The fate of aging hydropower plants: reinvestment or upgrading?

A case study from Norway

Anna Carozzani [1], Chiara D'Alpaos [1,2], Verena Hagspiel-Janssen [3], Michele Moretto [4,2]

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17. The challenges posed by renewable energy technologies (I)

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[1] Department of Civil, Environmental and Architectural Engineering University of Padova, ITALY

[2] Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, ITALY

[3] Department of Industrial Economics and Technology Management Norwegian University of Science and Technology, NORWAY

[4] Department of Economics and Management "Marco Fanno" University of Padova, ITALY

Two challenges in the hydropower sector

1

Aging hydropower plants

40% of global installed HP capacity, commissioned before 1980s, requires modernization (International Energy Agency)

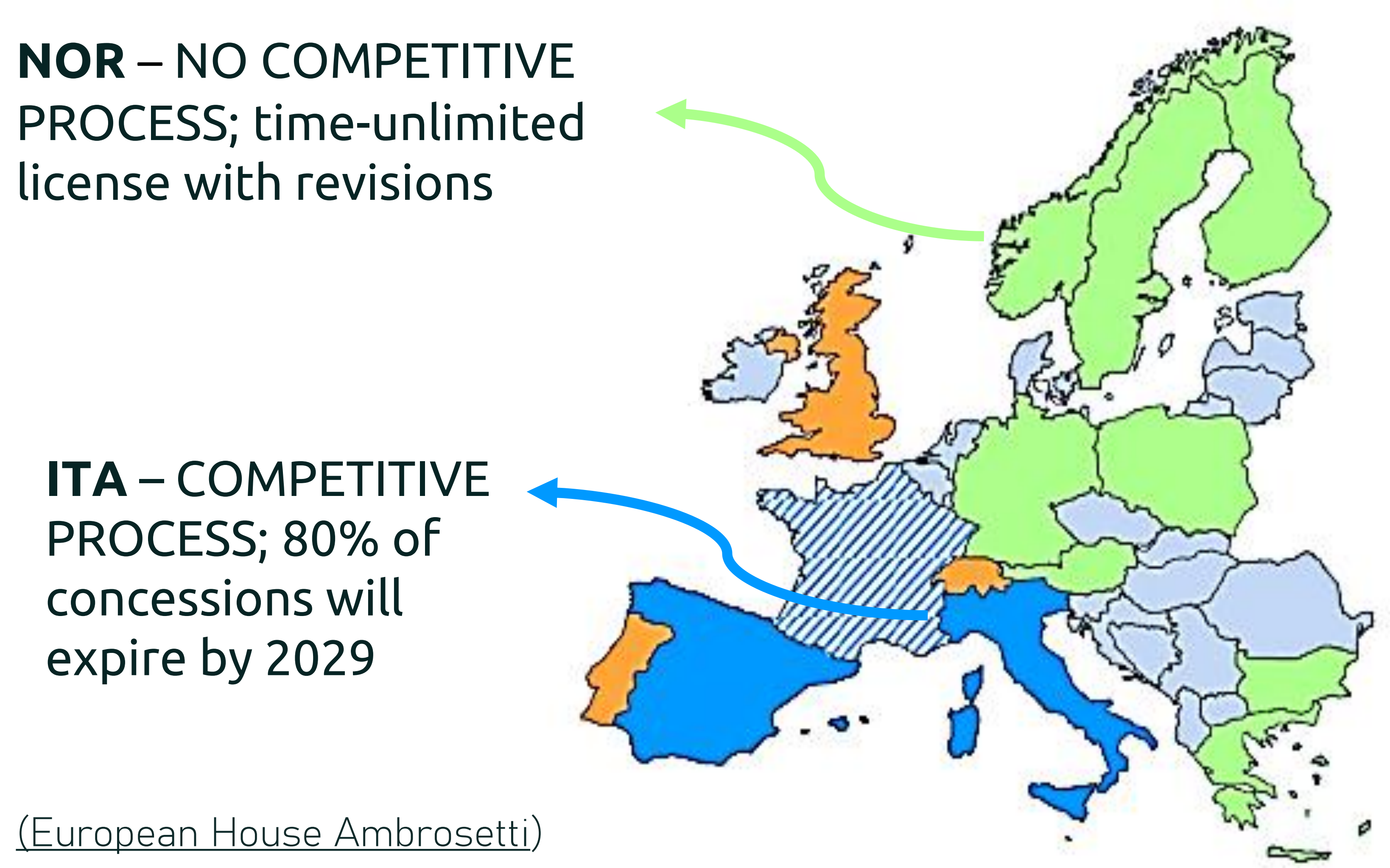
1950s turbine	New turbine

New Zealand's Roxburgh Hydropower Station (link)

2

Hydropower rights

Fragmented legal framework in EU
(Istituto B. Leoni)



1 Research question & framework

Research question

What is the optimal choice between reinvestment and upgrading when approaching the end of the concession for an aging HP?

