A Multi-dimensional Risk-based Optimization of a Fusion Pilot Plant

by

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with

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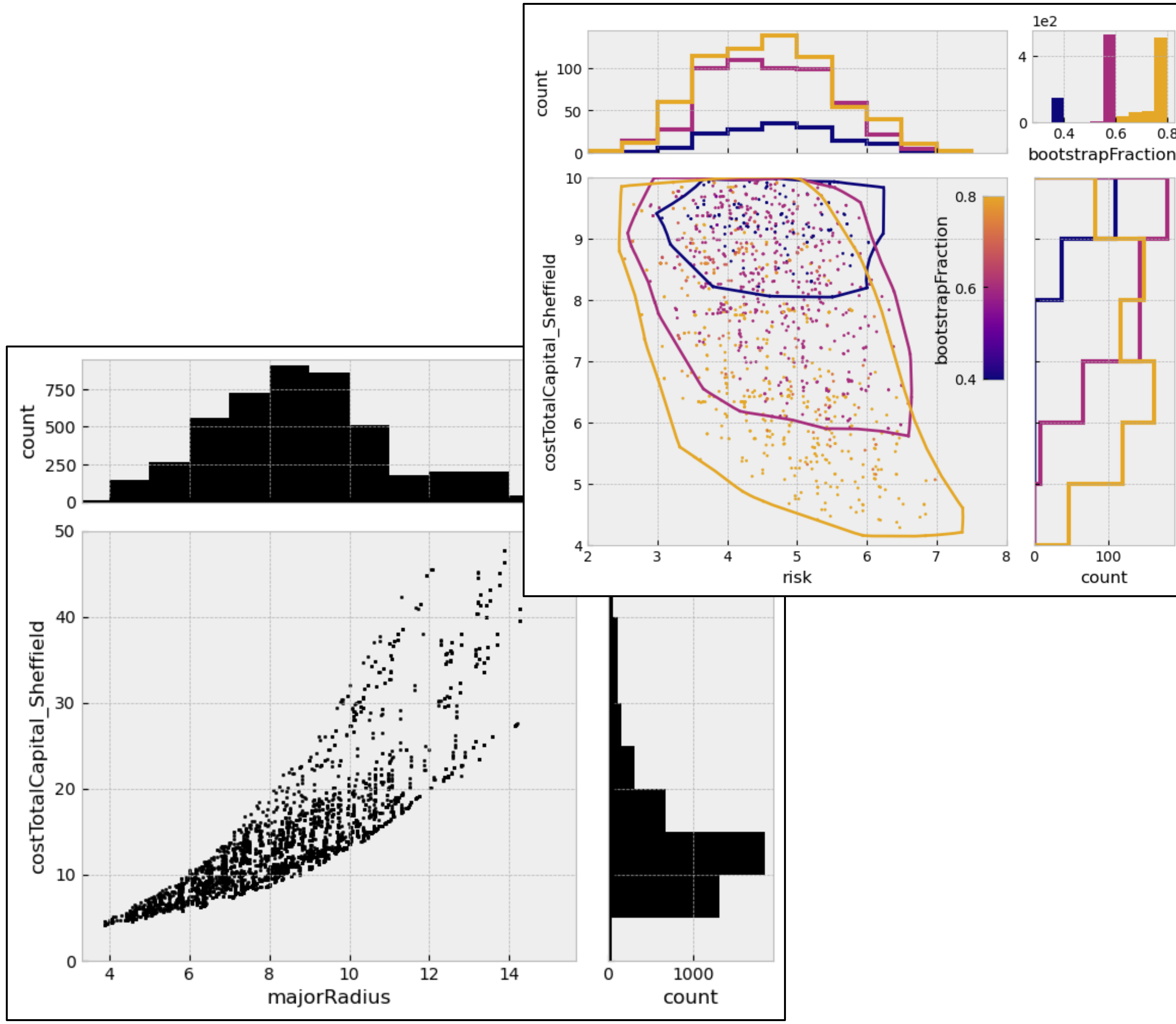
at the

64th APS-DPP Annual Meeting

Spokane, WA
October 20, 2022

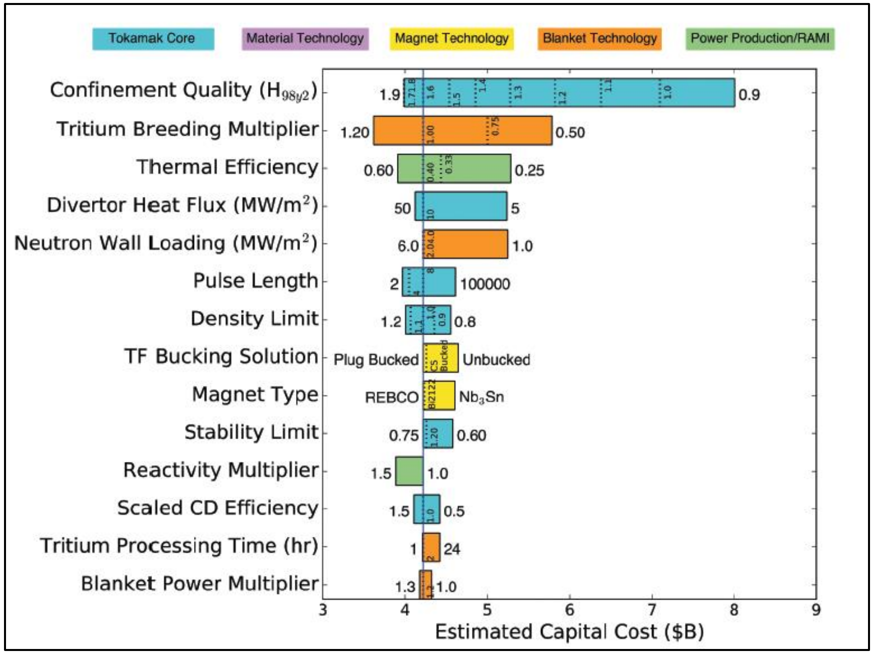


GENERAL ATOMICS

System codes aim to quantify FPP design trade-offs

- **High-level system studies can quickly approximate integrated solutions with relevant subsystem constraints**
- **Sensitivity scans show which parameters are most leveraging for an optimized FPP**
- **Past work has considered cost-optimization sensitivity, but only with respect to a single baseline design point**

- **This study expands this effort with a 10-parameter sensitivity scan and a risk assessment analysis of over 4,000 optimized design points**



"Tornado" plot (from Wade & Leuer, FST 2021) shows cost sensitivity study around a single baseline design point

GENERAL ATOMICS

GA Systems Code optimization workflow

- **The GA Systems Code (GASC) generates 0D solutions for a net-electric, steady-state tokamak**
- **GASC constrained optimization workflow requires:**
  - A set of constant input parameters
  - A set of free input parameters (with appropriate bounds)
  - A set of constrained output parameters
  - An optimization function to minimize: **Direct Capital Cost**

Free Inputs

- major radius
- toroidal field
- plasma current
- on-axis ion temp.
- normalized beta
- TF coil radial build
- CS coil radial build
- TF coil structural fraction
- CS coil structural fraction
- impurity fraction

Constant Inputs

- aspect ratio = 3.5
- triangularity = 0.7
- $T_e/T_i = 1.0$
- $T_{i0}/\langle T_i \rangle = 2.3$
- $n_{e0}/\langle n_e \rangle = 1.3$
- $n_{He}/n_e = 0.05$
- $Z_{impurity} = 36$
- $f_{NI} = 1.0$
- $\eta_{thermal} = 0.4$
- $\eta_{aux} = 0.4$
- $M_{blanket} = 1.2$
- and many more…

Constrained Outputs

- $\beta_N/\beta_{N,IW} < 0.8$
- $\kappa/\kappa_{max} < 0.9$
- $f_{BS} < 0.8$
- $f_{GW,ped} < 0.9$
- $q_{95} > 3.0$
- $P_{SOL}/P_{L\text{-}H} > 1.0$
- $Z_{eff} > 2.0$
- $H_{DS03} < 1.0$
- $N_W < 3.0$ MW/m^2
- $q_{pol} < 2.5$ GW/m^2
- $\omega_{ce0}^2/\omega_{pe0}^2 < 1.0$
- $P_{NET} > 200$ MWe

Multi-dimensional scan over 10 constrained parameters

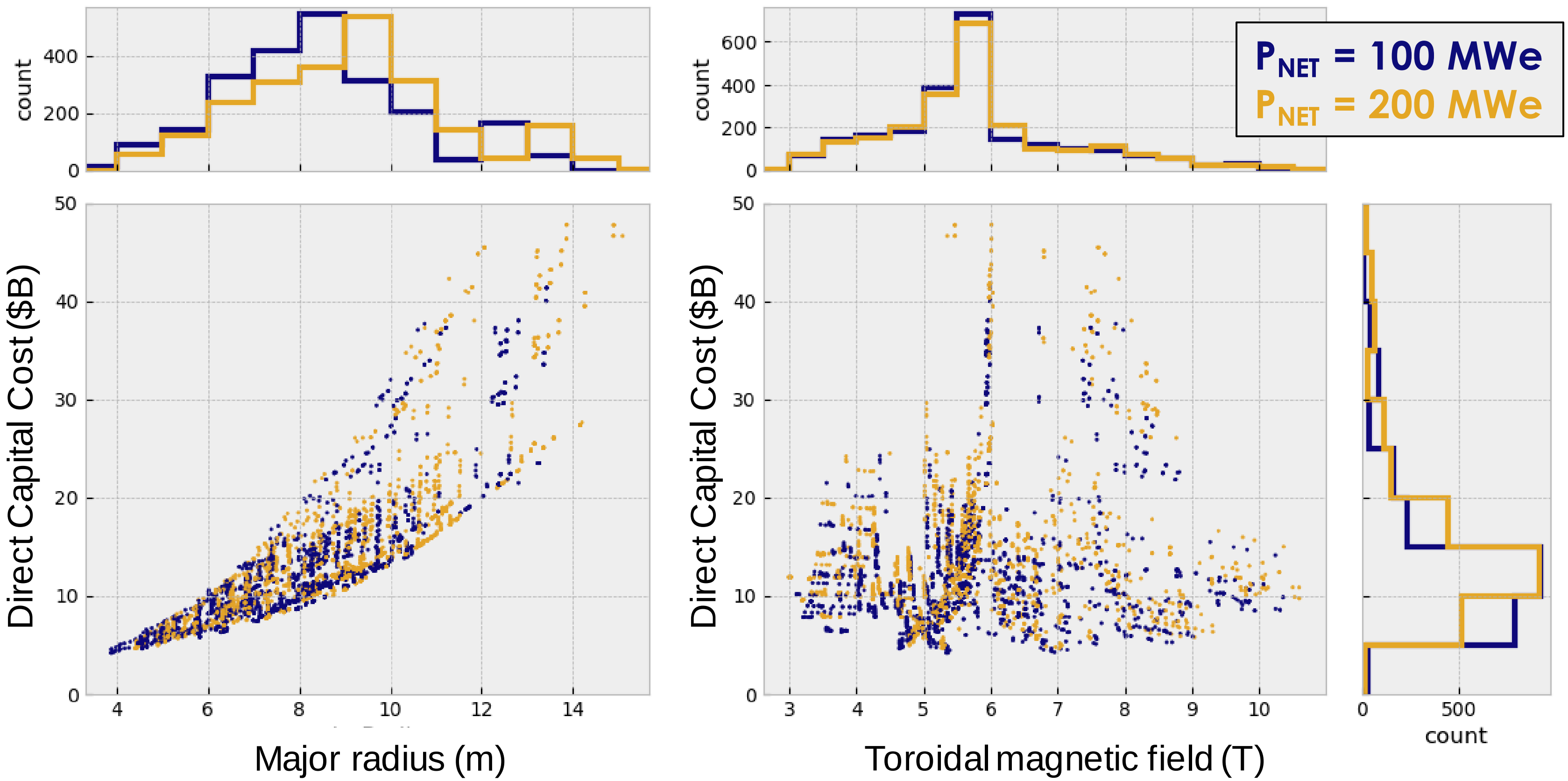
- **Each constraint is scanned over 2 or 3 values, ranging from conservative (ITER baseline) to aggressive**

