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Preliminary Version

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Production costs uncertainties of SMR-concepts - A model-based Monte Carlo analysis

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Agenda

3 Investment decision with uncertainty

- Computation of NPV and LCOE through simulation of uncertain parameter with the help of Monte Carlo technique
- Sensitivity analysis in case of NPV calculation

Production costs uncertainties of SMR-concepts

1 SMR concepts

- Definition & Cost Theory
- Current advertised SMR concept costs

2 Theory vs. Advertised costs:

- Current Cost theory vs. Advertised manufacturing costs and their differences

1 SMR CONCEPTS

- Definition & Theory
- Current advertised costs of selected SMR concepts

Motivation

Recently….

Recently there is a surge of SMR- research and literature on nuclear power with low capacity:

"SMR – concepts"

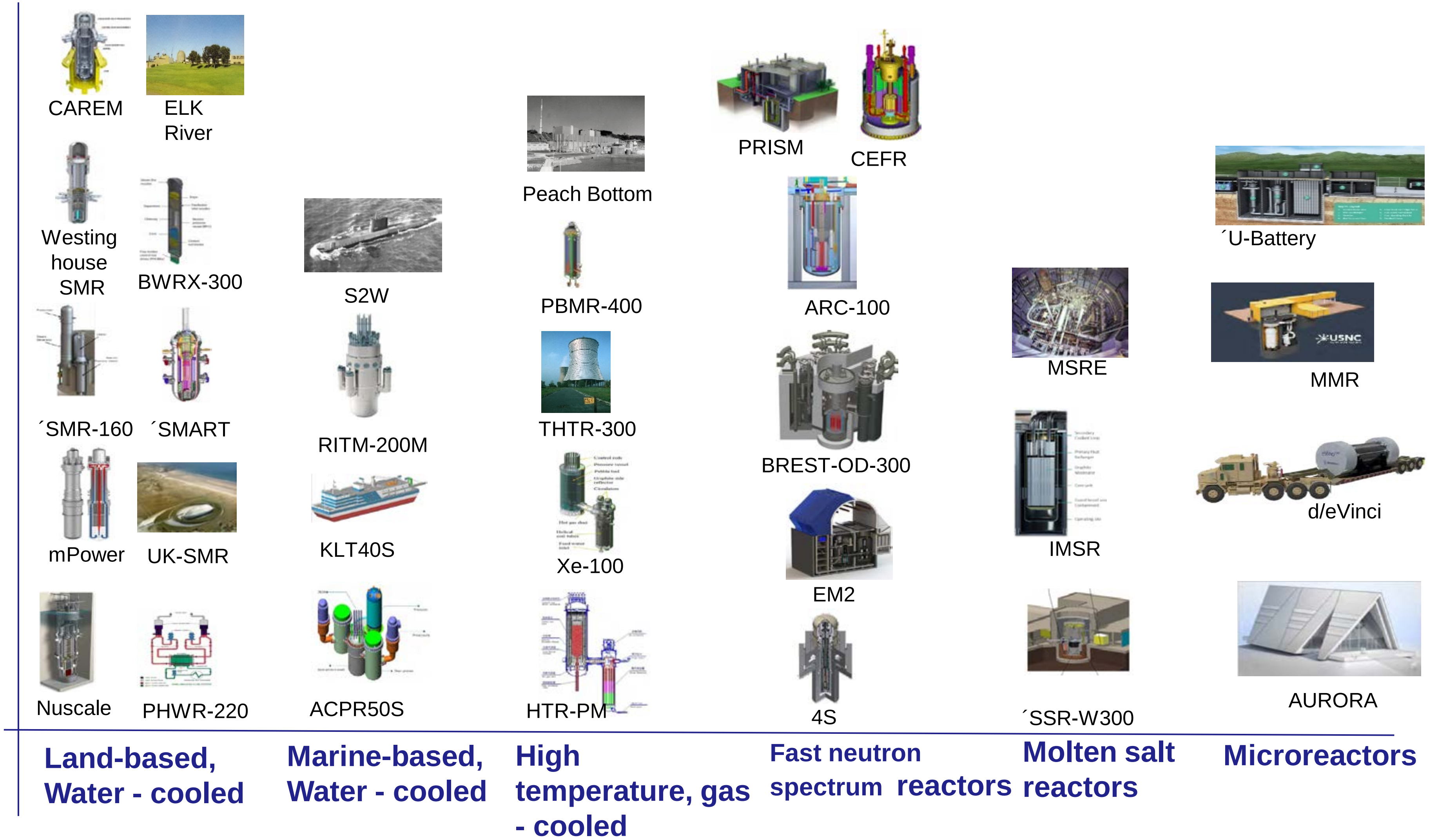
..to consider

- Not a new phenomenon, in fact going back to the 1950s
- Re-naming by the US-Department of Energy DOE, Minister Steven Chu (2010) in an attempt to work towards "Generation IV" reactors
- SMR traditionally stands for "Small and Medium-Sized Reactors" (IAEA 1961; 1971)
- Nuclear power plants of large capacities (> 1,000 MW) are not competitive (Wealer et al. 2021), can reactors of small capacity become competitive?

Definition

"SMRs are reactors in which a single reactor has an electrical power output of less than 300 MWe (or a thermal power output of less than 1000 MWth). These can be both based on water-cooled or other (non-water cooled) reactor designs" (Pistner et.al. 2021, 24)

A selection of SMR – concepts from the current ARIS 2020 publication



Source: ARIS 2020

Data – set of public available information for SMR - concepts

Available SMR - Concepts costs

Reaktor	Reactor Typ	Manufacturer costs [Total, m $ 2020]	Capacity [Mwe]	Design Lifetime [years]
UK-SMR	PWR	2.310,660.000	443	60
BWRX-300	BWR	675,000.000	300	60
EM2	HTR/GFR	1.158,924.500	265	60
HTR-PM	HTR	578,760.000	210	40
IMSR(300)	MSR	790,581.851	195	56-60
PBMR-400	HTGR	255,750.000	165	40
SMR-160	PWR	1.010,000.000	160	80
SMART	PWR	428,000.000	107	60
ARC-100	SFR	505,000.000	100	60
Nuscale	PWR	266,882.000	77	60
RITM 200M	PWR	223,236.000	53	60
ACPR 50S	PWR	341,280.000	40	40
KLT-40S	PWR	473,600.000	35	40
SSR-W	MSFR	58,500.000	30	60
CAREM	PWR	695,625.000	30	40
CEFR	SFR	460,690.724	20	30
4S	SFR	25,000.000	10	60
e-Vinci	MR	20,200.000	3,5	40