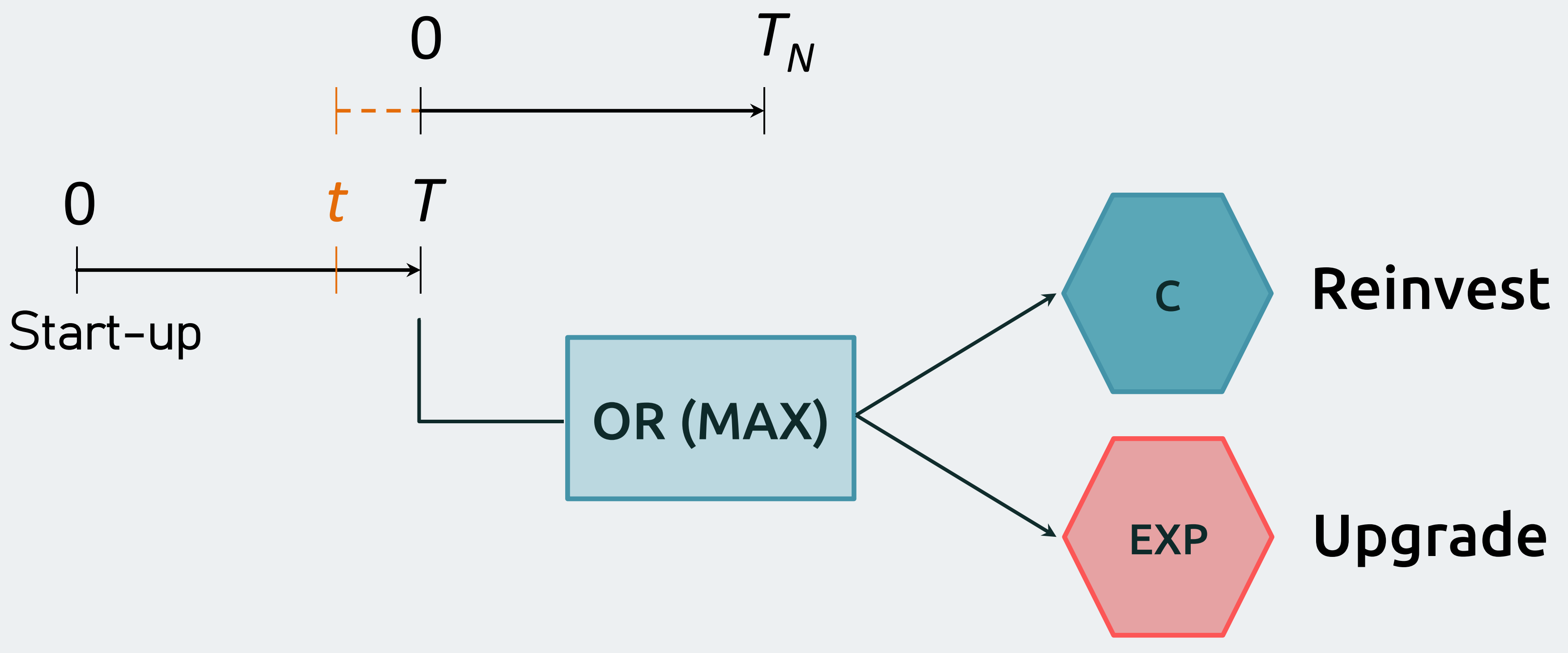
BEST OF 2 MUTUALLY EXCLUSIVE ALTERNATIVES

To **Reinvest (R)** replace old components, e.g., change turbine

To **Upgrade (U)** expand capacity, e.g., increasing water flow

How to frame this with Real Options?

Investor	Investment time	Real option type
Incumbent	anytime (t) before expiration time (T)	American Option (Barone-Adesi and Whaley, 1987)
New entrant	only at expiration time (T)	European Option (Black and Scholes-Merton, 1973)



* Source: elaboration from Trigeorgis (2005)

