1204	0.001	-96.413	0.000	-0.123	-0.118
finDisp_invCost	2.779e-06	2.63e-08	105.687	0.000	2.73e-06	2.83e-06
finDisp_OM	4.568e-05	4.67e-06	9.773	0.000	3.65e-05	5.48e-05
uox_odc	0.3978	0.095	4.196	0.000	0.212	0.584
front_ODC	0.1289	0.028	4.594	0.000	0.074	0.184
uox_orc	0.8811	0.031	28.113	0.000	0.820	0.943
U_cost	0.0278	0.001	29.431	0.000	0.026	0.030
u_def_cost	2.3737	0.030	79.227	0.000	2.315	2.432
uapp_cycletime	-0.1468	0.001	-117.623	0.000	-0.149	-0.144

```

=====
Omnibus:                1390.923    Durbin-Watson:        1.976
Prob(Omnibus):          0.000    Jarque-Bera (JB):     2404.914
Skew:                   0.923    Prob(JB):              0.00
Kurtosis:               4.538    Cond. No.              1.52e+07
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Open Cycle

OLS Regression Results

```

=====
Dep. Variable:          CENS      R-squared:          0.828
Model:                 OLS       Adj. R-squared:    0.828
Method:                Least Squares  F-statistic:       2827.
Date:                  Fri, 03 Apr 2026  Prob (F-statistic): 0.00
Time:                  13:57:06    Log-Likelihood:   -14337.
No. Observations:     10000      AIC:              2.871e+04
Df Residuals:         9982       BIC:              2.884e+04
Df Model:              17
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	40.0832	0.086	465.301	0.000	39.914	40.252
mox_fraction	16.1369	0.396	40.801	0.000	15.362	16.912
finDisp_invCost	9.502e-07	1.24e-08	76.885	0.000	9.26e-07	9.74e-07
finDisp_OM	1.502e-05	2.2e-06	6.835	0.000	1.07e-05	1.93e-05
int_uox_invCost	1.21e-06	1.62e-08	74.705	0.000	1.18e-06	1.24e-06
int_uox_OM	1.674e-05	3.11e-06	5.391	0.000	1.07e-05	2.28e-05
int_mox_invCost	5.082e-08	6.48e-09	7.845	0.000	3.81e-08	6.35e-08
int_mox_OM	1.81e-06	1.25e-06	1.451	0.147	-6.34e-07	4.25e-06
u_def_cost	0.5865	0.014	41.635	0.000	0.559	0.614
uox_orc	0.8288	0.015	56.258	0.000	0.800	0.858
uox_odc	0.4173	0.045	9.364	0.000	0.330	0.505
rp_factor	1.6947	0.013	128.537	0.000	1.669	1.721
fp_factor	0.2023	0.013	15.338	0.000	0.176	0.228
pfma_def_factor	0.0903	0.004	24.624	0.000	0.083	0.098
mox_cycletime	-0.0517	0.001	-87.993	0.000	-0.053	-0.051
pfma_cycletime	-0.0177	0.001	-30.153	0.000	-0.019	-0.017
urt_cycletime	-0.0076	0.001	-12.996	0.000	-0.009	-0.006
U_cost	0.0265	0.000	59.234	0.000	0.026	0.027

```

=====
Omnibus:                819.187    Durbin-Watson:        1.970
Prob(Omnibus):          0.000    Jarque-Bera (JB):     4394.466
Skew:                   0.191    Prob(JB):              0.00
Kurtosis:               6.225    Cond. No.              1.45e+08
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Pu Mono-Recycling Cycle

RLM log-log – Log-normal distribution

OLS Regression Results

```

=====
Dep. Variable:          CENS      R-squared:                0.824
Model:                 OLS      Adj. R-squared:           0.824
Method:                Least Squares      F-statistic:              4250.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  14:01:55          Log-Likelihood:           24951.
No. Observations:     10000          AIC:                      -4.988e+04
Df Residuals:         9988           BIC:                      -4.979e+04
Df Model:              11
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	3.5479	0.006	588.743	0.000	3.536	3.560
int_uox_invCost	0.0116	0.000	37.566	0.000	0.011	0.012
int_uox_OM	0.0010	0.000	3.429	0.001	0.000	0.002
uox_cycletime	-0.0080	0.000	-40.110	0.000	-0.008	-0.008
finDisp_invCost	0.0127	0.000	49.176	0.000	0.012	0.013
finDisp_OM	0.0024	0.000	7.315	0.000	0.002	0.003
uox_odc	0.0066	0.001	7.631	0.000	0.005	0.008
front_ODC	0.0031	0.001	4.241	0.000	0.002	0.005
uox_orc	0.0307	0.001	27.353	0.000	0.029	0.033
U_cost	0.0142	0.000	50.211	0.000	0.014	0.015
u_def_cost	0.0573	0.001	78.826	0.000	0.056	0.059
uapp_cycletime	-0.0354	0.000	-177.356	0.000	-0.036	-0.035

```

=====
Omnibus:                1765.384      Durbin-Watson:            1.995
Prob(Omnibus):          0.000      Jarque-Bera (JB):         38857.785
Skew:                   -0.181      Prob(JB):                 0.00
Kurtosis:                12.650      Cond. No.                 624.
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Open Cycle

OLS Regression Results