Reference Nuclear Power Plants

Reactor	Typ	Referenz Kosten [$/KWe]	Referenz Kosten [$/MWe]	Referenz Leistung [MWe]	Totale Kosten [m USD 2020]
Vogtle, AP1000	PWR	11.550	11.550.000	1.117	12.901,350.000
Superphénix	SFR	28.413	28.412.800	1.250	35.516,000.000
Clinton - 1	BWR	8.758	8.758.079	950	8.320,175.240
Fort St.Vrain -1	HTGR	200.000	200.000.000	330	66.000,000.000

In General:
- Costs are not available for every reactor
- USD are adapted to USD 2020

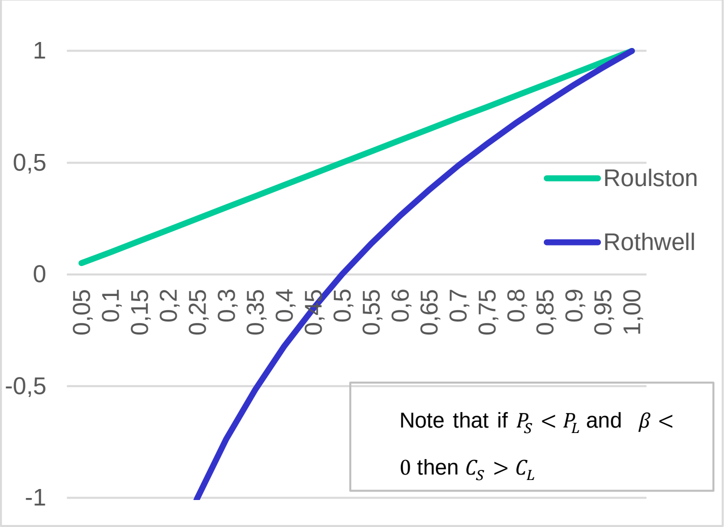
Current theory regarding cost estimation for SMR concepts

Two main theories.....

Rothwell: $C_S = C_L * \left(\frac{P_S}{P_L}\right) * \alpha^{(lnP_S - lnP_L)/ln2}(1-x)$

Roulston: $C_S = C_L * \left(\frac{P_S}{P_L}\right)^{\beta} (1-x)$

C_S, C_L denotes the costs, P_S, P_L denotes the power output and α, β scaling factors and x for the learning factor



same structure… ??

Since by elementary computations:

$$\alpha^{(lnP_S - lnP_L)/ln2} = \alpha^{(\ln(\frac{P_S}{P_L}))/ln2} = e^{\frac{ln\alpha}{ln2} * ln\frac{P_S}{P_L}} = (\frac{P_S}{P_L})^{\frac{ln\alpha}{ln2}}$$

the formula of Rothwell can be written as $C_S = C_L * (\frac{P_S}{P_L})^{1+\frac{ln\alpha}{ln2}}$. Thus, this formulas of Rothwell and Roulston have the same structure if we set $\beta^{Rothwell}(\alpha) = 1 + \frac{ln\alpha}{ln2}$ and $\beta^{Roulston}(\alpha) = \alpha$,

….Consequence ??
For the theory of Rothwell, scaling actor below 0.5 will deliver costs taller than Cost - Reference

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THEORY VS. ADVERTISED COSTS

- Current Theory vs. Advertised manufacturing costs

Example – case, computation of NuScale costs in dependence of learn –effects and scaling factor

Formula in respect to Roulstone 2020:

$$Cost_{SMR_k} = (Cost_{LR} * (\frac{Size_{SMR}}{Size_{LR}})^{\beta})_k * (1-x)^d$$

$$Cost_{NuScale} = 12.901.350.000 * (\frac{77\ MWe}{1117\ MWe})^{0,6} \quad * (1-0,1)^1$$

$$Cost_{NuScale} = 12.901.350.000 * 0,7653 * 0,9 \approx 3.048.571.904$$

Formula in respect to Rothwell 2020:

$$Cost_{SMR} = Cost_{LR} * \left(\frac{Size_{SMR}}{Size_{LR}}\right) * (1-x) * \alpha^{[(ln(Size_{SMR})-ln(Size_{LR}))/ln(2)]}$$

$$Cost_{NuScale} = 12.901.350.000 * \left(\frac{77\ MWe}{1117\ MWe}\right) * (1-0,1) * 0,6^{\left[\frac{ln(77MWe)-ln(1117MWe)}{ln(2)}\right]}$$