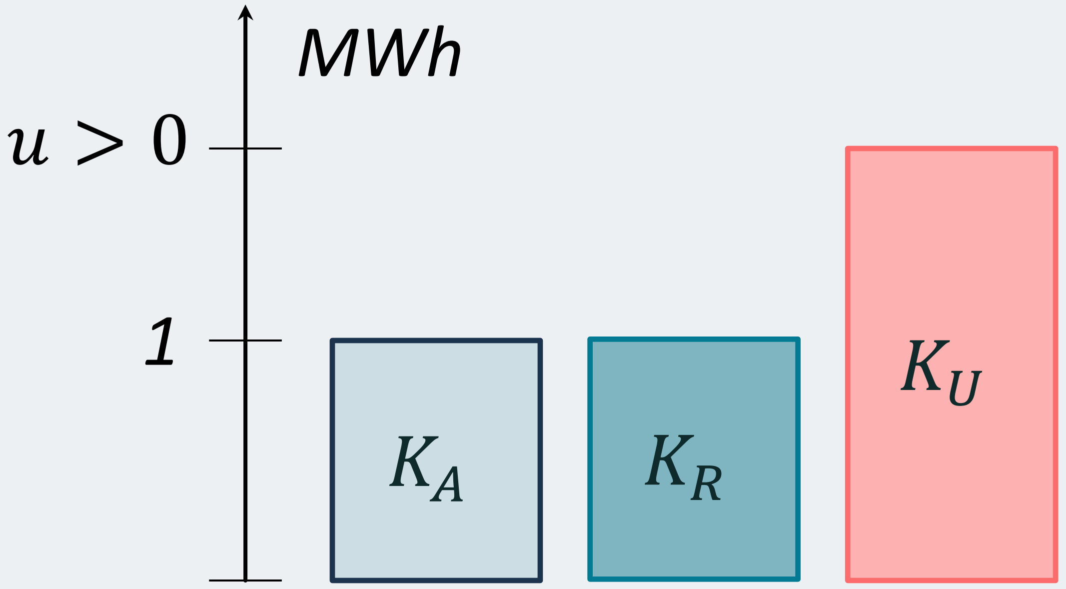
2 The model

Basic assumptions

Electricity price follows a Geometric Brownian Motion: $dP(t) = \alpha P(t)dt + \sigma P(t)dZ(t)$, with discount rate $r > \alpha$ for convergence

Incremental energy production

$$K_{i=R,U} = \begin{cases} K_R = 1 \\ K_U = 1 + u \end{cases}$$



The **extra value** from reinvestment (generating actual K) to upgrading

→ Option value of increasing production

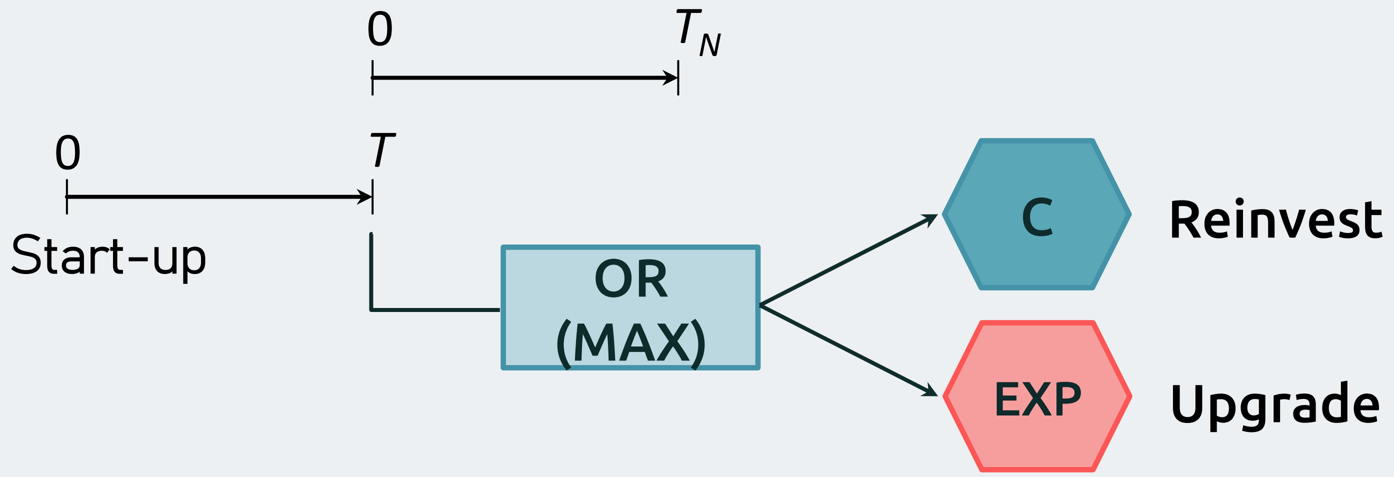
Investment cost - f(production)

$$I_{i=R,U} = \begin{cases} \delta_R \cdot K_R \\ \delta_U \cdot K_U \end{cases} \quad \text{where } \delta_U > \delta_R$$

Profit flows are defined as $\prod^i(t) = P(t) \cdot K_i$ where operating costs are negligible

2 The model

European option formulation



The **investment value** is the NPV of future profits from $i = R, U$

$$V_i(\Pi_T^i) = \underbrace{\frac{\Pi^i}{\mu}\left(1 - e^{-\mu(T_N)}\right)}_{\text{discounted profits}} - \underbrace{\delta_i K_i}_{\text{investment cost}} \qquad with \;\; \Pi_T = \Pi$$

The **option to increase production** is modeled as a European call option

$$F(\Pi_t^i, t) = \mathbb{E}_t\left[e^{-r(T-t)} \max[V_R(\Pi_t^R), V_U(\Pi_t^U), 0]\right]$$