Parameter	Definition	Constraint Values	ITER Q=10 Value
Bootstrap faction	$f_{BS} = C_{BS}\ \beta_P\ A^{-1/2},\ C_{BS} = 2/3$	[0.4, 0.6, 0.8]	0.28
H_{DS03}	Energy confinement scaling factor	[0.8, 1.0]	0.85
Neutron wall loading	Peak neutron power flux at first wall	[1.0, 3.0] MW/m^2	0.75
BetaN limit fraction	$\beta_N\ /\ \beta_{N,IW}$ (MHD control)	[0.4, 0.6, 0.8]	0.37
Elongation fraction	$\kappa\ /\ \kappa_{max}$ (VDE control)	[0.7, 0.9]	0.75
Poloidal heat flux	Poloidal heat flux at OMP	[1.5, 2.5] GW/m^2	1.2
Peak coil stress	Peak Von Mises stress at IMP	[600, 800] MPa	600
Coil current margin	J_{crit}/J_{op} margin in coil current	[3.0, 2.0]	3.0
Superconductor	Magnet conductor technology	[LTS, HTS]	LTS
Coil bucking	CS-TF contact with central plug	[No, Yes]	No

GENERAL ATOMICS

Cost-optimization scan yields 4,608 FPP solutions

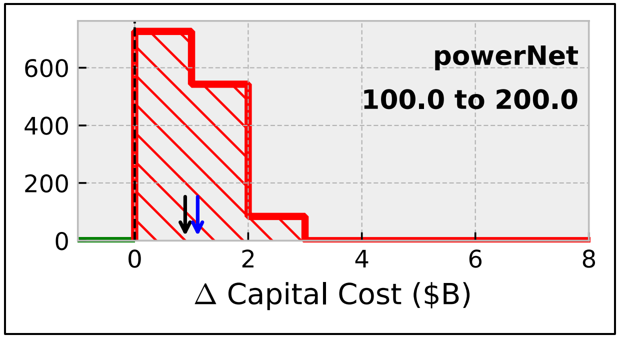
- Two net power targets considered: 100MWe and 200MWe
- Cost roughly correlates with facility size, with significant spread
- 30% of optimized design points are below $10B

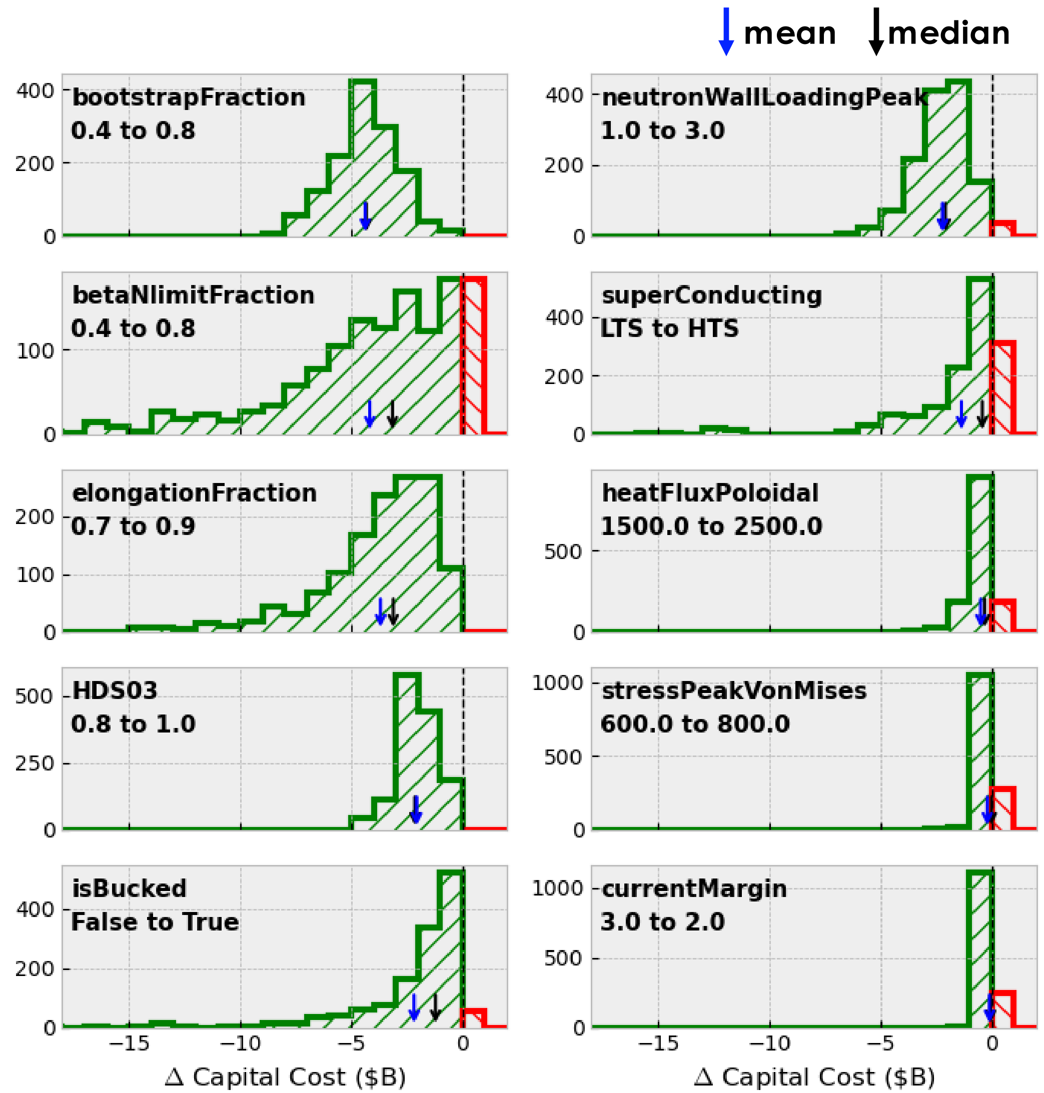


GENERAL ATOMICS

Constraints ranked based on cost-reduction sensitivity

- **Given a design point with a conservative constraint:**
  - How much is cost lowered by changing the constraint to be more aggressive?
- **Plasma-related constraints have a more leveraging impact on FPP cost**
  - exception is poloidal heat flux





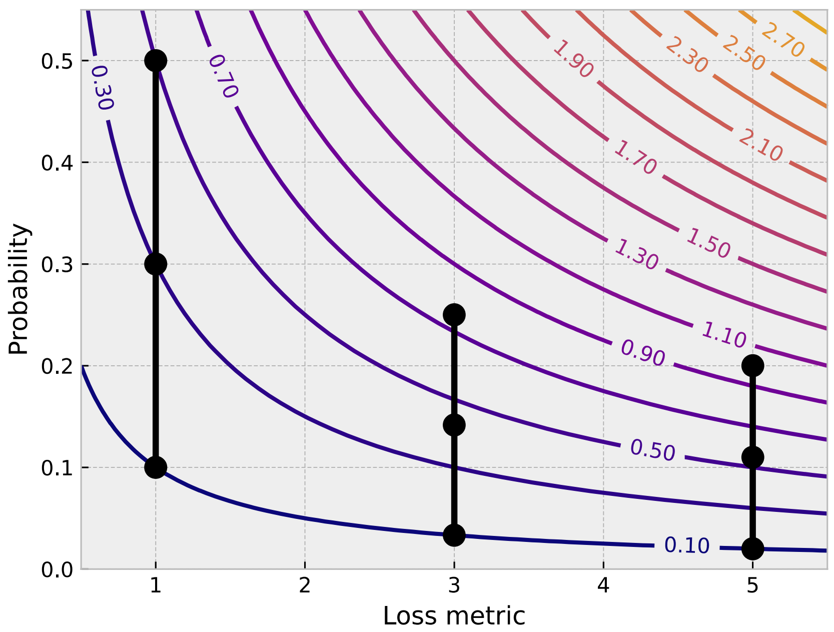
GENERAL ATOMICS

Risk assessment is used to quantify design risk

- **Risk management process can be expressed mathematically**
- **Total risk is defined as sum over individual risks, R_i, which can be computed as the product of potential losses, L_i, and their probabilities, $p(L_i)$:**
  - $R_i = L_i\, p(L_i)$
  - $R_{total} = \sum_i L_i\, p(L_i)$

- **Assume that risks are independent and linear (i.e. they are not correlated, and they do not compound)**

Risk = loss x probability



Constraints are divided into three risk categories:

- Low: loss = 1
- Medium: loss = 3
- High: loss = 5

GENERAL ATOMICS

Risk assessment categorization definitions

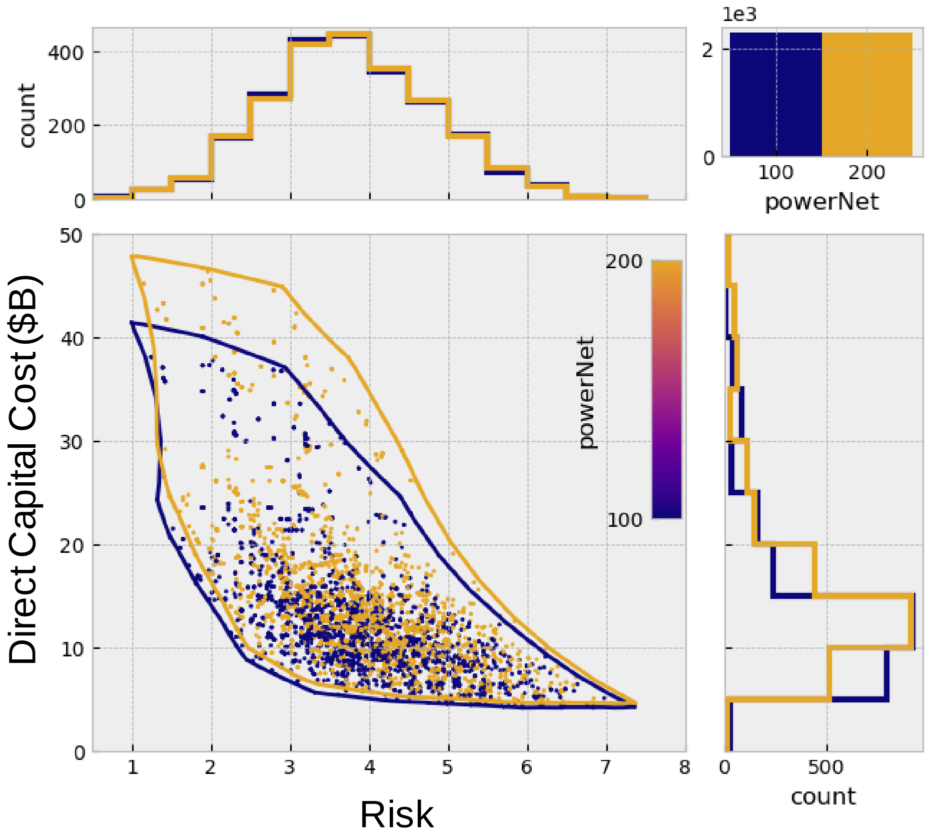
- **Low-risk losses are more probable but less damaging**
- **High-risk losses have the potential to severely disrupt entire project**

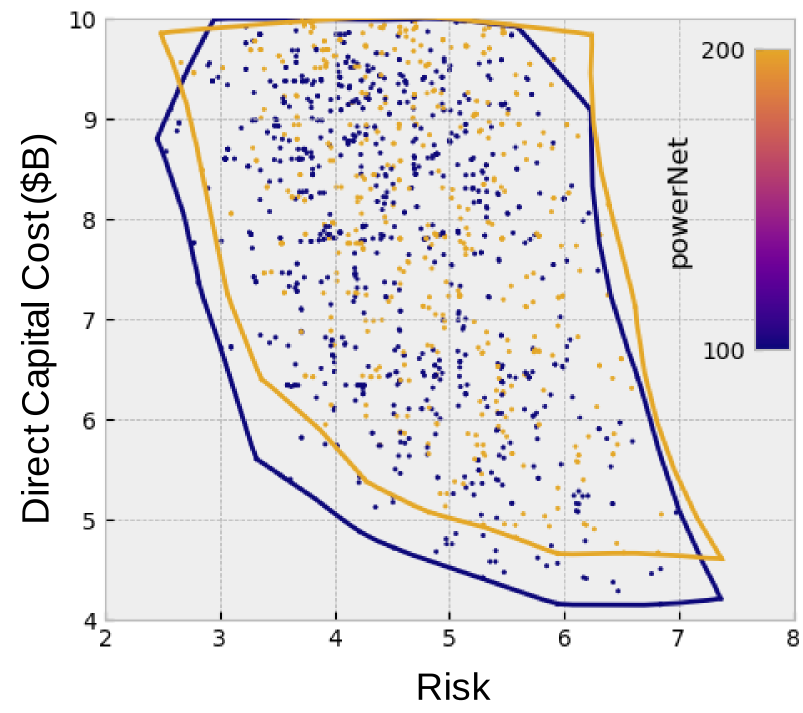
Parameter	Loss Method	Loss Severity	Risk
Bootstrap faction	Sub-par performance		
H_{DS03}	Sub-par performance	Low (1)	0.1 – 0.5
Neutron wall loading	Shortened operational cycle		
BetaN limit fraction	MHD / transient heat flux		
Elongation fraction	VDE / disruption damage	Medium (3)	0.1 – 0.75
Poloidal heat flux	PFC erosion / melting		
Peak coil stress	Magnet damage		
Coil current margin	Magnet damage	High (5)	0.1 – 1.0
Superconductor type	TRL gateway fail		
Coil bucking	TRL gateway fail		