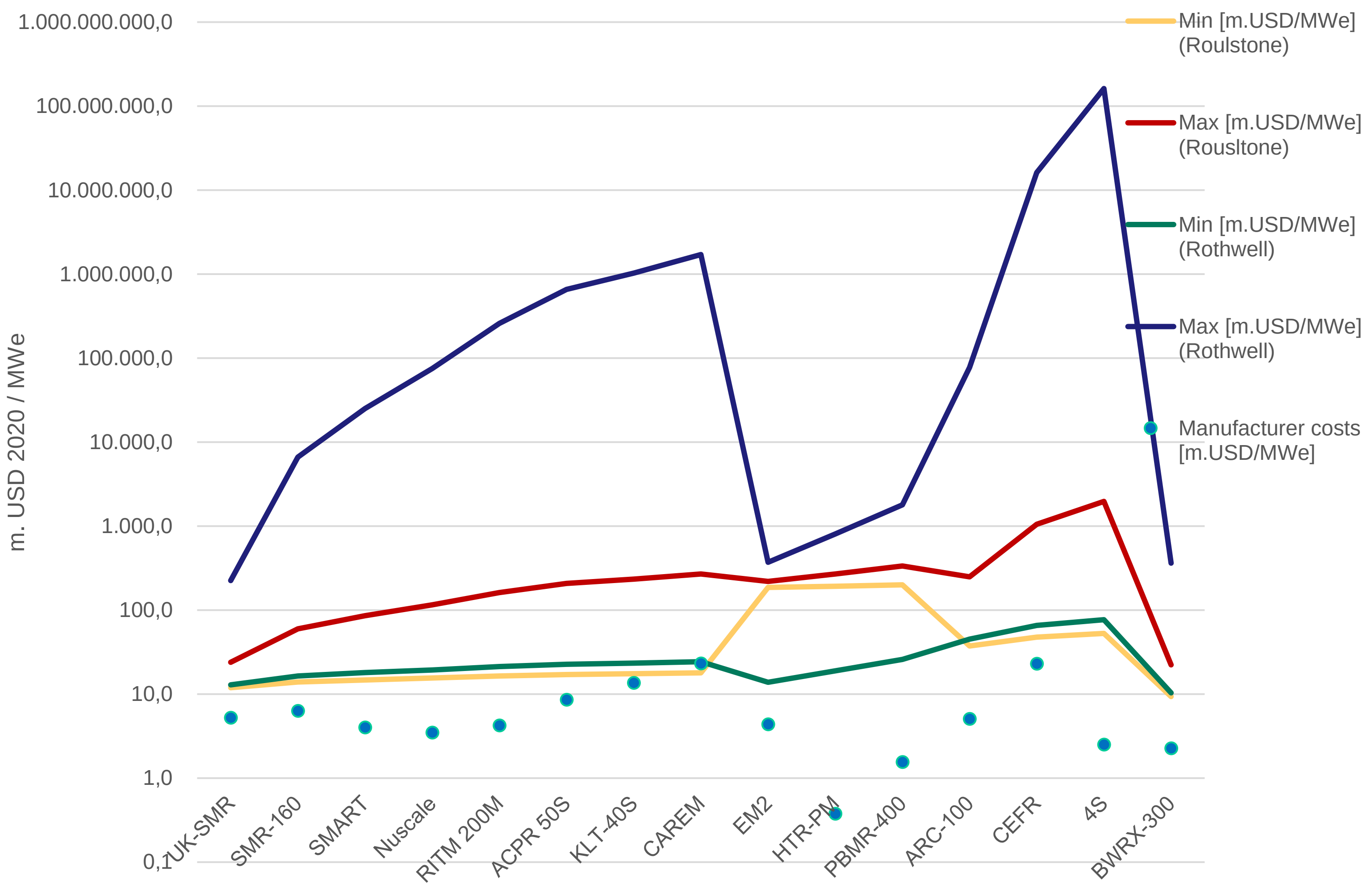
$$Cost_{NuScale} = 12.901.350.000 * 0,0689 * 0,9 * 0,5^{[-3,8586]} \approx 5.504.943.292.249$$

General assumptions for re-computation:

- A doubling d in production from 1
- A "**best case**" learn effect from 10% (Mignacca and Locatelli 2020)

Variable	Description & Unit
C_{SMR_k}	Cost estimation for an SMR – concept (</=300MWe)
C_{LR}	Cost estimation for an NPP (>/= 300 MWe)
P_{SMR}	Capacity in MWe
P_{LR}	Capacity in MWe
β	Scaling factor
k	"Index for costs of SMR concept k"
x	Learn – Effect
d	"Doubles" of production

Advertised manufacturer costs vs. recalculated cost theory – do manufacturer underestimate ?



Source: Own calculation and drawing, with help of Pistner et.al. 2021

In General:

- Advertised manufacturing costs seems to be pretty underestimated compared with current theory
- Current finished projects of constructed SMR – concepts (KLT-40S, HTR-10, got underestimated first and finished far above first estimation