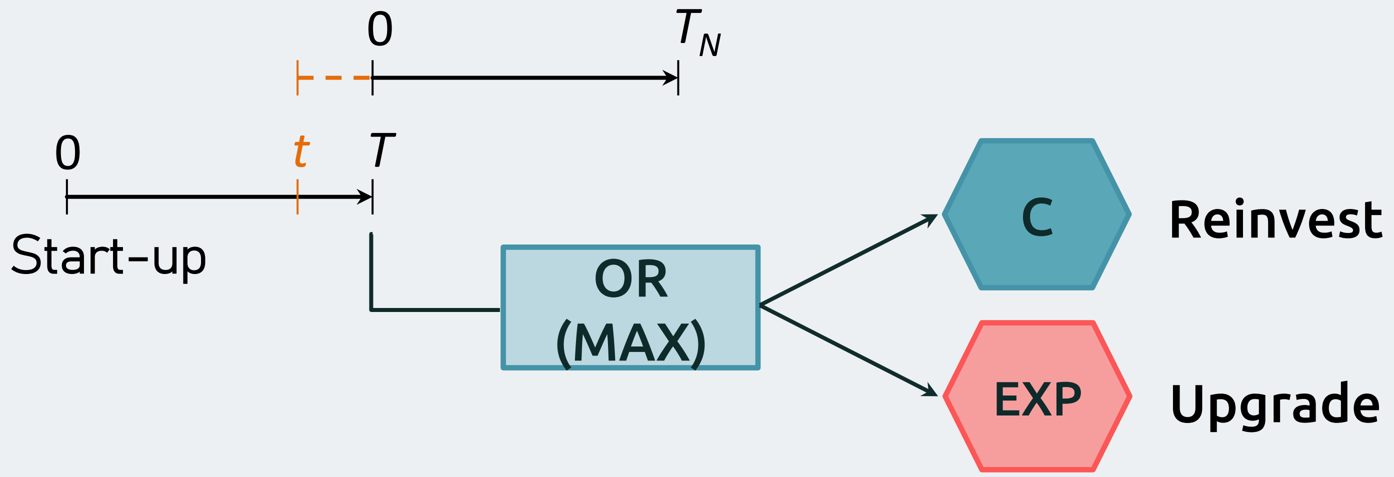
closed form solution of Black-Scholes and Merton

$$F(\Pi_t^i, t) = \Pi_t^i \; e^{-\mu(T-t)} N(d_1) - I_i \; e^{-r(T-t)} N(d_2)$$

where $N(\,)$ is the cumulative standard normal distribution and d_1, d_2 are BSM terms.

2 The model

American option formulation



The **option to increase production** is modeled as an American option

approximated solution of Barone-Adesi and Whaley

$$F(\Pi_t^i, t) = \begin{cases} f(\Pi_t^i) + A_i \Pi_t^{\alpha_i}, & if \;\; \Pi_t^i < \Pi_i^* \\ \Pi_t^i - I_i, & if \;\; \Pi_t^i \geq \Pi_i^* \end{cases}$$

where $f(\Pi_t^i)$ is the value of the european option

$A_i \Pi_t^{\alpha_i}$ is the early-exercise premium

Π_i^* threshold (applying value-matching and smooth-pasting conditions)

Expected revenue losses from early concession termination

$$\text{Loss} = \mathbb{P}(\tau \leq T) \left(\frac{p_0}{p^*}\right)^{\beta_1} \left[\frac{p^* K_A}{r} \left(1 - e^{-rT}\right)\right]$$

→ The **net value** of the American option is: $\text{US}^{net} = F(\Pi_i^*) - \text{Loss}$