GENERAL ATOMICS

Risk assessment differentiates designs with similar cost

- **Lowest cost design points span a large range in risk**
  - Design choices should prefer lower risk at comparable cost
- **Higher net power is not inherently riskier, but is achieved via higher cost (15-20% more expensive to double output power)**



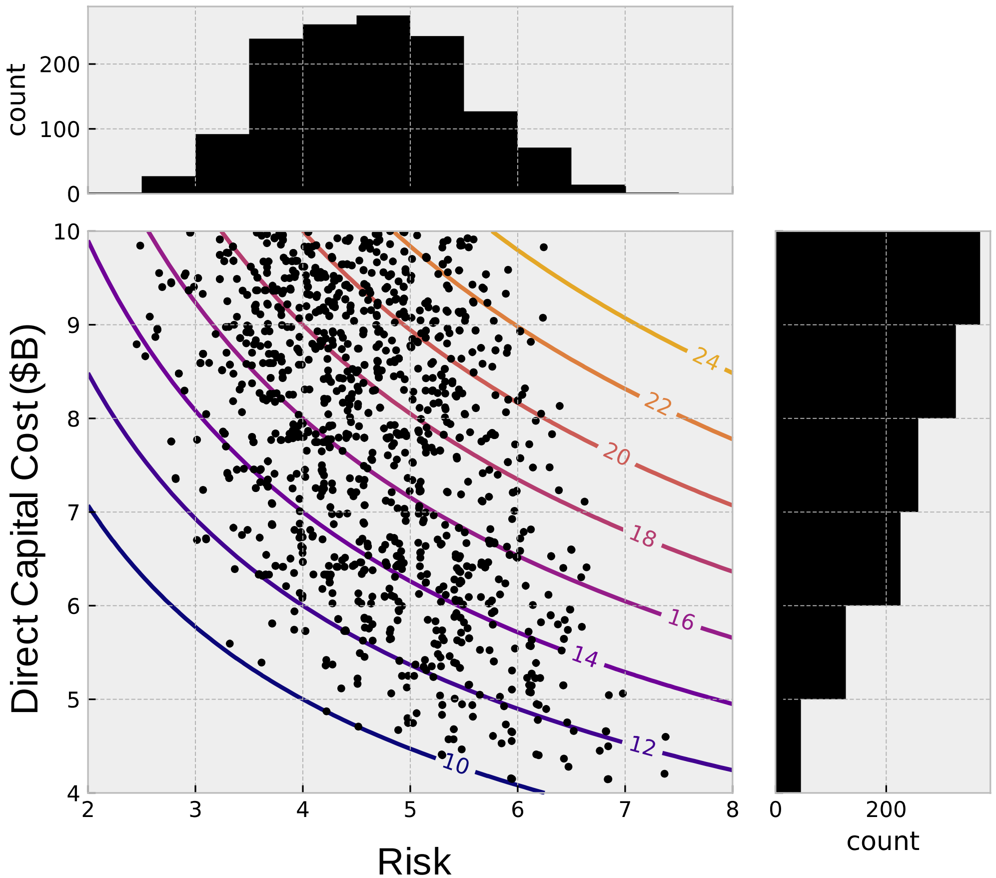


Risk-cost metric allows comparison of parameters

- **It is desirable to quantify a combination of cost and risk into a single metric**
  - Will allow for direct comparison of parameters
- **Bottom-left boundary of dataset corresponds to a logical function:**

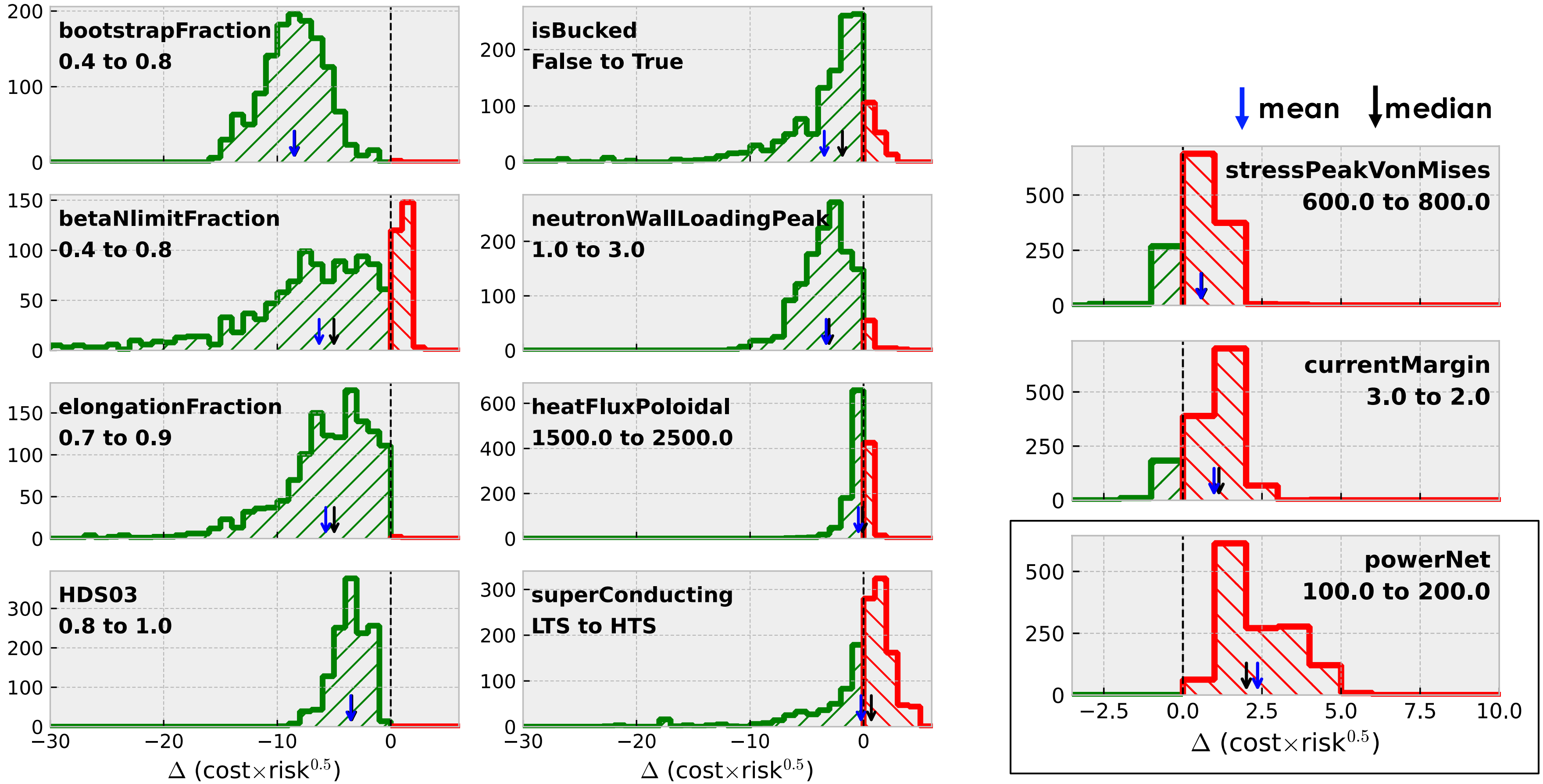
$$F = (cost) \times (risk)^{0.5}$$

  - This metric weights cost twice as much as risk
- **This is a subjective measure of risk vs. cost trade-off**



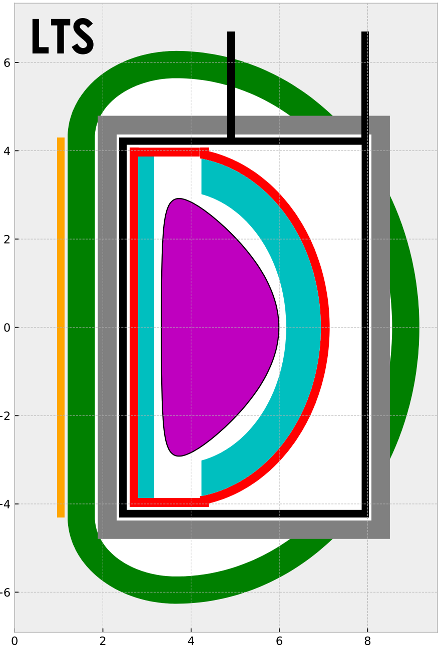
Risk-cost metric identifies plasma as highly leveraging

- Bootstrap, and betaN limit, and elongation fractions significantly reduce risk-cost, as does H_{DS03} confinement factor
- Coil constraints (stress and current margin) increase risk-cost

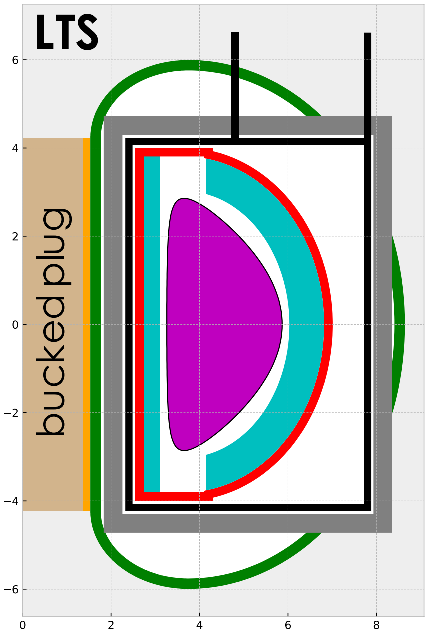


GENERAL ATOMICS

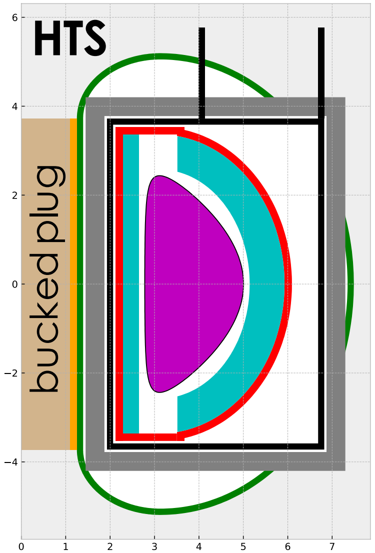
P_{NET} = 100MWe design points



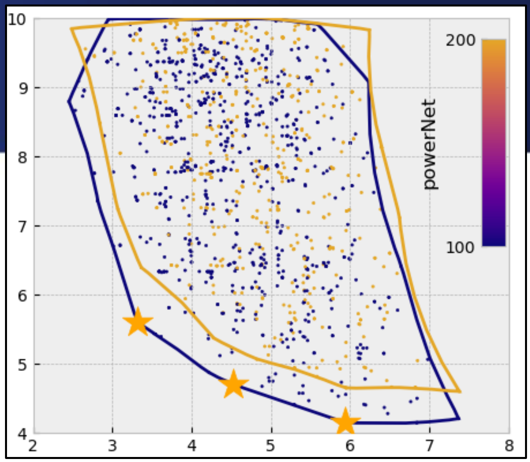
R_0 = 4.66m
B_T = 4.68T
I_P = 8.65MA
P_{aux} = 84MW
β_N = 4.27
q_{pol} = 1.5GW/m^2
Risk = 3.3
Cost = $5.6B



R_0 = 4.56m
B_T = 4.65T
I_P = 8.41MA
P_{aux} = 77MW
β_N = 4.27
q_{pol} = 2.0GW/m^2
Risk = 4.5
Cost = $4.7B