3

INVESTMENT DECISION

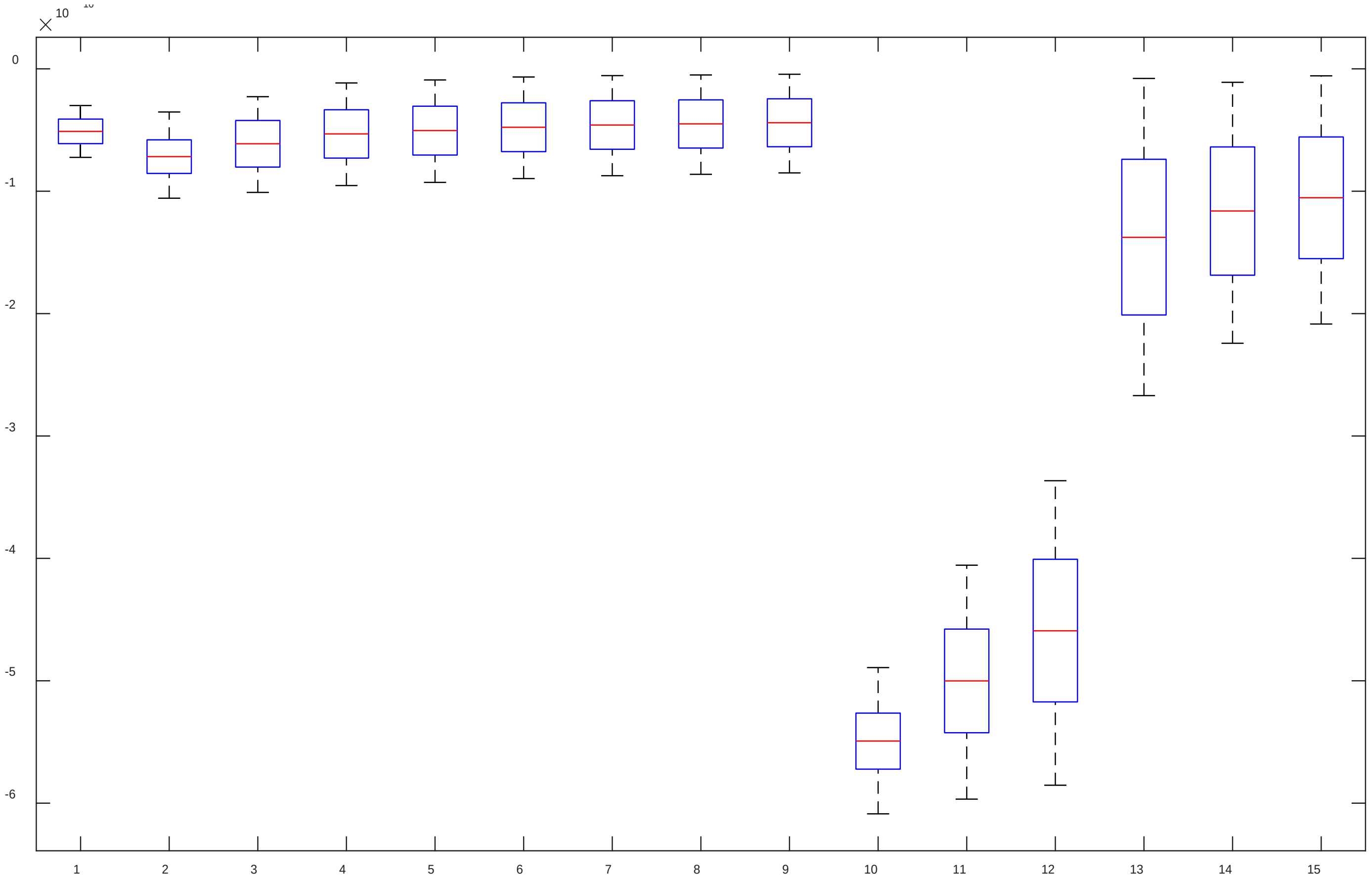
Investment decision with uncertainty

- Computation of NPV and LCOE through simulation of uncertain parameter with the help of Monte Carlo Simulation
- Sensitivity analysis in case of NPV calculation

Computation of NPV and LCOE through simulation of uncertain parameter with the help of Monte Carlo Simulation

Measurement to promote an investment decision	Net Present Value (NPV)	Leverage cost of electricity (LCOE)
Definition	$NPV = \sum_{t=0}^{T} e_t * (1 + r_t \ )^{-t}$	$\text{LCOE} = \frac{\sum_{t=0}^{T}(TCC_t + O\&M_t + Fuel_t + Carbon_t) * (1 + r_t \ )^{-t}}{\sum_{t=0}^{T} Electricity * (1 + r_t)^{-t}}$
Model adaptions (per time frame)	• $r \approx$ weighted average cost of capital (WACC) • $e \stackrel{\text{def}}{=}$ flow of payments (income from selling electricity – costs) • Total construction costs: $TCC \stackrel{\text{def}}{=}$ OCC (1+idc) • Interest during construction: $idc = \frac{r}{2} T_{con} + \frac{r^2}{6} {T_{con}}^2$ • Time : $T \stackrel{\text{def}}{=} T_{const.} + T_{operational}$ • Electricity: EEX wholesale electricity price for 2020 in USD	
Uncertain Parameter	• Used common technique of Monte Carlo Simulation to simulate unified investment costs, WACC, load factor and wholesale electricity price due 1.000.000 simulations	

NPV calculation in respect to theory after Roulstone with uncertain parameter simulated



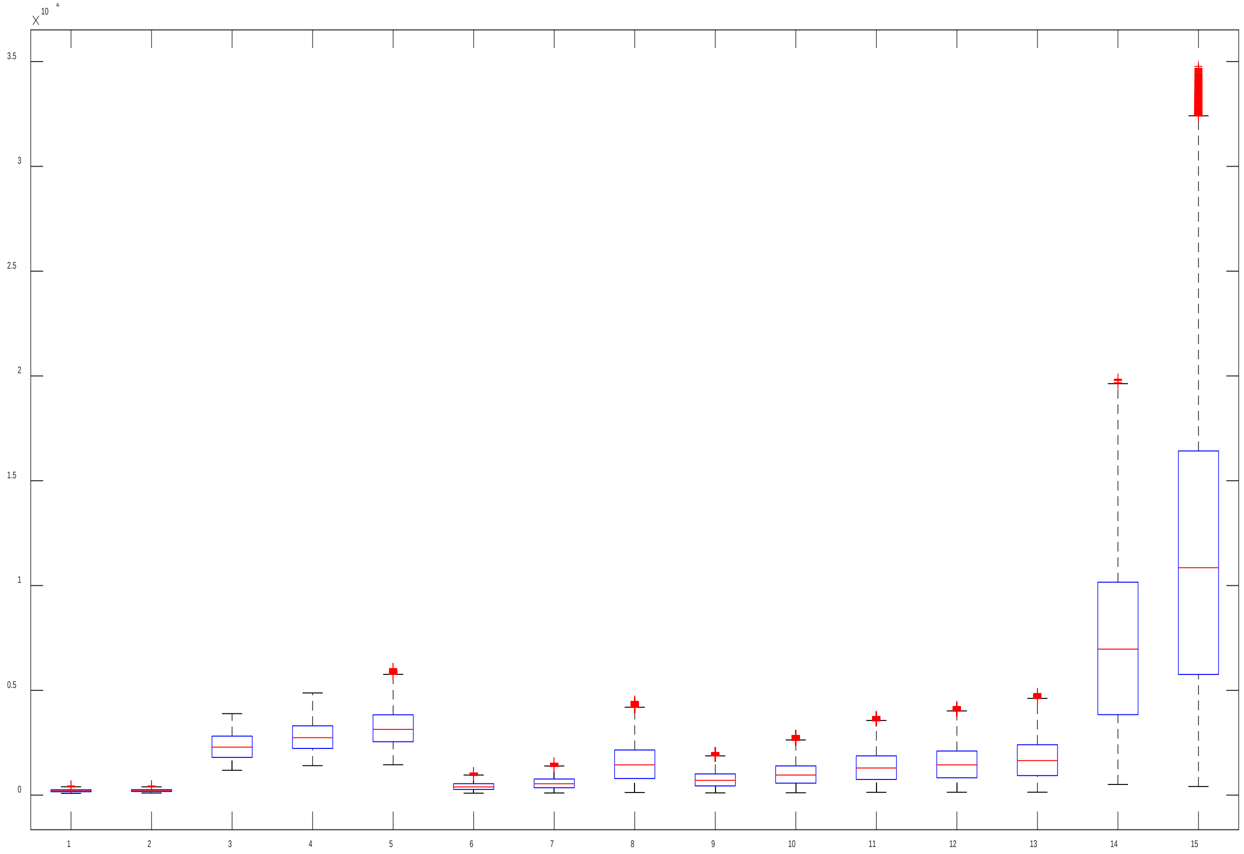
Number in Graph	Reactor	Type
1	BWRX-300	BWR
2	UK-SMR	PWR
3	SMR-160	PWR
4	SMART	PWR
5	Nuscale	PWR
6	RITM 200M	PWR
7	ACPR 50S	PWR
8	KLT-40S	PWR
9	CAREM	PWR
10	EM2	HTR/GFR
11	HTR-PM	HTR
12	PBMR-400	HTGR
13	ARC-100	SFR
14	CEFR	SFR
15	4S	SFR