```

=====
Dep. Variable:          CENS      R-squared:                0.854
Model:                 OLS      Adj. R-squared:           0.854
Method:                Least Squares      F-statistic:              3431.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  13:53:32          Log-Likelihood:           31582.
No. Observations:     10000          AIC:                      -6.313e+04
Df Residuals:         9982           BIC:                      -6.300e+04
Df Model:              17
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	3.6701	0.004	964.886	0.000	3.663	3.678
mox_fraction	0.0245	0.000	159.777	0.000	0.024	0.025
finDisp_invCost	0.0049	0.000	37.726	0.000	0.005	0.005
finDisp_OM	0.0004	0.000	2.888	0.004	0.000	0.001
int_uox_invCost	0.0071	0.000	44.430	0.000	0.007	0.007
int_uox_OM	0.0004	0.000	3.055	0.002	0.000	0.001
int_mox_invCost	0.0005	0.000	3.142	0.002	0.000	0.001
int_mox_OM	0.0001	0.000	0.928	0.354	-0.000	0.000
u_def_cost	0.0154	0.000	41.086	0.000	0.015	0.016
uox_orc	0.0320	0.001	55.305	0.000	0.031	0.033
uox_odc	0.0055	0.000	12.302	0.000	0.005	0.006
rp_factor	0.0419	0.000	111.925	0.000	0.041	0.043
fp_factor	0.0057	0.000	15.305	0.000	0.005	0.006
pfma_def_factor	0.0030	0.000	15.779	0.000	0.003	0.003
mox_cycletime	-0.0038	0.000	-37.332	0.000	-0.004	-0.004
pfma_cycletime	-0.0019	0.000	-18.669	0.000	-0.002	-0.002
urt_cycletime	-0.0013	0.000	-12.744	0.000	-0.002	-0.001
U_cost	0.0142	0.000	97.094	0.000	0.014	0.014

```

=====
Omnibus:                7181.750      Durbin-Watson:            1.982
Prob(Omnibus):          0.000      Jarque-Bera (JB):         709862.417
Skew:                   2.680      Prob(JB):                 0.00
Kurtosis:                43.926      Cond. No.                 953.
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Pu Mono-Recycling Cycle

RLM log-log – Uniform distribution

```

=====
                        OLS Regression Results
=====
Dep. Variable:          CENS      R-squared:                0.790
Model:                 OLS      Adj. R-squared:           0.790
Method:                Least Squares      F-statistic:              3412.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  14:06:48          Log-Likelihood:           17180.
No. Observations:     10000          AIC:                     -3.434e+04
Df Residuals:         9988           BIC:                     -3.425e+04
Df Model:              11
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	3.0204	0.013	229.639	0.000	2.995	3.046
int_uox_invCost	0.0285	0.001	51.377	0.000	0.027	0.030
int_uox_OM	0.0022	0.001	4.050	0.000	0.001	0.003
uox_cycletime	-0.0401	0.000	-92.297	0.000	-0.041	-0.039
finDisp_invCost	0.0463	0.001	91.395	0.000	0.045	0.047
finDisp_OM	0.0054	0.001	7.999	0.000	0.004	0.007
uox_odc	0.0056	0.001	4.359	0.000	0.003	0.008
front_ODC	0.0023	0.001	2.975	0.003	0.001	0.004
uox_orc	0.0291	0.001	25.675	0.000	0.027	0.031
U_cost	0.0147	0.001	24.540	0.000	0.014	0.016
u_def_cost	0.0654	0.001	72.085	0.000	0.064	0.067
uapp_cycletime	-0.0471	0.000	-108.796	0.000	-0.048	-0.046

```

=====
Omnibus:                786.927      Durbin-Watson:            2.000
Prob(Omnibus):          0.000      Jarque-Bera (JB):         4336.633
Skew:                   -0.135      Prob(JB):                 0.00
Kurtosis:                6.215      Cond. No.:                 721.
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Open Cycle

```

=====
                        OLS Regression Results
=====
Dep. Variable:          CENS      R-squared:                0.760
Model:                 OLS      Adj. R-squared:           0.760
Method:                Least Squares      F-statistic:              1862.
Date:                  Fri, 03 Apr 2026    Prob (F-statistic):       0.00
Time:                  13:58:49          Log-Likelihood:           22992.
No. Observations:     10000          AIC:                     -4.595e+04
Df Residuals:         9982           BIC:                     -4.582e+04
Df Model:              17
Covariance Type:      nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	3.3498	0.009	363.049	0.000	3.332	3.368
mox_fraction	0.0132	0.000	36.397	0.000	0.012	0.014
finDisp_invCost	0.0170	0.000	59.774	0.000	0.016	0.018
finDisp_OM	0.0021	0.000	5.556	0.000	0.001	0.003
int_uox_invCost	0.0187	0.000	60.044	0.000	0.018	0.019
int_uox_OM	0.0014	0.000	4.787	0.000	0.001	0.002
int_mox_invCost	0.0023	0.000	7.442	0.000	0.002	0.003
int_mox_OM	0.0001	0.000	0.430	0.667	-0.000	0.001
u_def_cost	0.0178	0.001	35.114	0.000	0.017	0.019
uox_orc	0.0295	0.001	46.486	0.000	0.028	0.031
uox_odc	0.0055	0.001	7.669	0.000	0.004	0.007
rp_factor	0.0449	0.000	104.958	0.000	0.044	0.046
fp_factor	0.0054	0.000	12.698	0.000	0.005	0.006
pfma_def factor	0.0066	0.000	20.259	0.000	0.006	0.007
mox_cycletime	-0.0175	0.000	-72.085	0.000	-0.018	-0.017
pfma_cycletime	-0.0054	0.000	-22.412	0.000	-0.006	-0.005
urt_cycletime	-0.0006	0.000	-2.501	0.012	-0.001	-0.000
U_cost	0.0154	0.000	46.119	0.000	0.015	0.016

```

=====
Omnibus:                515.144      Durbin-Watson:            1.988
Prob(Omnibus):          0.000      Jarque-Bera (JB):         1518.009
Skew:                   0.234      Prob(JB):                 0.00
Kurtosis:                4.850      Cond. No.:                 1.13e+03
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```

Pu Mono-Recycling Cycle