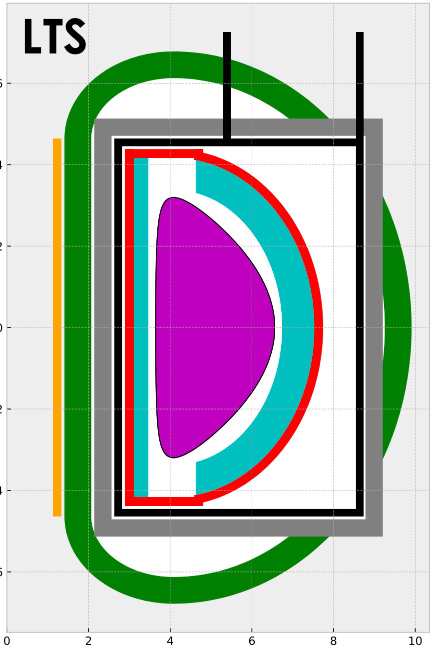
R_0 = 3.89m
B_T = 5.36T
I_P = 8.23MA
P_{aux} = 83MW
β_N = 4.25
q_{pol} = 2.5GW/m^2
Risk = 5.9
Cost = $4.2B



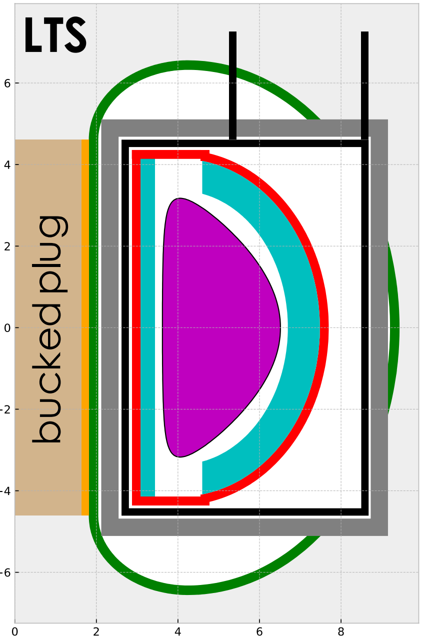
- **Three 'best' design points are shown for the 100MWe case**
- **All have similar β_N and P_{aux}**
- **Increasing risk allows inclusion of bucking, and then HTS magnets**
- **Poloidal heat flux also increases**

GENERAL ATOMICS

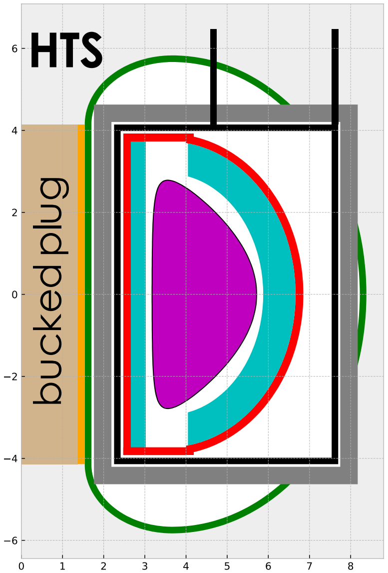
P_{NET} = 200MWe design points



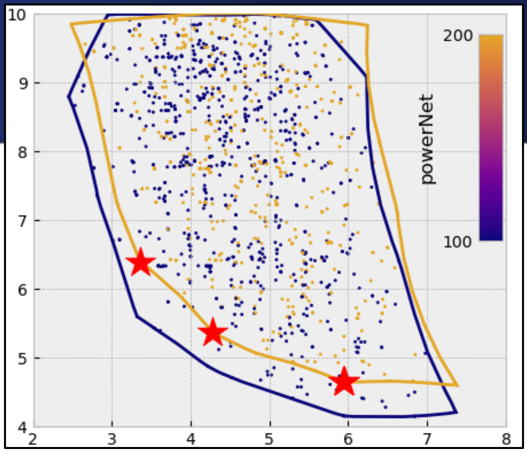
R_0 = 5.10m
B_T = 4.83T
I_P = 9.77MA
P_{aux} = 88MW
β_N = 4.27
q_{pol} = 1.5GW/m^2
Risk = 3.4
Cost = $6.4B



R_0 = 5.07m
B_T = 4.85T
I_P = 9.74MA
P_{aux} = 88MW
β_N = 4.27
q_{pol} = 1.5GW/m^2
Risk = 4.3
Cost = $5.4B



R_0 = 4.45m
B_T = 5.28T
I_P = 9.28MA
P_{aux} = 82MW
β_N = 4.26
q_{pol} = 2.5GW/m^2
Risk = 5.9
Cost = $4.7B



- **200MWe case shows similar trends**
- **Size and cost is higher than low-power case, but β_N is the same**
- **HTS magnets can be cost-competitive due to reduced SC volume**

Summary and Future Work

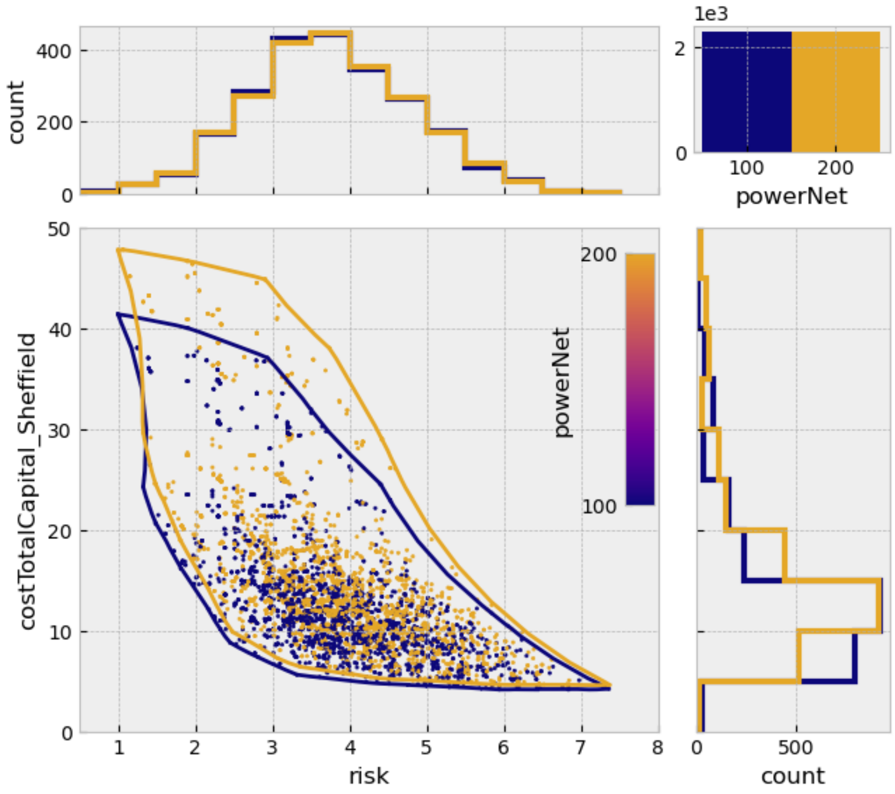
- GA Systems Code generates a cost-based optimization scan over 10 constrained parameters and identifies a large steady-state FPP design space
- Aggressive plasma-related constraints achieve target FPP power output at a lower cost than coil-related constraints
- Inclusion of a risk assessment study allows for differentiation between comparably costed solutions
- Subjective risk-cost metric further isolates bootstrap, elongation, and betaN limit fractions as highly leveraging

- Future work will address the inductive (pulsed) operation strategy, using physics-based constraints for ramp-up duration, flattop length, and dwell time
- Addition of thermal energy storage may provide a path to reduced cost, but only if tokamak cost savings from lower P_{NET} outweigh extra cost of storage system