Findings:

- Reactor Technology drives NPV of SMR – concepts – Groups can be identified (BWR &PWR, HTR, SFR)
- Theory after Rothwell is strongly influenced by its scaling factors (a scaling factor below 0.5 delivers a drastic spread in investment interval)
- Scaling theory is highly hypothetical – last cited sources are from 1978

Source: Own calculation and drawing, with help of Pistner et.al. 2021

LCOE calculation in respect to theory after Roulstone with uncertain parameter simulated



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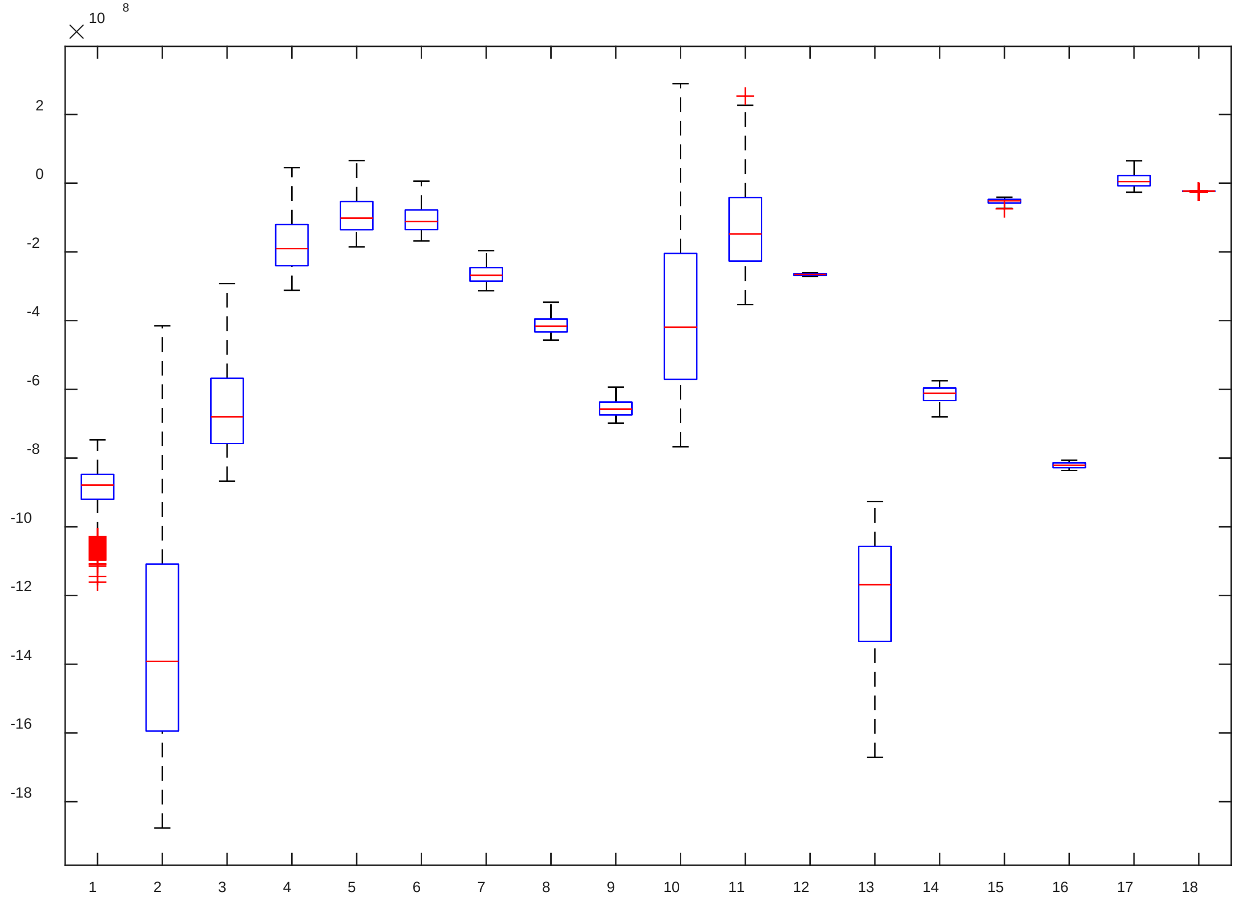
8	KLT-40S	PWR
9	CAREM	PWR
10	EM2	HTR/GFR
11	HTR-PM	HTR
12	PBMR-400	HTGR
13	ARC-100	SFR
14	CEFR	SFR
15	4S	SFR

Source: Own calculation and drawing, with help of Pistner et.al. 2021

NPV calculation in respect to advertised manufacturing costs with uncertain parameter simulated



