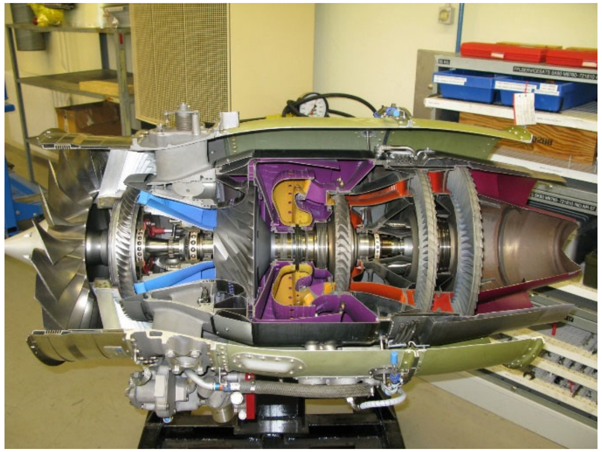
GT workshop 221129

Lund University

Full engine rig @ TFHS

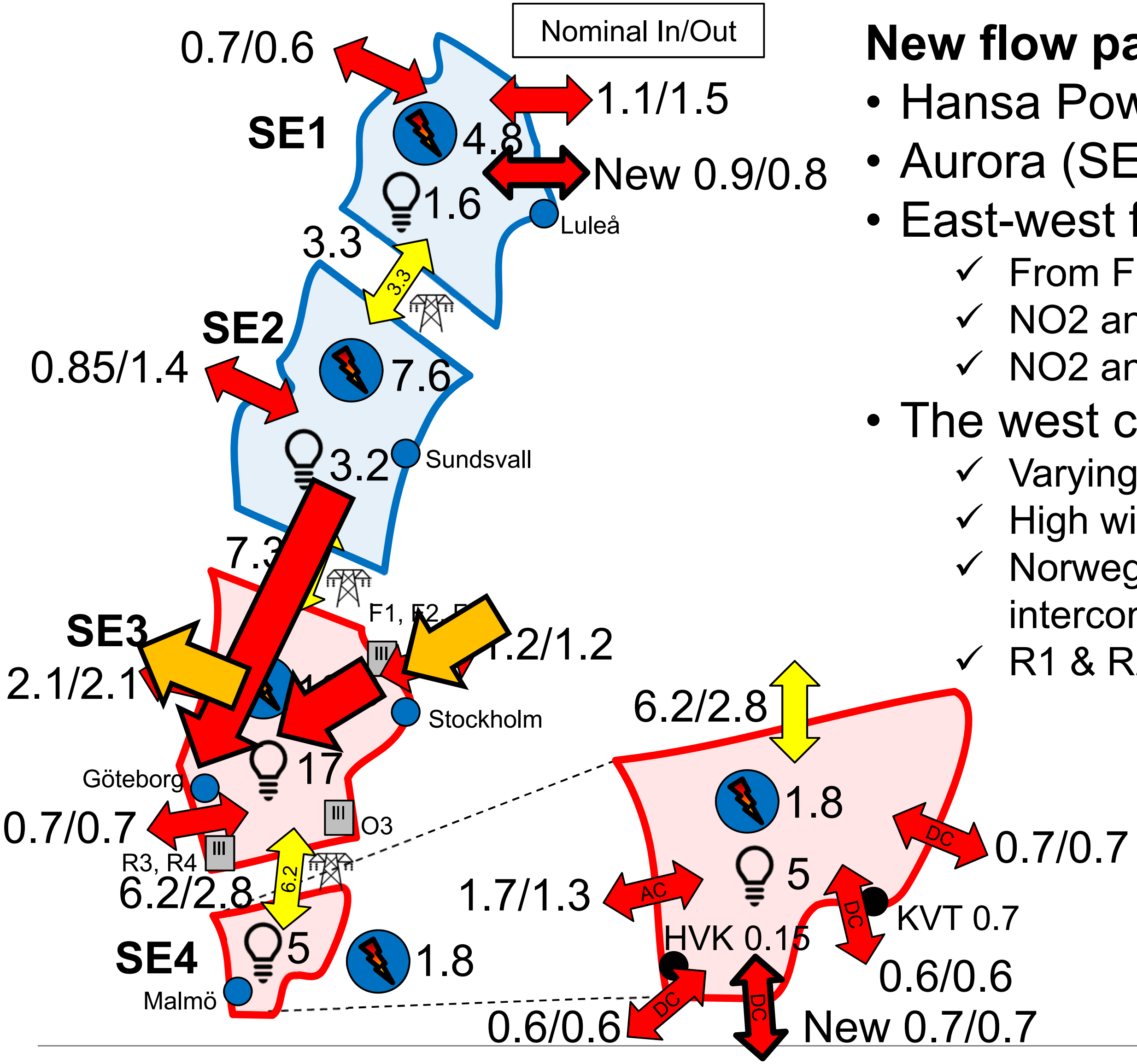
RM15



Agenda

- Nya maskiner
- Kostnader (LCOE)