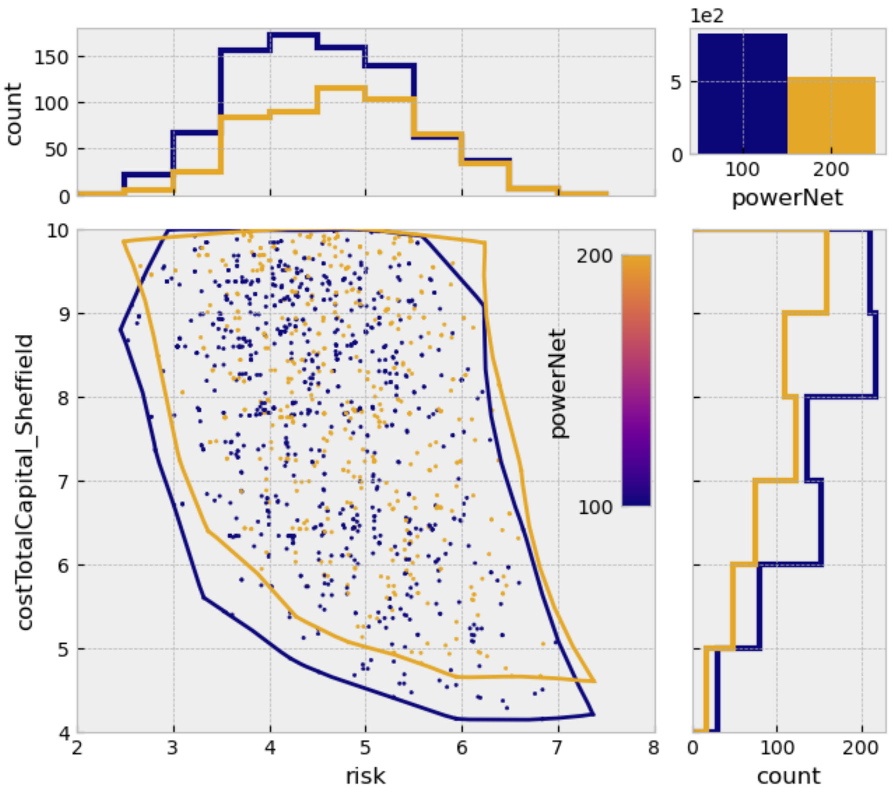
Backup Slides

Net power

full dataset

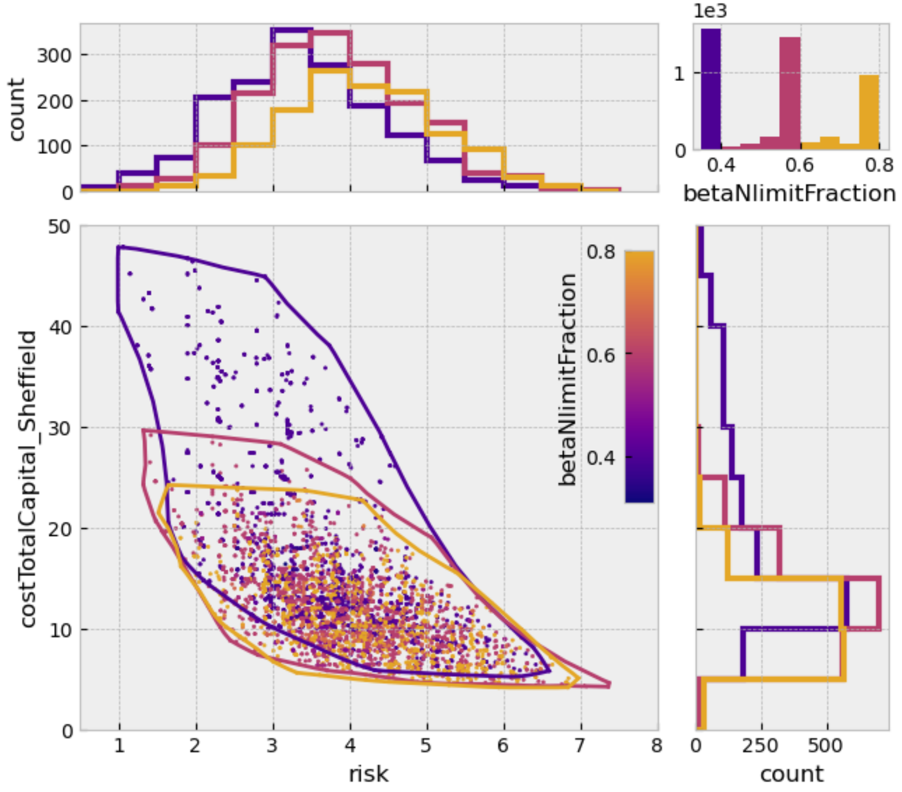


cost < $10B

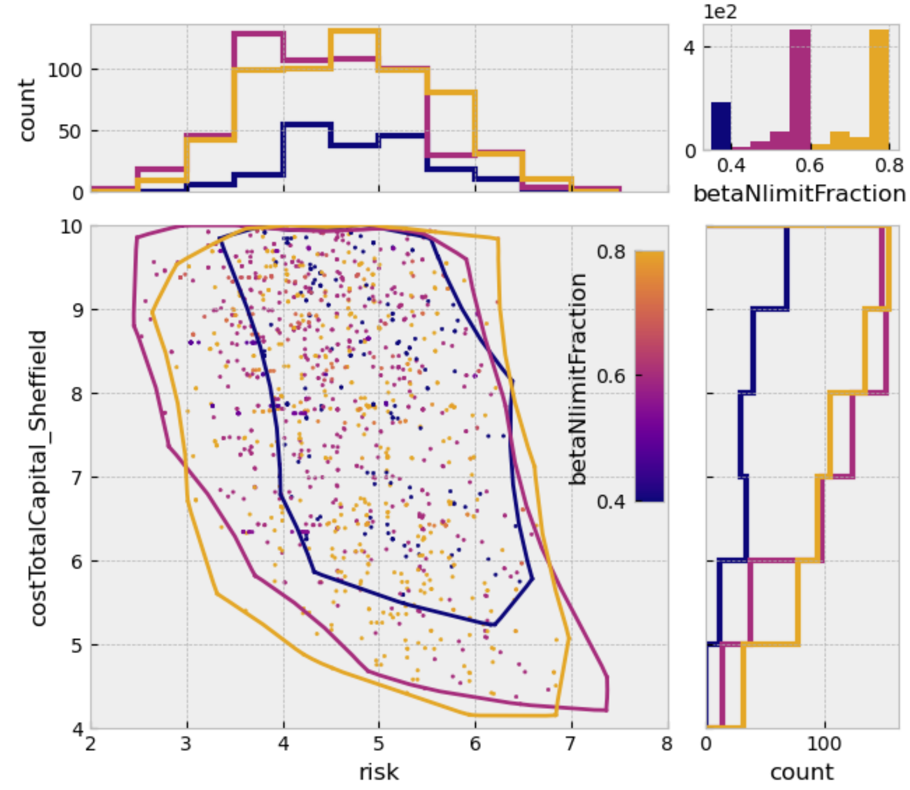


BetaN limit fraction

full dataset

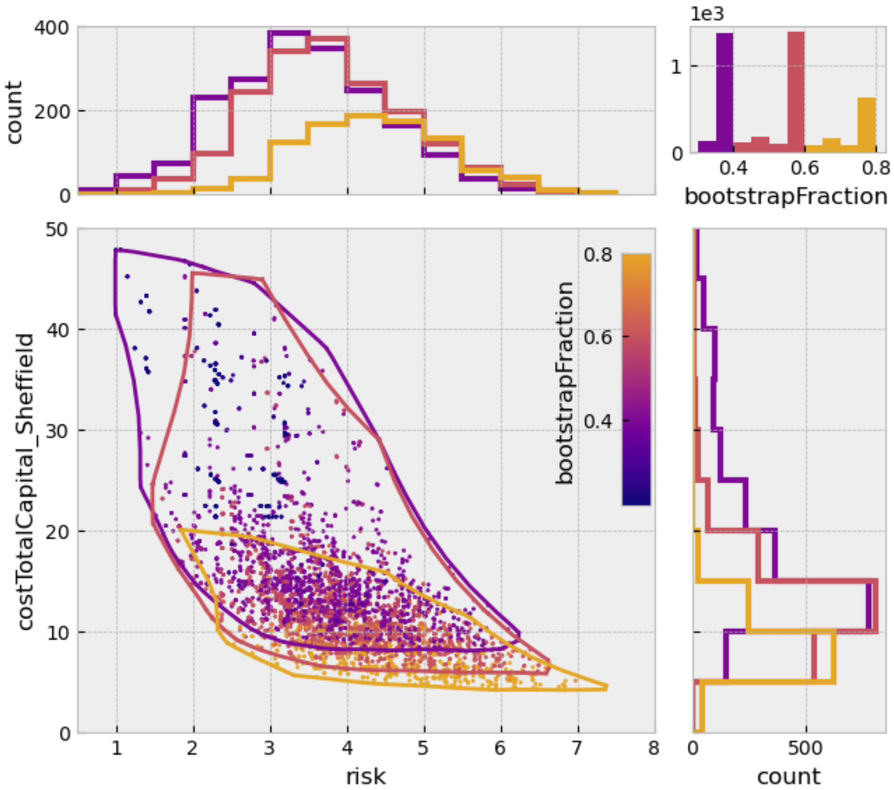


cost < $10B

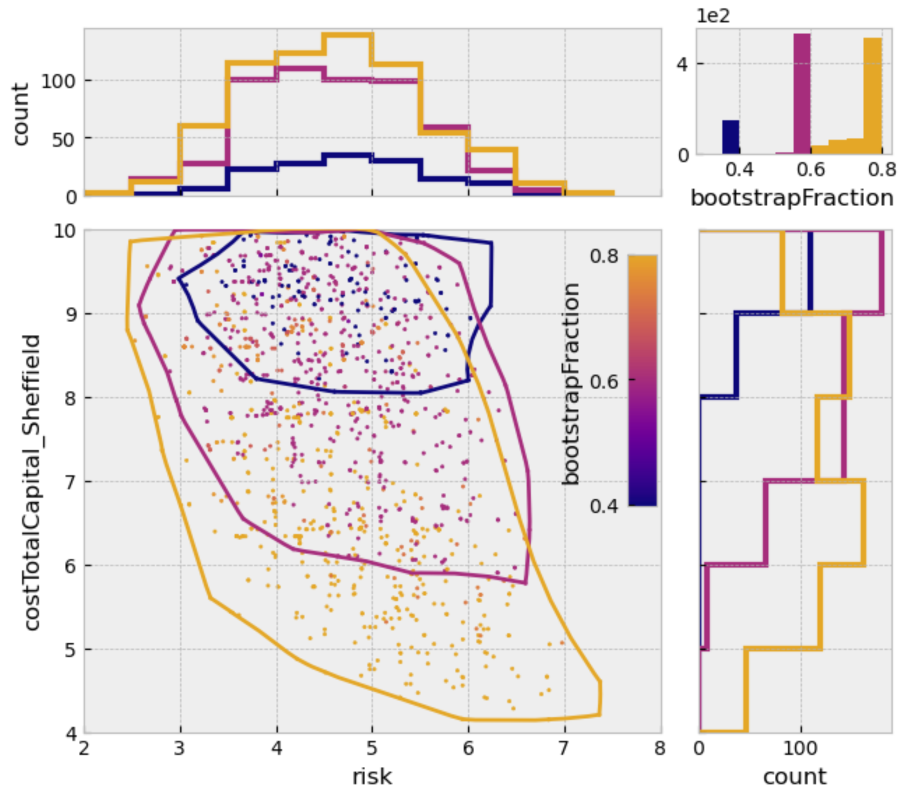


Bootstrap fraction

full dataset

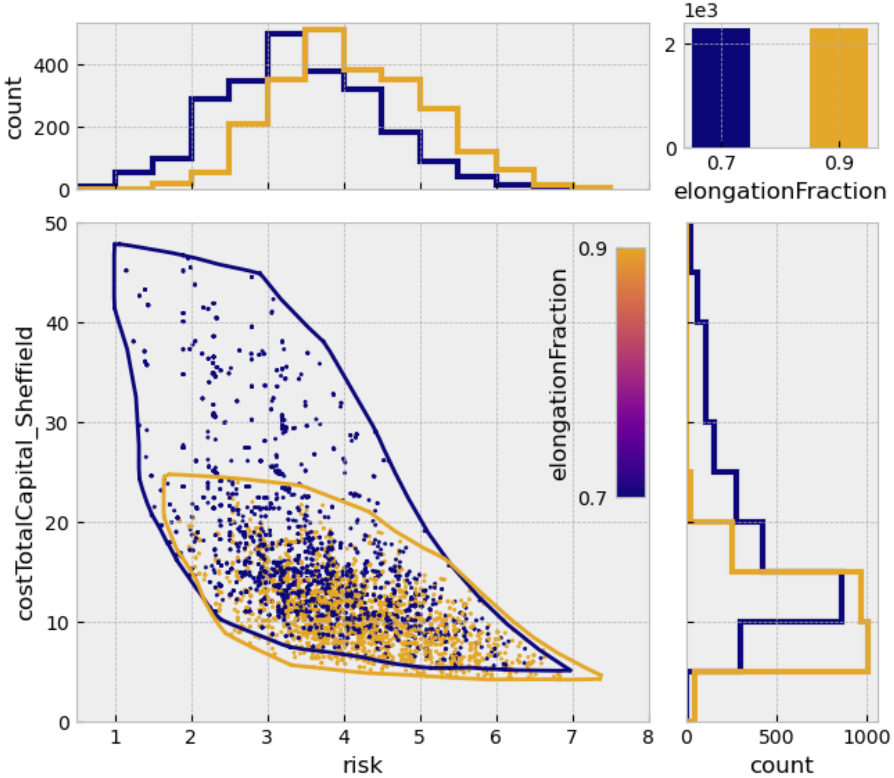


cost < $10B

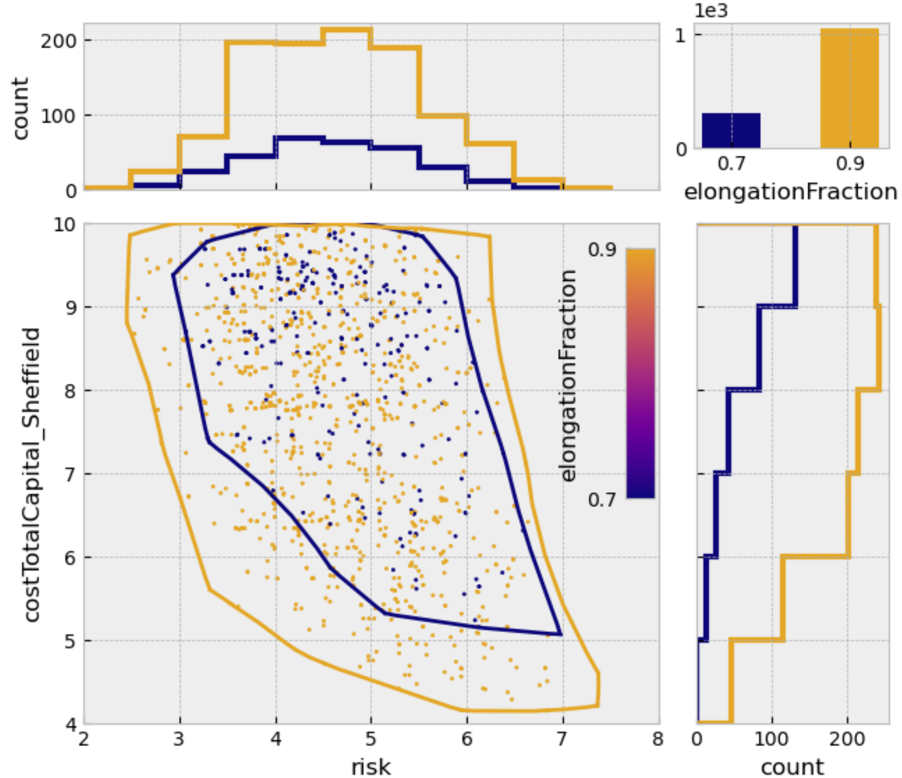