3 Calibration

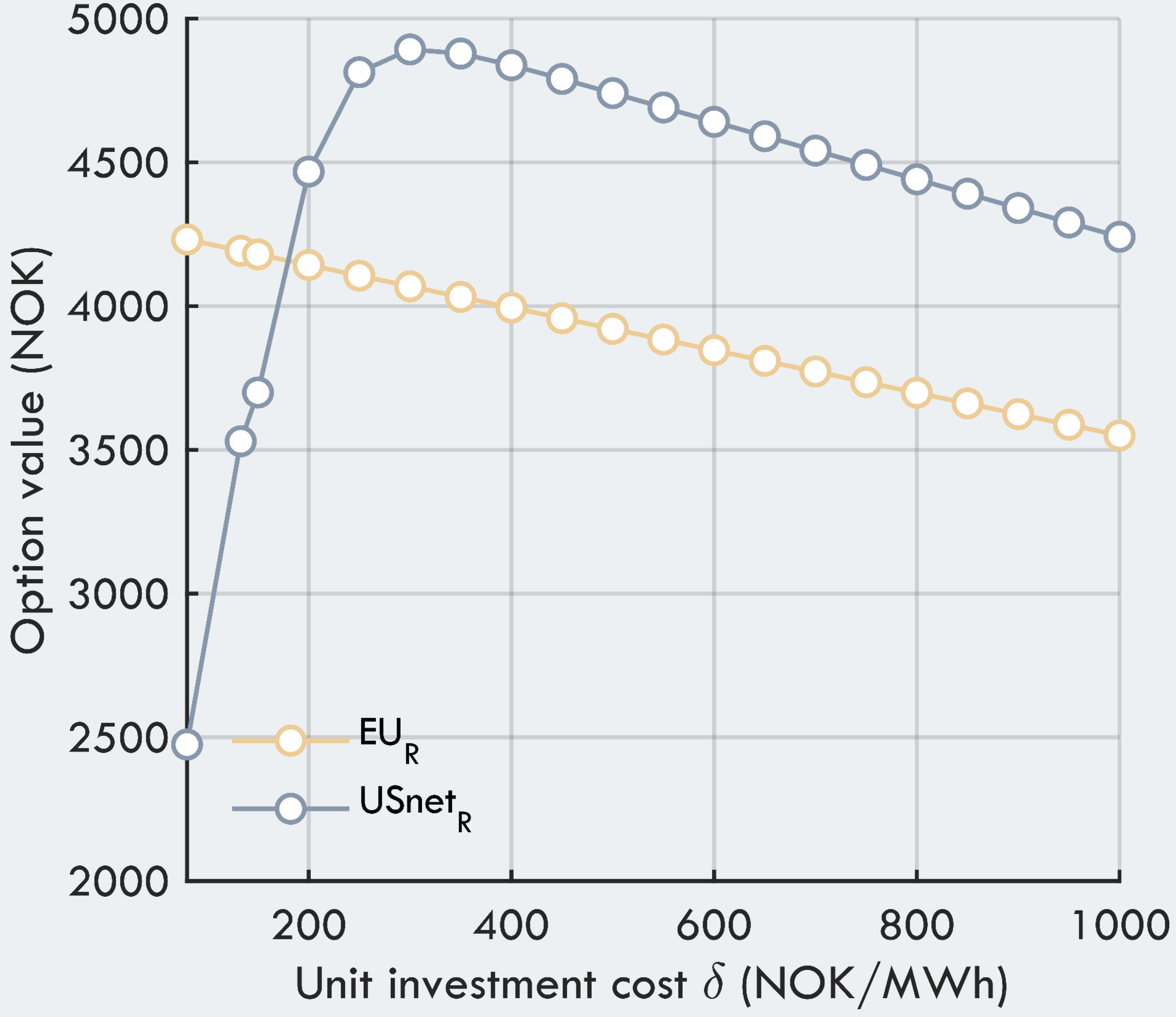
Norwegian dataset

Parameter	Description	Value	Source/Reference
p_T	Long-term electricity price at t=T (NOK/MWh)	**300**	Haukeli et al. (2021)
Q	Annual inflow (GWh/y)	**150**	Backer et al. (2022)
I_R	Reinvestment cost in turbine replacement only (MNOK)	**20 - 30**	Backer et al. (2022) – Donnestad et al. (2024)
δ_R	Reinvestment unit cost (NOK/MWh)	**133**	Computed: I_R/Q
δ_U	Upgrading unit cost (NOK/MWh)	**80 - 1000**	Assumed
K_R	Reinvestment energy production (MWh)	**1**	Assumed (baseline)
K_U	Upgraded plant energy production (MWh)	**1-2.5**	Assumed
r	Risk-free discount rate	**0.06**	Backer et al. (2022) - Donnestad et al. (2024)
α	Annual growth rate	**0.02-0.025**	Backer et al. (2022) - Donnestad et al. (2024)
μ	Opportunity cost	**0.04**	Computed: $r - \alpha$
σ	Volatility	**0.1335**	Backer et al. (2022)
T_N	Expected lifetime of the new turbine (y)	**30**	Backer et al. (2022)
T	Investment exercise time (y)	**4-6**	Our assumption

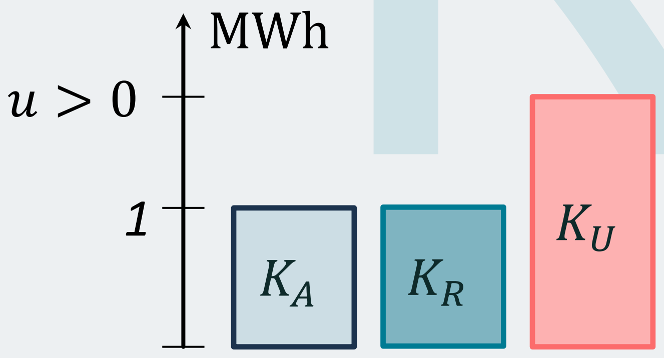
4 Results

Reinvestment option

European option (EU)
vs net American option (USnet)



Reinvestment energy production is the benchmark ($K_R = K_A = 1\ MWh$)