- Bränslen
- Regelverk
- Gasturbin + BESS
- H-värde och FRT
- Service
- CCS

Production and transfer capacity I

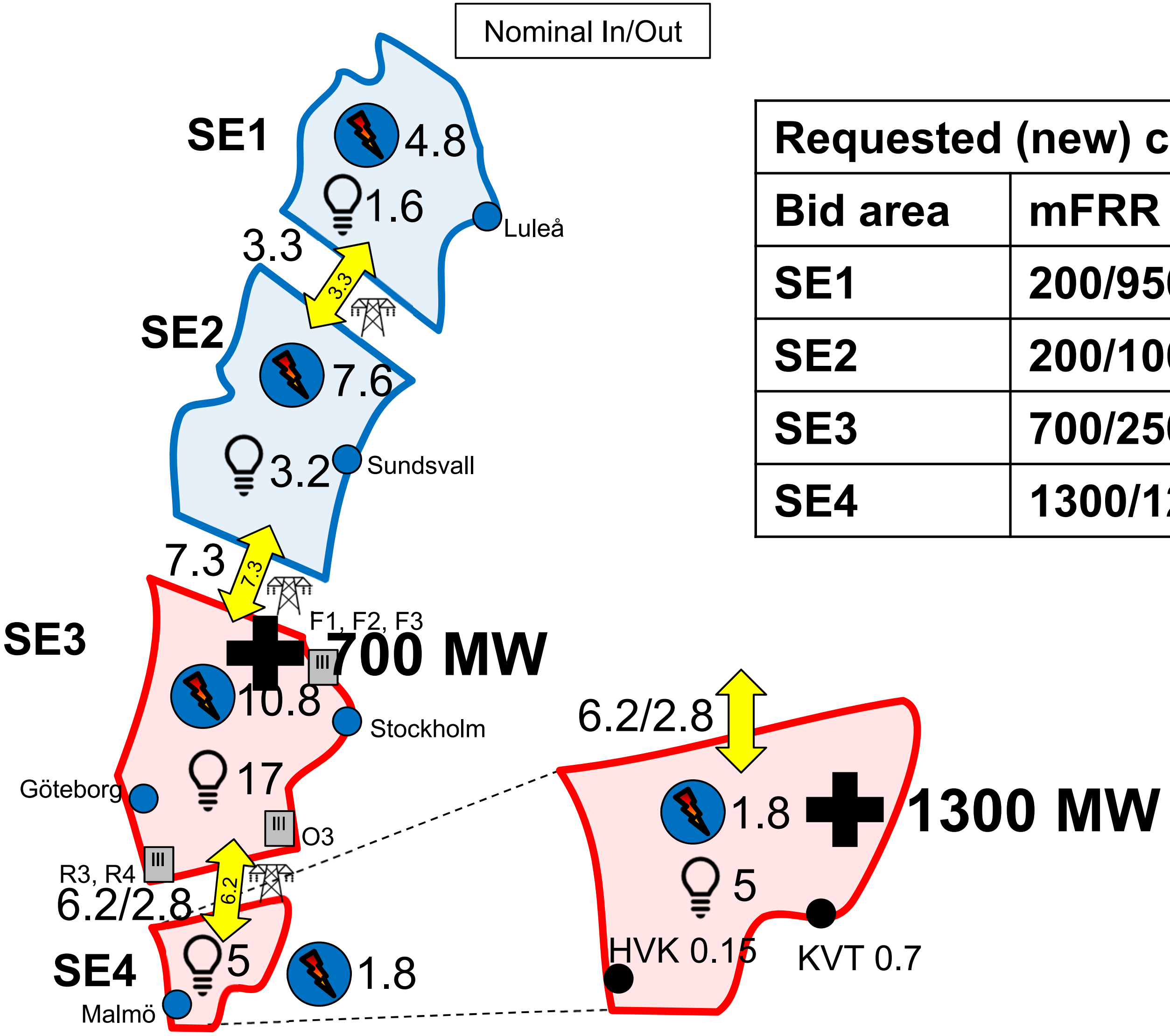


New flow patterns and scenarios!