Elongation fraction

full dataset



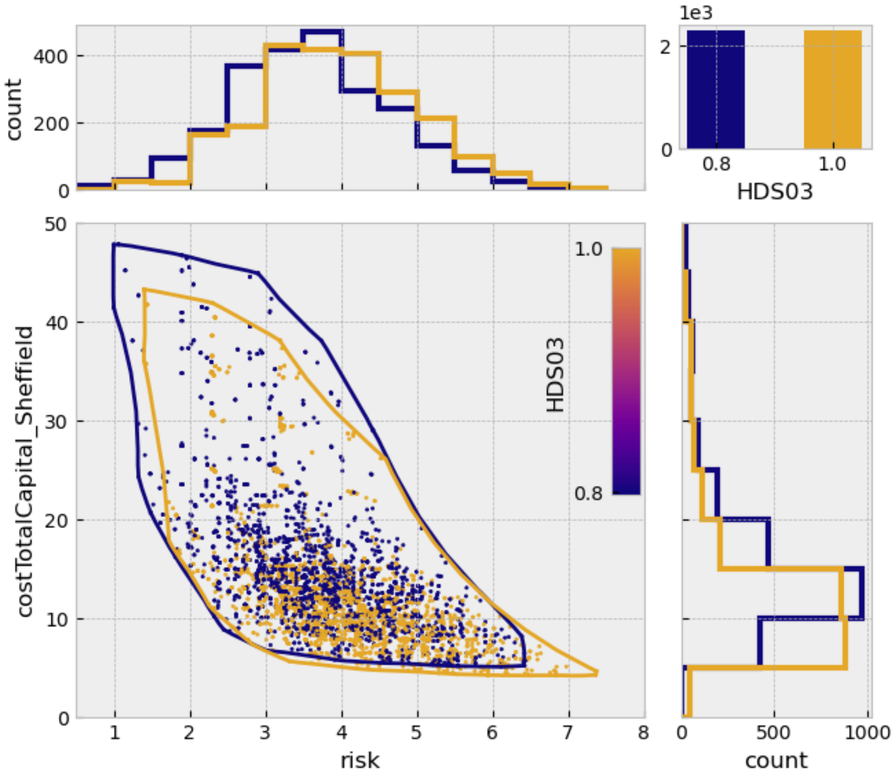
cost < $10B



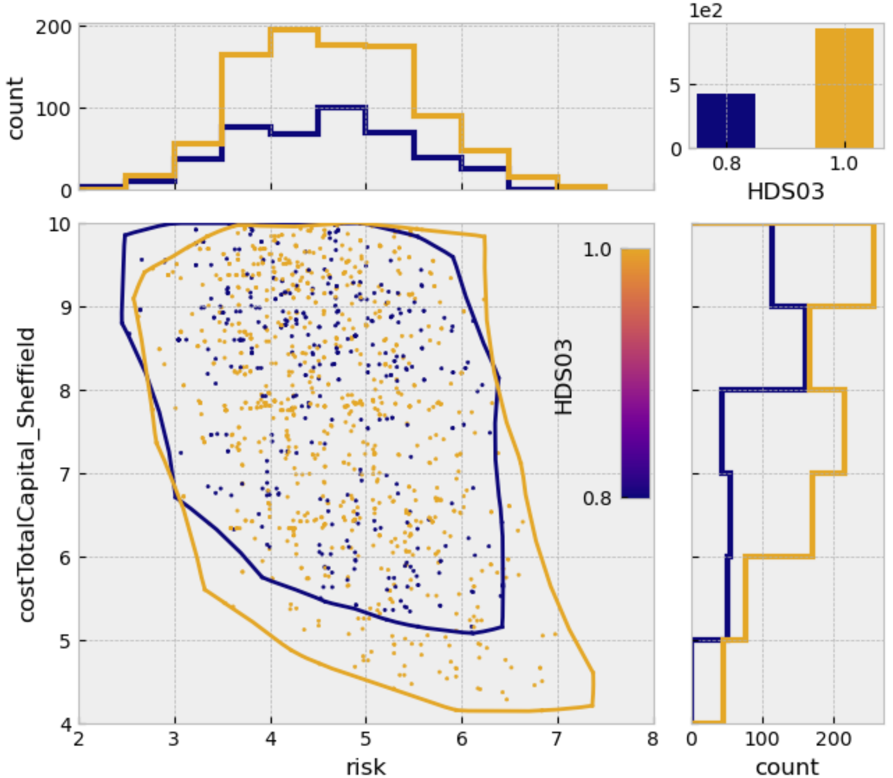
GENERAL ATOMICS

H_{DS03}

full dataset



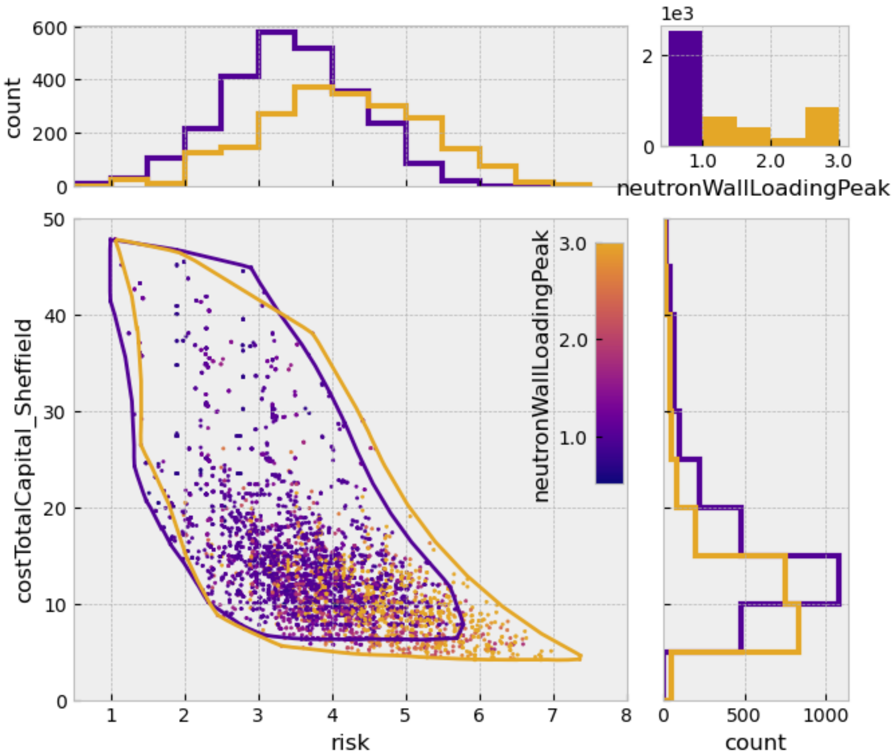
cost < $10B



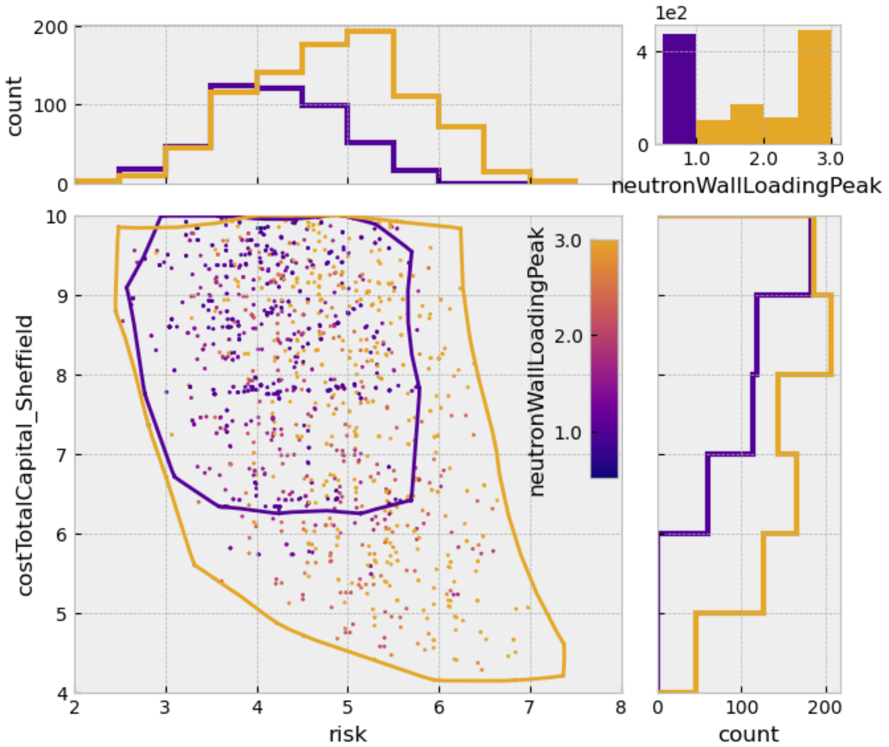
GENERAL ATOMICS

Peak neutron wall loading

full dataset

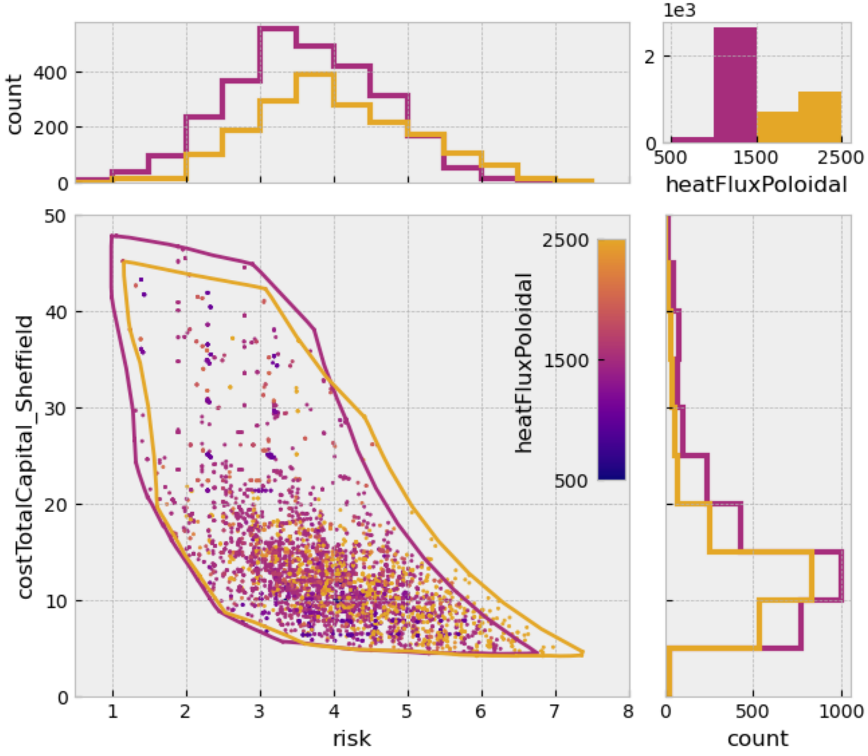


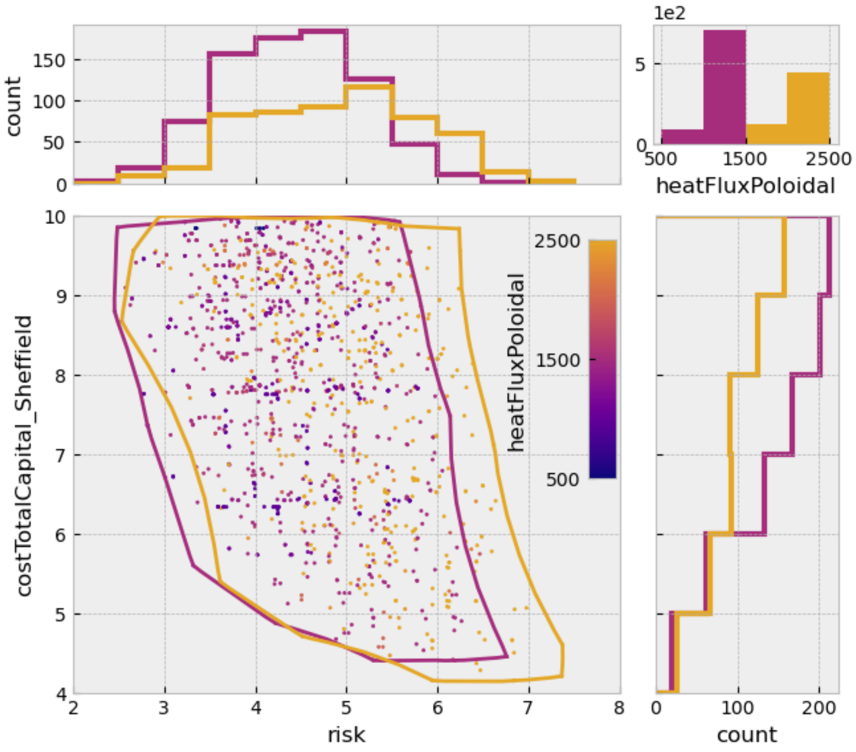
cost < $10B



GENERAL ATOMICS

Poloidal heat flux