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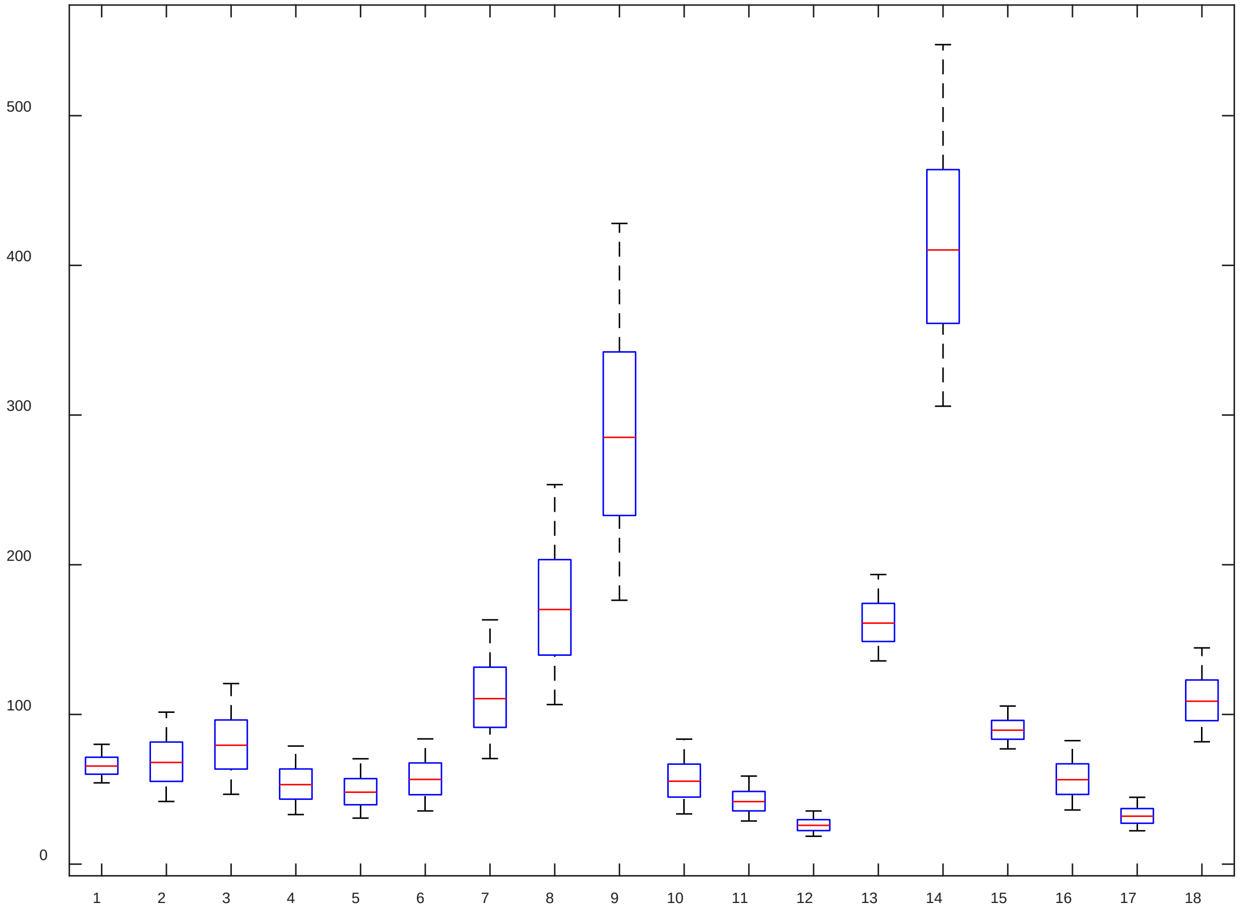
12	PBMR-400	HTGR
13	ARC-100	SFR
14	CEFR	SFR
15	4S	SFR
5	IMSR(300)	MSR
14	SSR-W	MSFR
18	e-Vinci	MR

Findings:

- NPV differences in reactor – technologies seems to be higher then in theory
- None PWR & BWR SMR concepts seems to have an lower NPV with smaller capacity which can be explained through none linear effects
- In case of PWR reactors, NPV seems to have a linear correlation to the concept's capacity with exclusion of the SMR – concept of the UK-SMR, SMR- 160 and SMART

Source: Own calculation and drawing, with help of Pistner et.al. 2021

LCOE computation in respect to advertised manufacturing costs with uncertain parameter simulated