- Hansa PowerBridge (SE4)
- Aurora (SE1)
- East-west flow (cf. R1 & R2)
  - ✓ From Finland…
  - ✓ NO2 and DE
  - ✓ NO2 and UK
- The west coast corridor
  - ✓ Varying demand
  - ✓ High wind with northbound flow
  - ✓ Norwegian hydro and new interconnectors
  - ✓ R1 & R2…

$$\frac{\sum \text{Export}_{@SE4}}{\text{Produktion}_{@SE4}} = \frac{3.2}{1.8} \approx 1.8$$

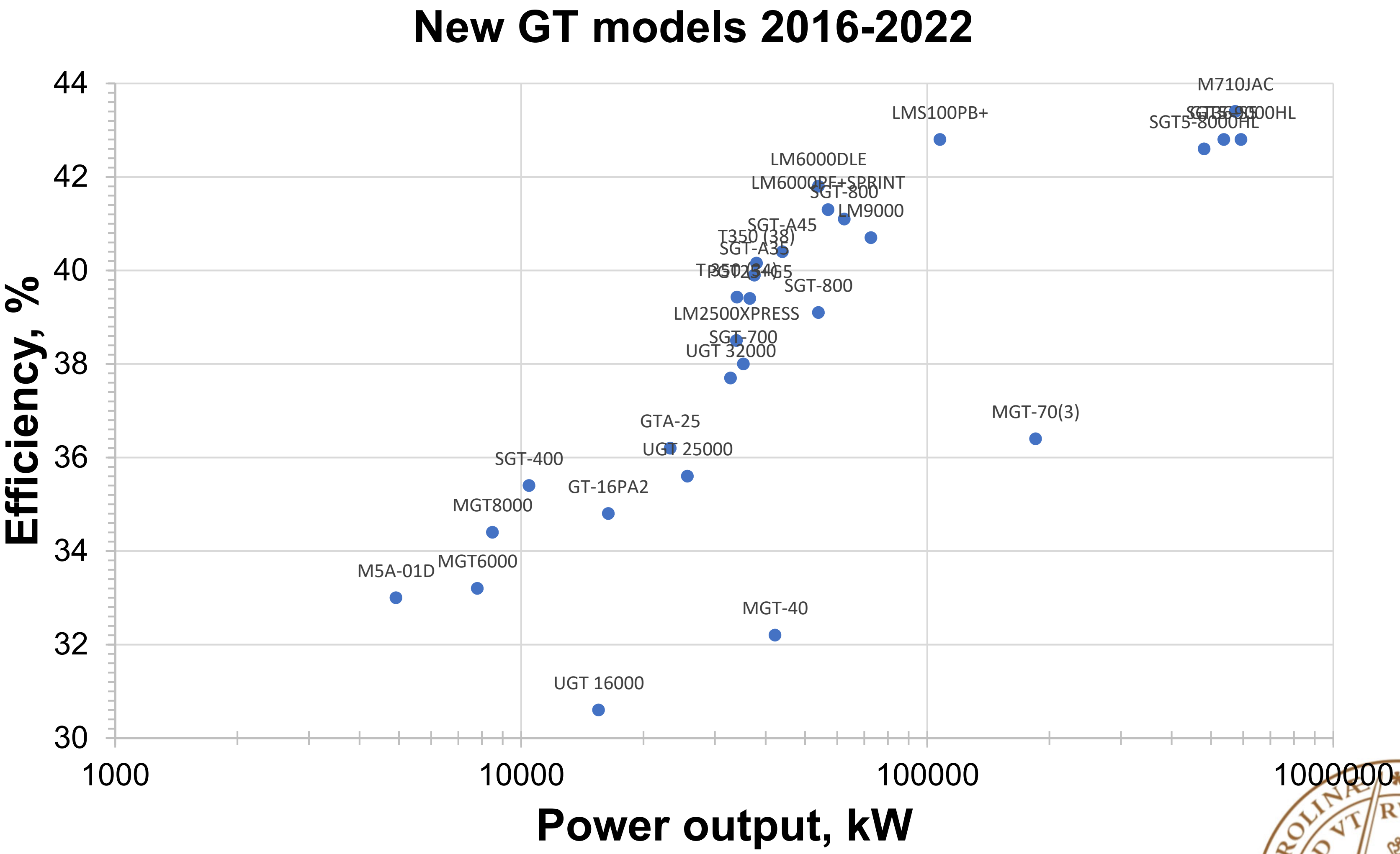
Production and transfer capacity II



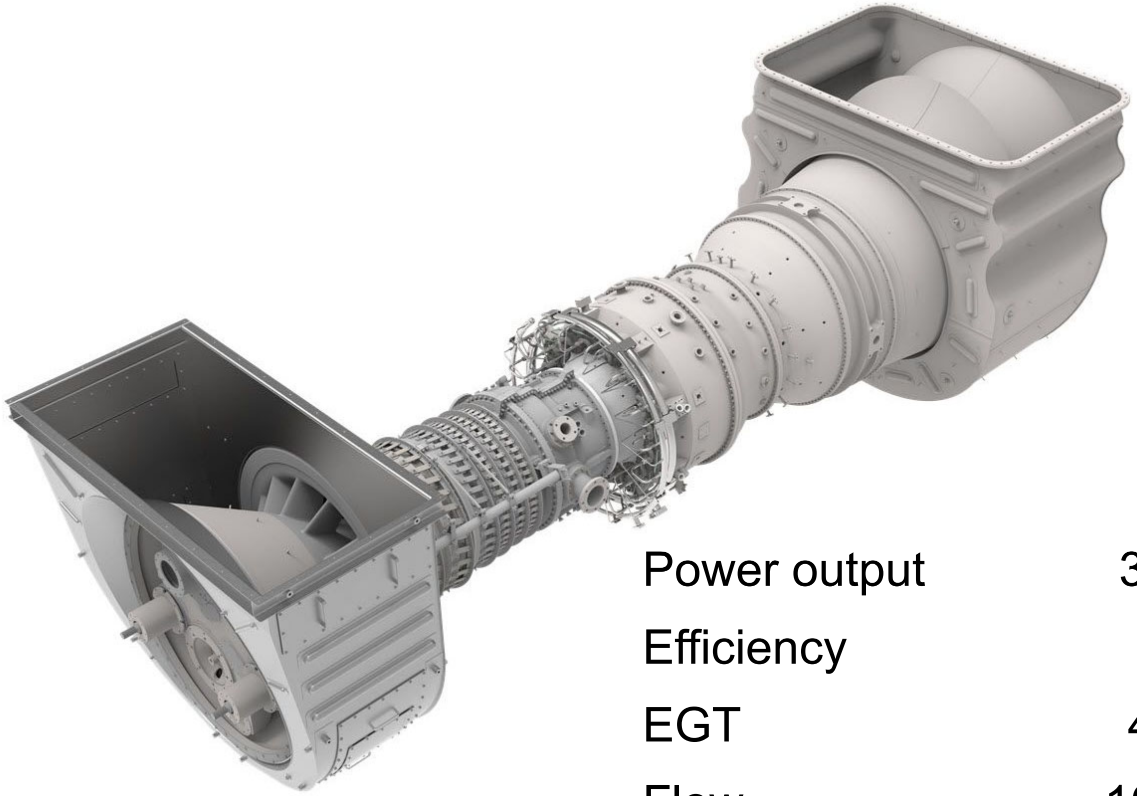
Requested (new) capacity [MW]:		
Bid area	**mFRR**	**aFRR**
SE1	**200/950**	**44/47**
SE2	**200/1000**	**44/47**
SE3	**700/250**	**47/48**
SE4	**1300/1250**	**48/47**