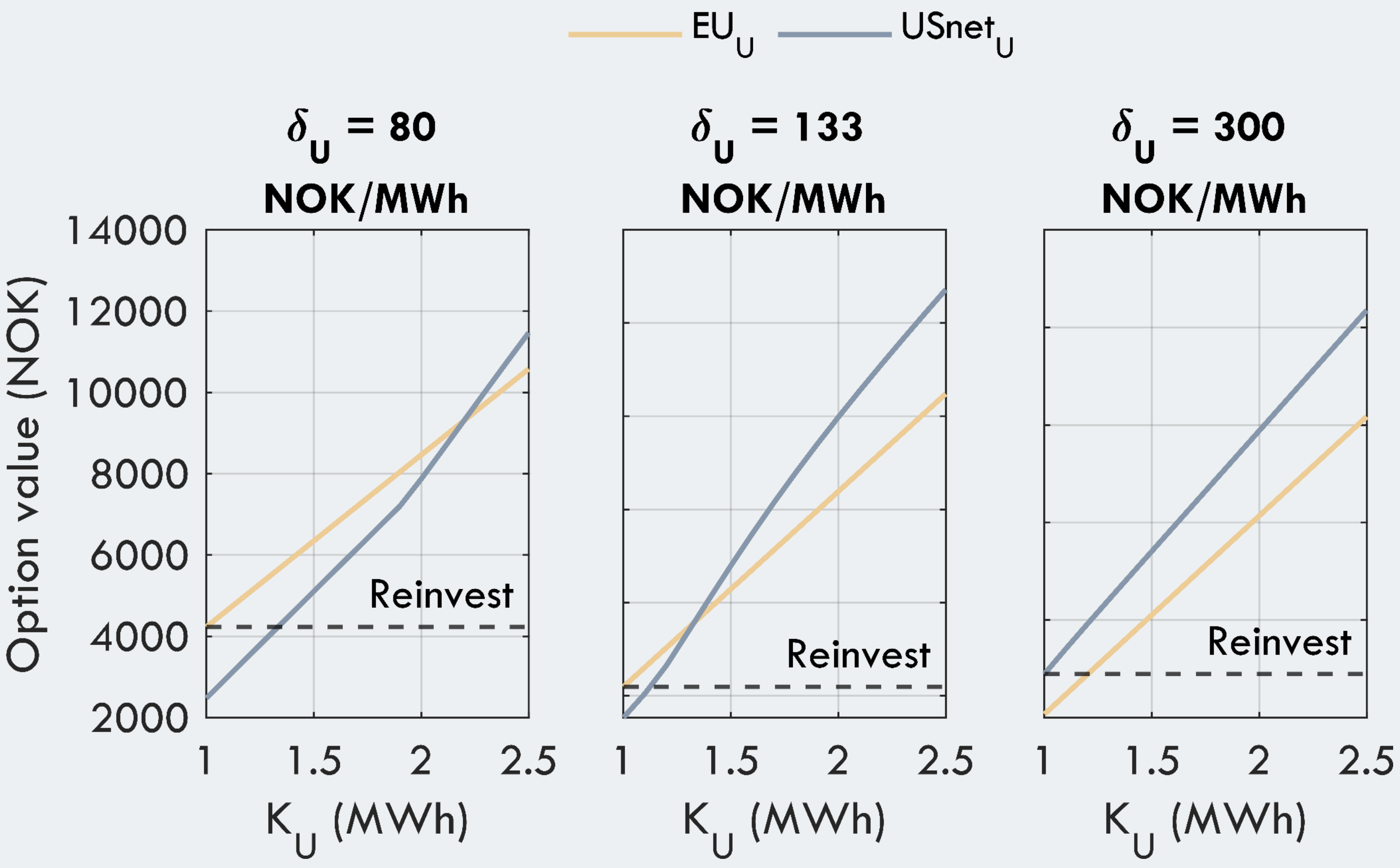


Cost level (unit cost) [NOK/MWh]	Early-exercise losses [NOK]	Option values [NOK]
Low δ_R (<150)	Large	**EU > USnet**
High δ_R (>200)	Small / 0	**USnet > EU**

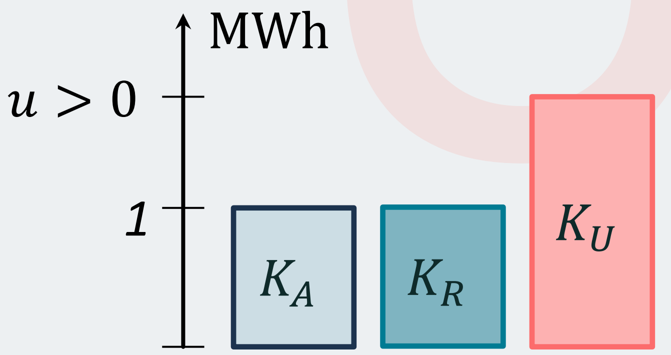
4 Results

Upgrading option

European option (EU)
vs net American option (USnet)