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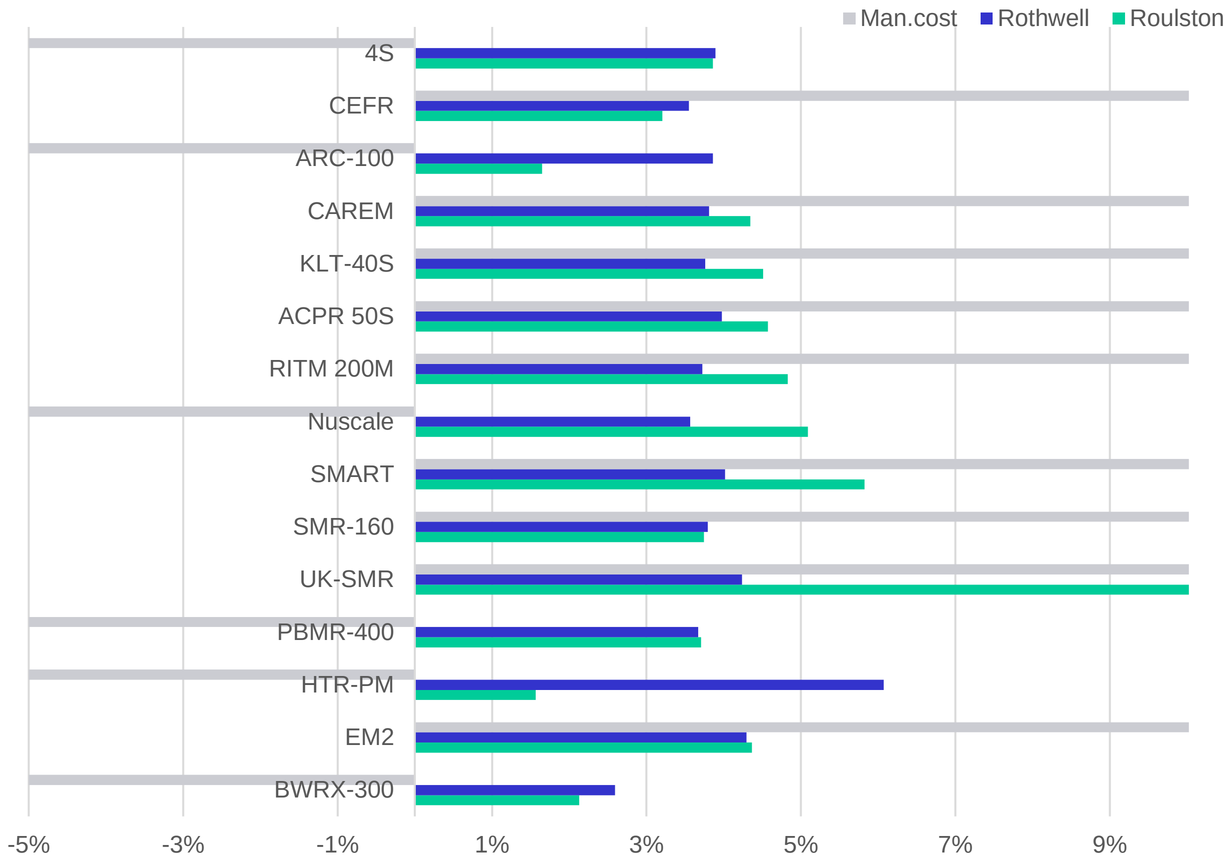
5	IMSR(300)	MSR
14	SSR-W	MSFR
18	e-Vinci	MR

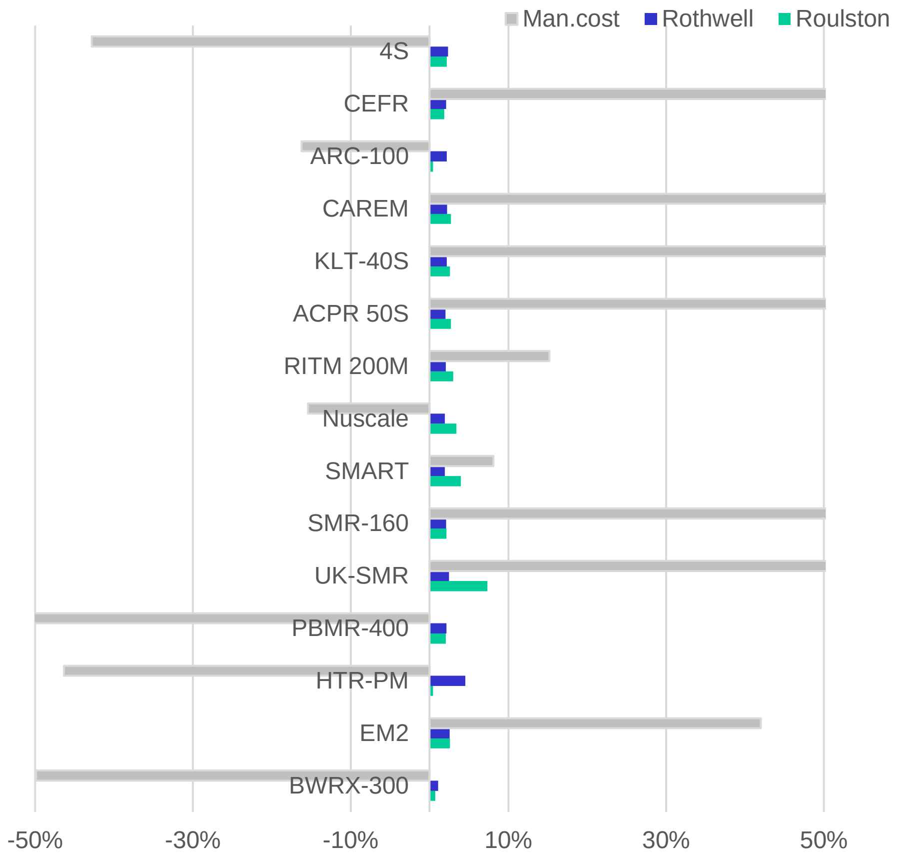
Source: Own calculation and drawing, with help of Pistner et.al. 2021