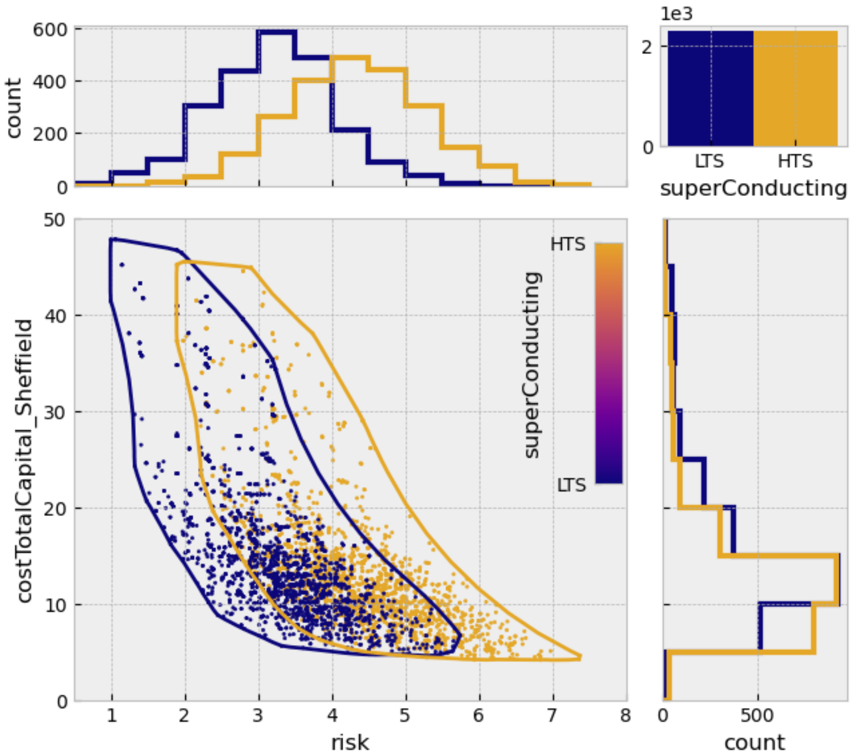




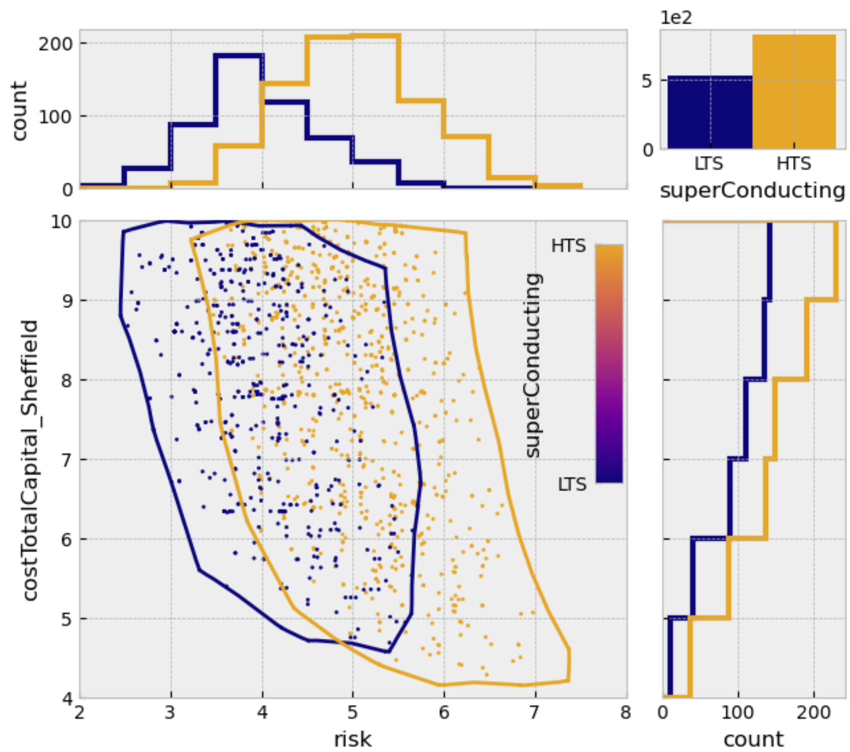
GENERAL ATOMICS

Superconductor type

full dataset



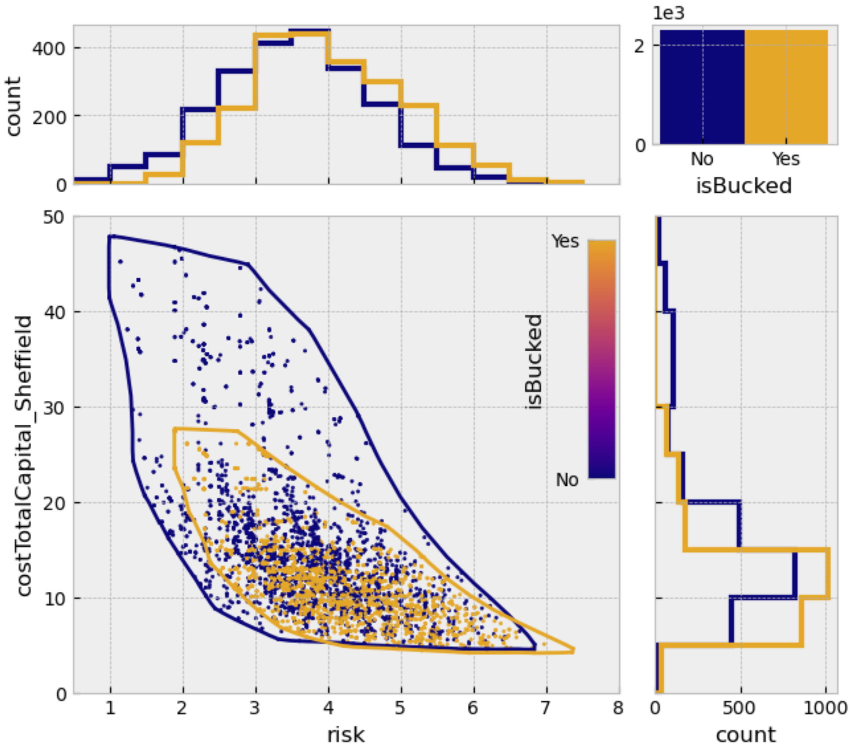
cost < $10B



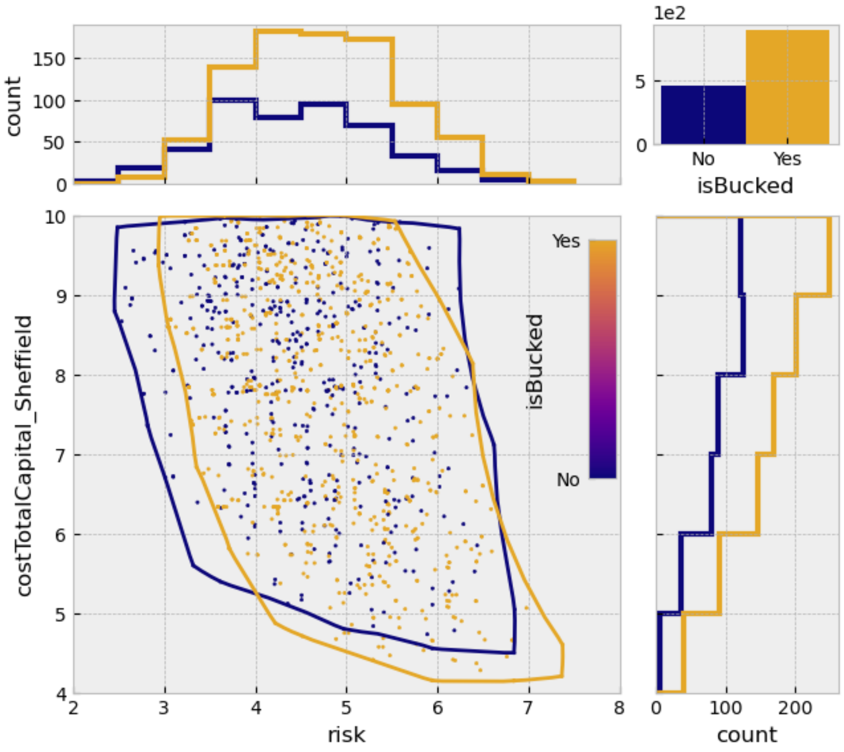
GENERAL ATOMICS

Freestanding vs. bucked coils

full dataset



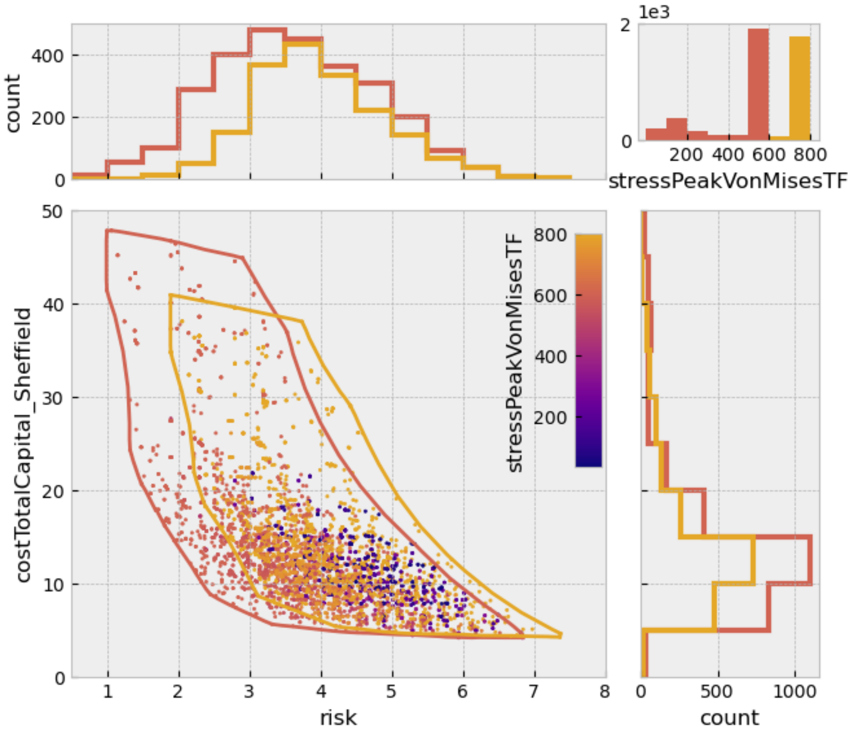
cost < $10B



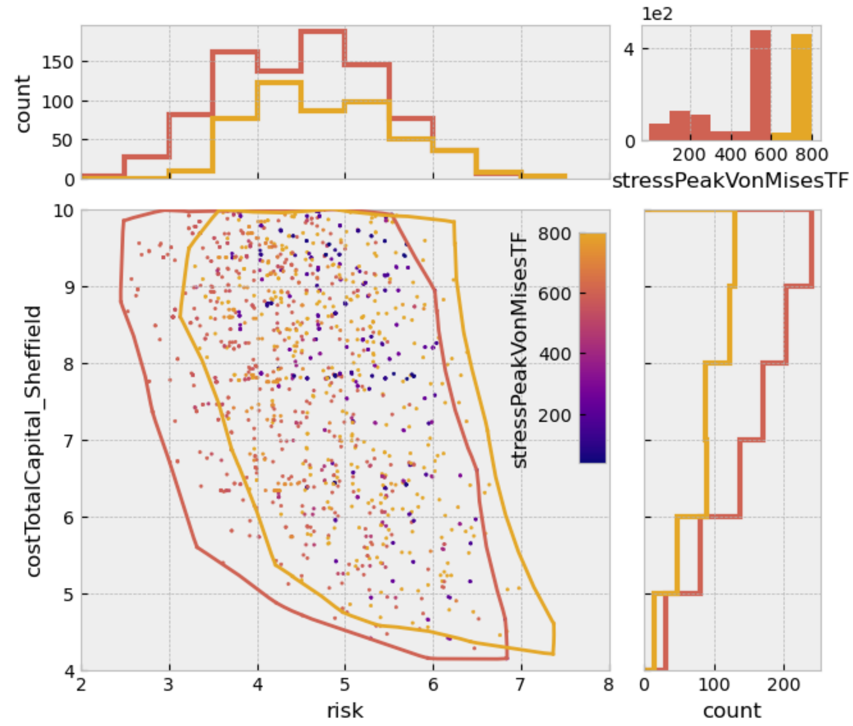
GENERAL ATOMICS

Peak coil stress (Von Mises)