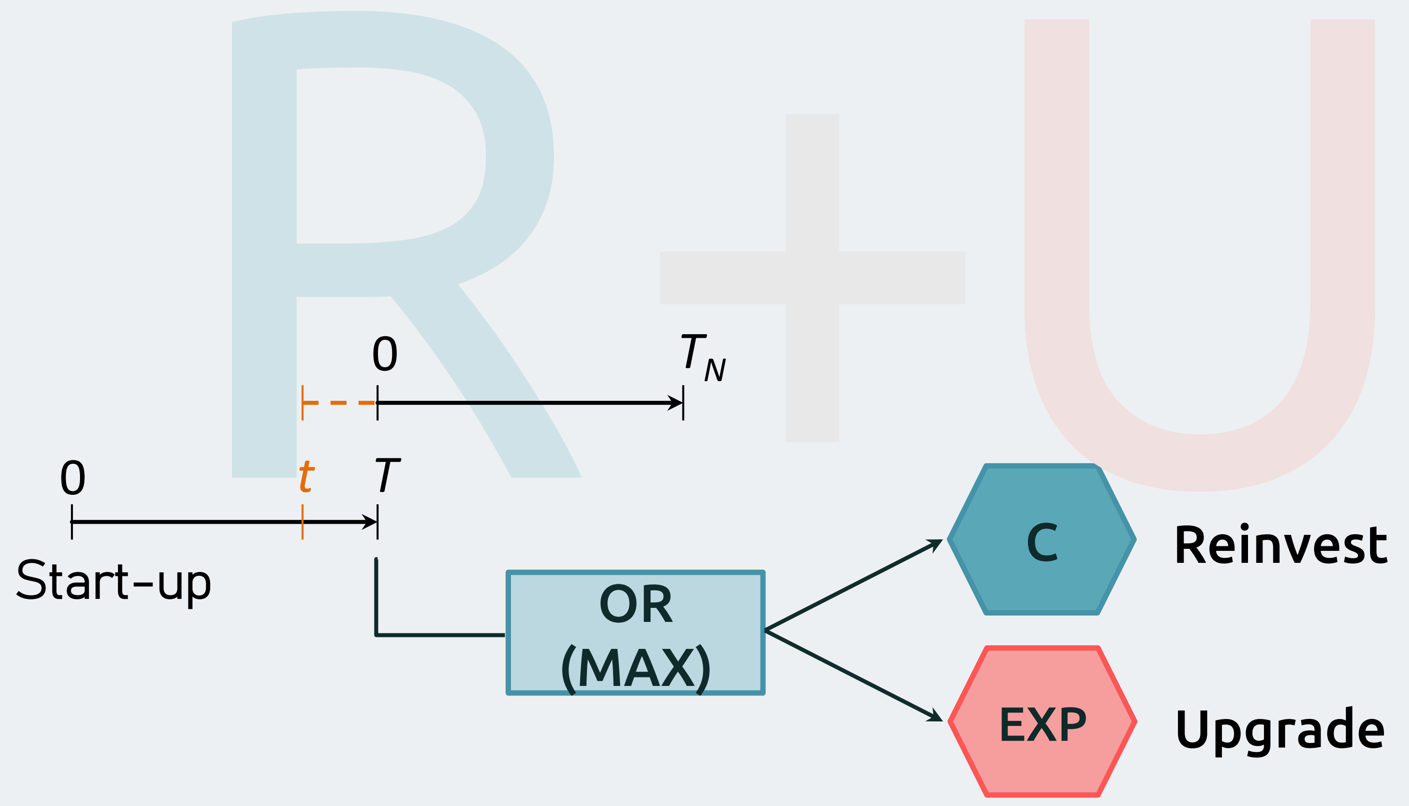
Upgrading energy production i.e., $K_U > K_R$