Sensitivity for parameter construction time and WACC

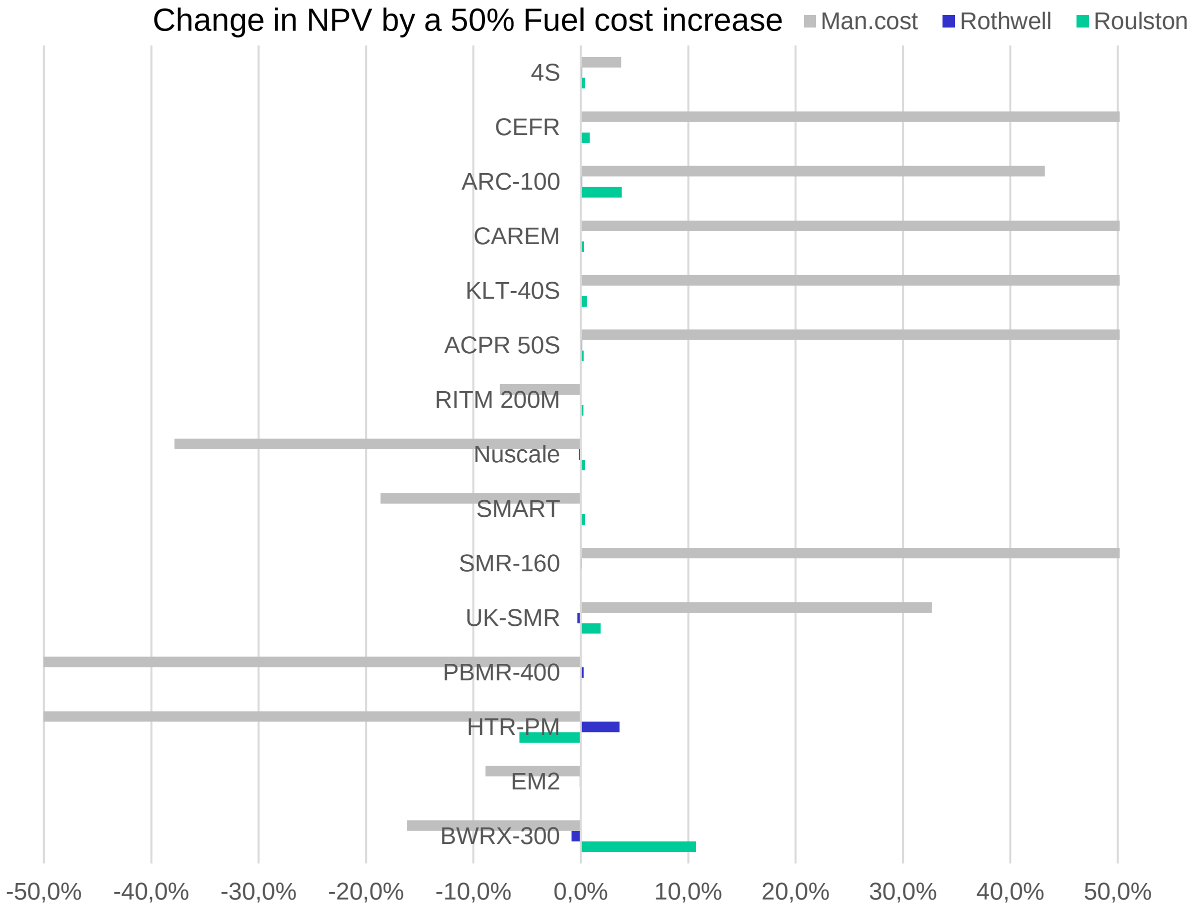
Change in NPV by construction time increase of 10 years

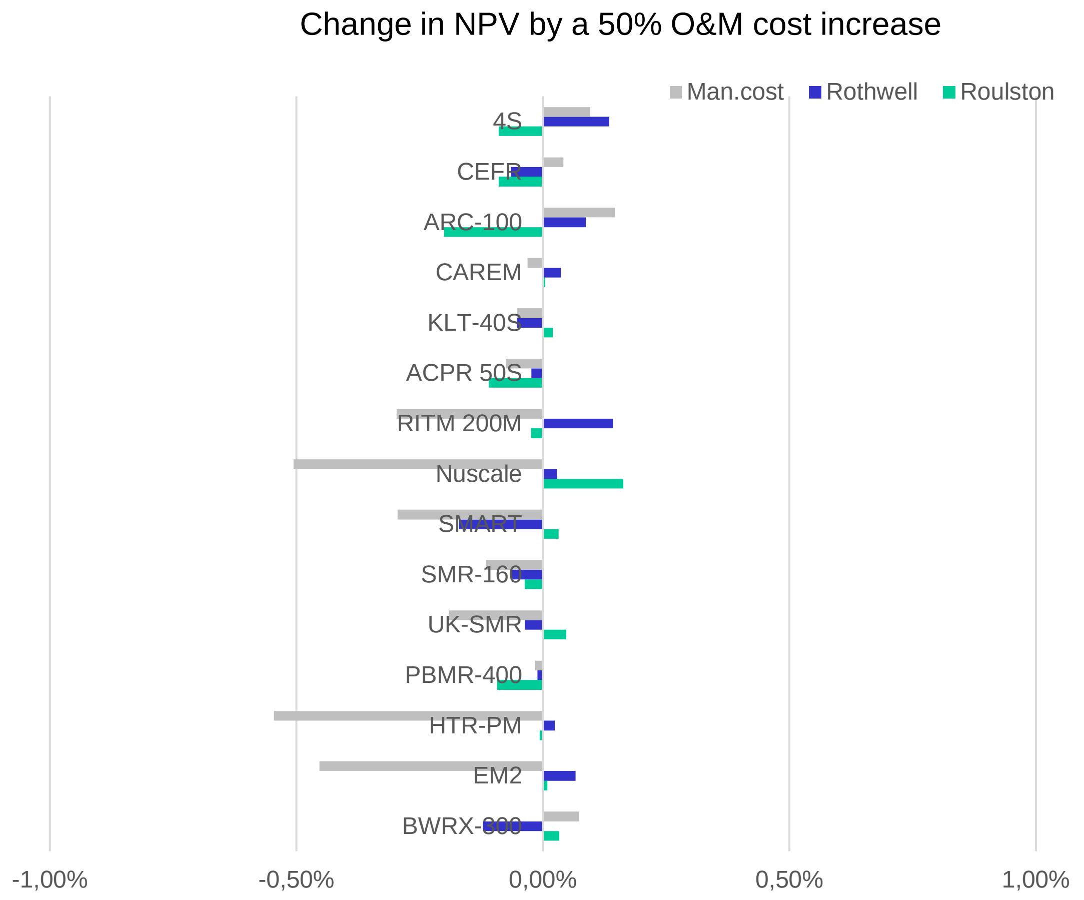


Change in NPV by a 50% WACC increase



Source: Own calculation and drawing, with help of Pistner et.al. 2021





Source: Own calculation and drawing, with help of Pistner et.al. 2021

Results

In General we can conclude…

- Production economics are not favourable to SMRs, given the small capacities and lack of mass production options
- Effects of mass production and learning unlikely to be attained, due to stringent safety evaluations (by country) and lack of demand
- SMRs might be pursued for specific research or military applications, but are no option for competitive, low-carbon electricity

In terms of an possible investment…

- LCOE costs got underestimated by current SMR – concept manufacturers in their advertisements
- The Net Present value with respect to the German traded wholesale electricity price will be negative, which indicates a none competitiveness for SMR concepts

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