full dataset



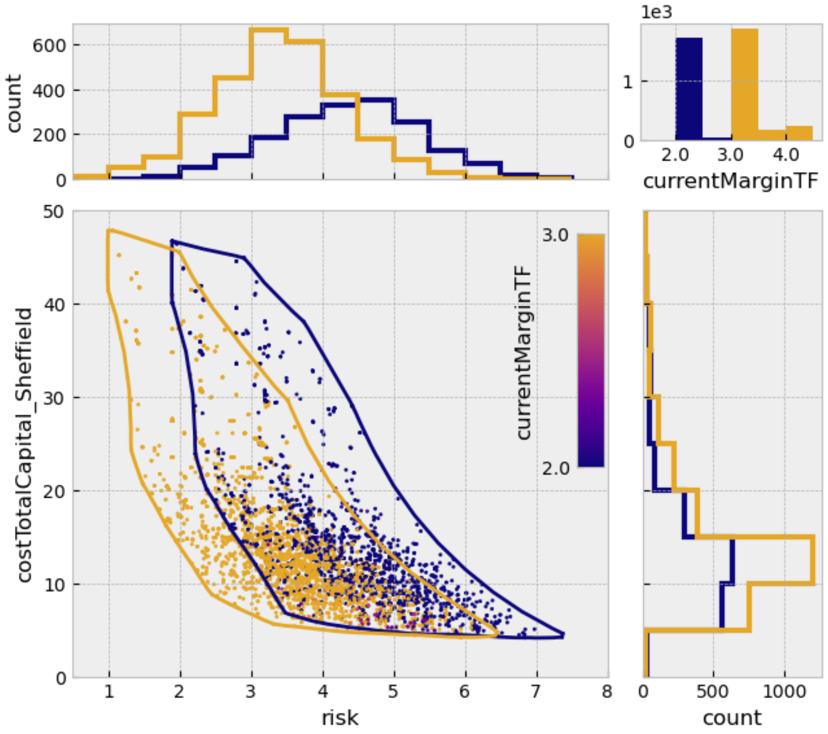
cost < $10B



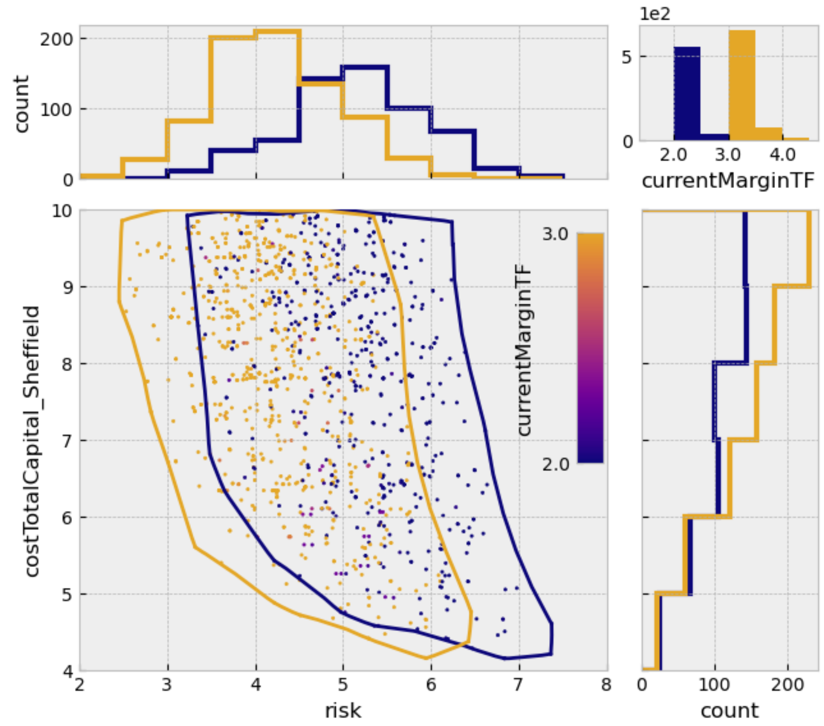
GENERAL ATOMICS

Coil current margin

full dataset



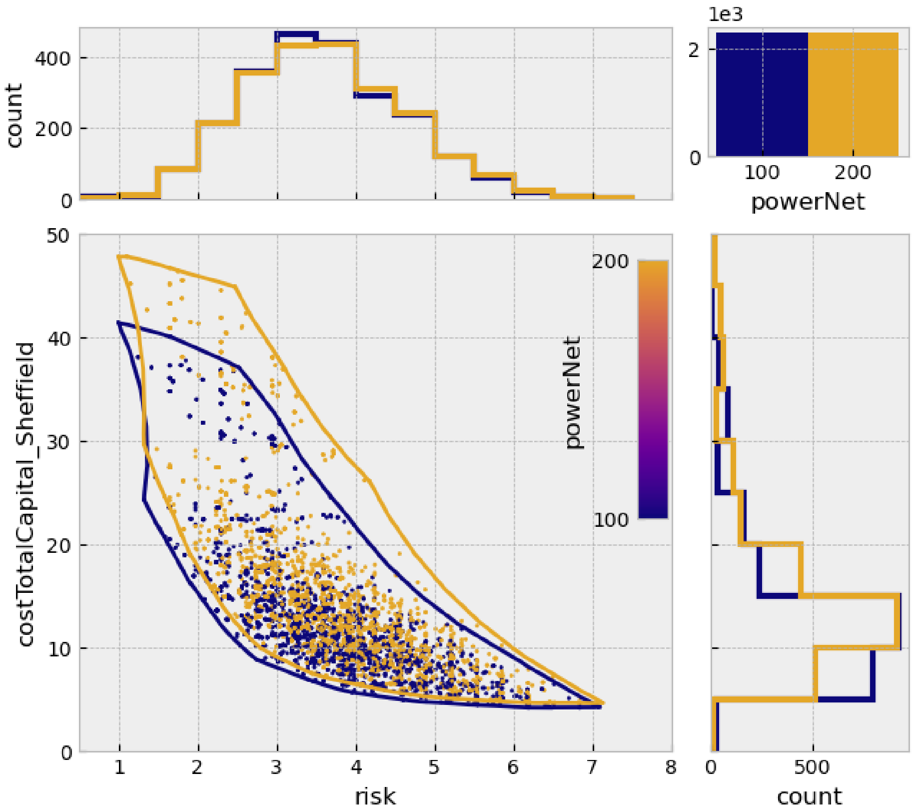
cost < $10B



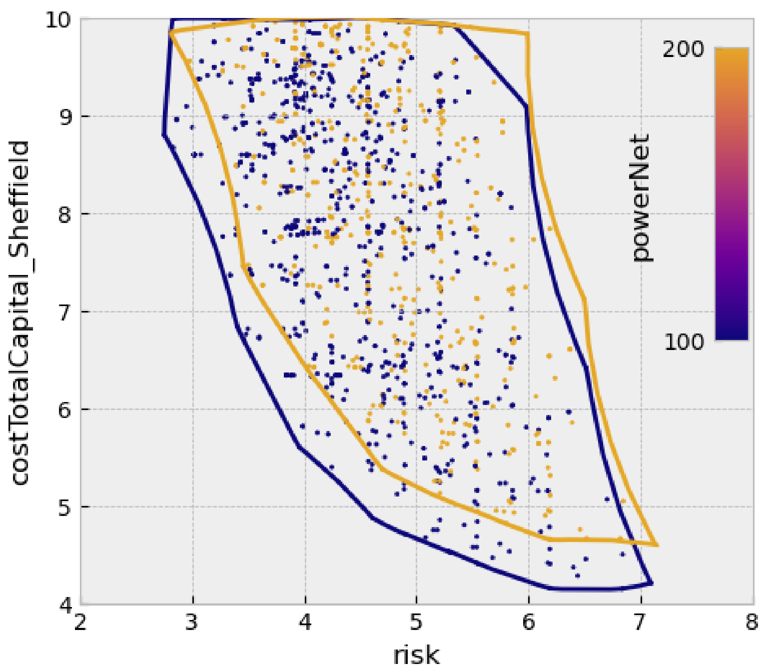
Alternate risk assessment definition

Alternate risk assessment definition

- What if all parameters are assigned to the same risk category: Medium (3)?
- Similar results, although less pronounced spread in risk at lower costs



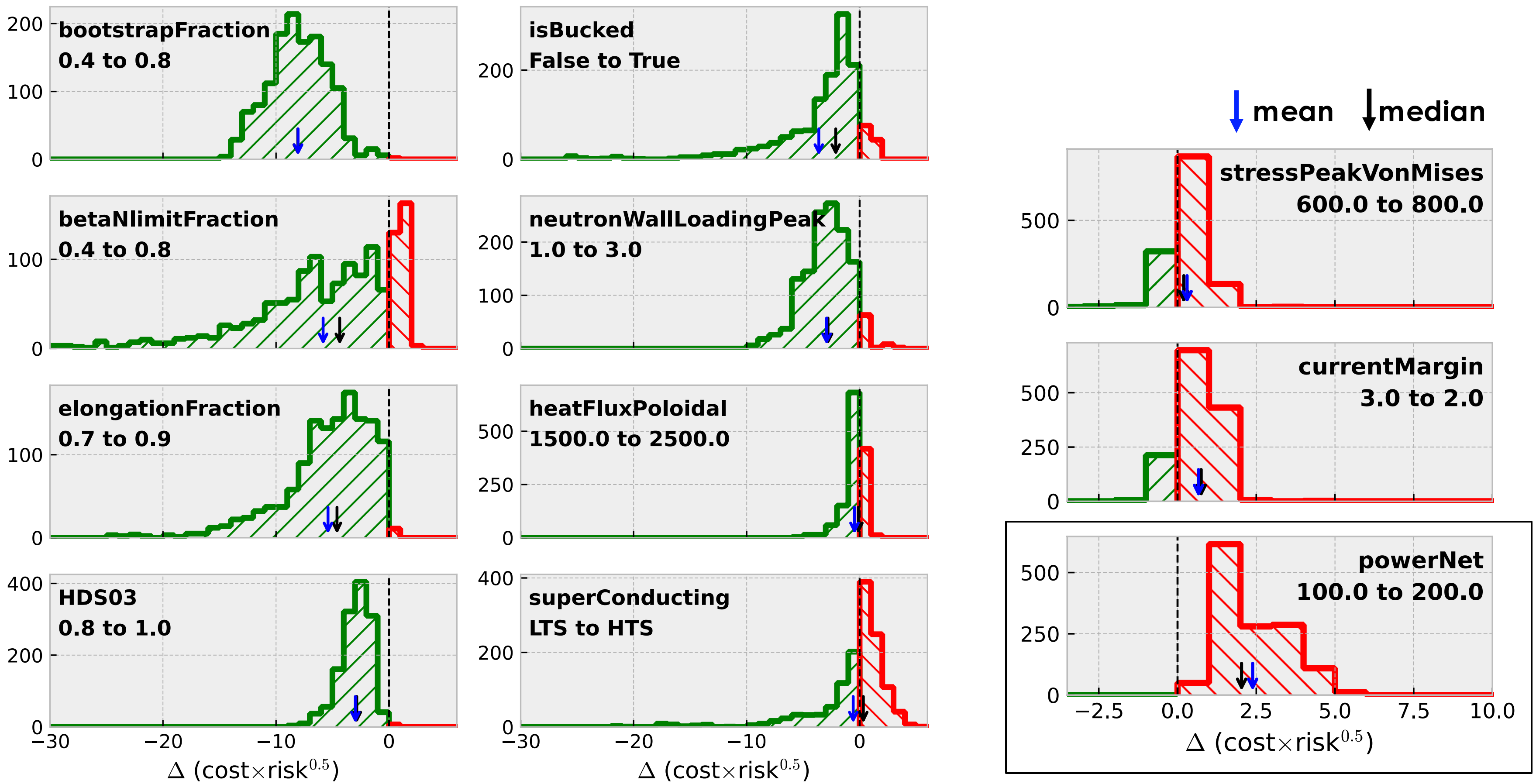
Cost < $10B



GENERAL ATOMICS

Alternate risk assessment definition

- No change in ordering of parameter effect on risk-cost metric
- Coil-related parameters become slightly more risk-cost effective



GENERAL ATOMICS