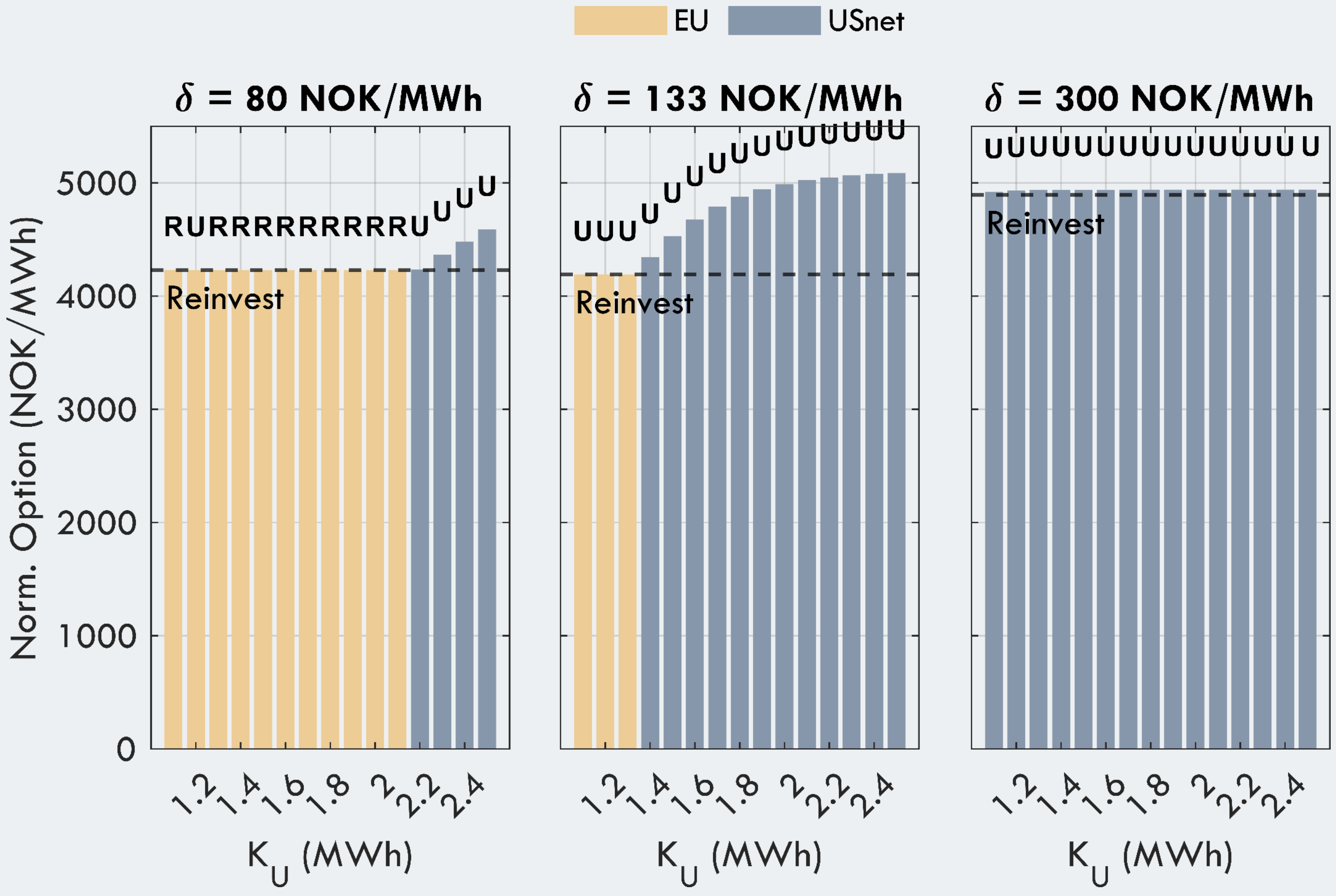
Cost [NOK/MWh] and Production [MWh]	Early-exercise losses [NOK]	Option values [NOK]
Low δ_U (<150) Small K_U (<1.3)	Large	**EU > USnet**
High δ_U(>200) Large K_U (<1.3)	Small / 0	**USnet > EU**

4 Results

Reinvestment and upgrading



R vs U and EU vs USnet
per unit of energy production

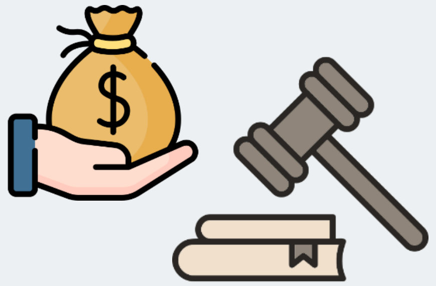


Cost [NOK/MWh] and Production [MWh]	Optimal choice	Option values [NOK]
Low δ (<100) K_U <2.1	Reinvest	**EU > USnet**
High δ (>150) K_U >1.3	Upgrade	**USnet > EU**

*option values per unit of energy production

5 Discussion

Stylized bidding process



Option values represent the **maximum bid** a hydropower operator is willing to submit in a first-price auction for concession renewal

The incumbent wins by upgrading early

Under flexible tender rules, early-exercise option deliver the highest value per unit, giving incumbents a structural bidding advantage.

new entrant → / incumbent ↓	EU_R	EU_U
EU_R	(4180 ; 4180)	(4180 ; 4180)
$USnet_R$	(3699 ; 4180)	(3699 ; 4180)
EU_U	(4180 ; 4180)	(4180 ; 4180)
$USnet_U$	(4231 ; 4180)	**(4231; 4180)**

*option values per unit of energy production

6 Conclusions

Timing

Low unit cost → wait
High unit cost → invest early

Strategy

Upgrading for high unit cost and at least +30% output

Sizing

Higher energy production boosts option value per MWh

Policy

Timing flexibility shapes competitive concession allocation

Questions ???

e-mail

anna.carozzani@phd.unipd.it

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