up/down

New engines 2016-2022



Notable new engines’ – the Titan 350

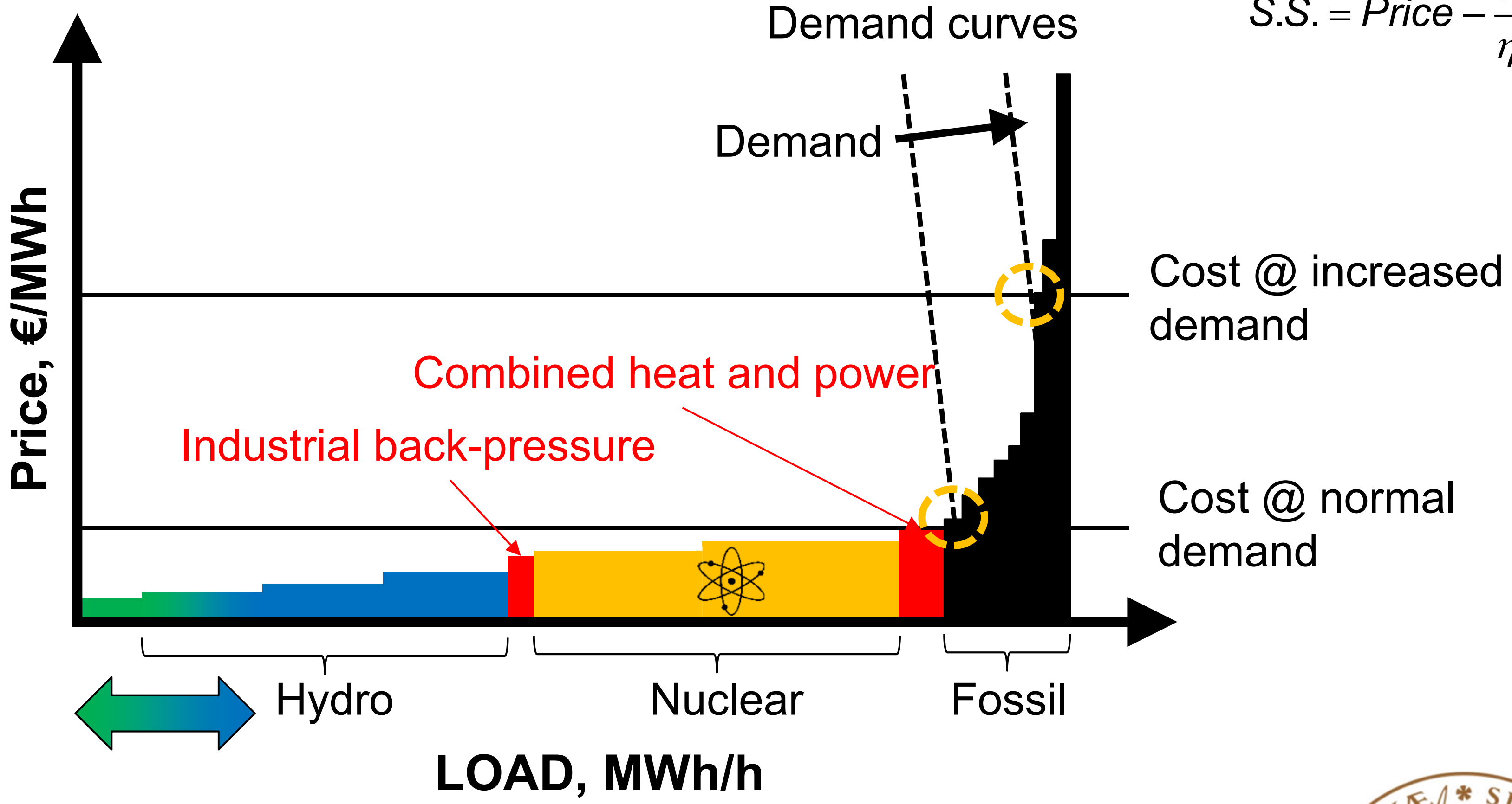


	Titan 350	
Power output	35 MW	39 MW
Efficiency	41 %	41 %
EGT	460°C	490°C
Flow	103 kg/s	108 kg/s
Spec power	339 kWs/kg	362 kWs/kg

Levelized cost of electricity

Spark spread:

$$S.S. = Price - \frac{f}{\eta}$$



Demand curves

Demand

Cost @ increased demand

Cost @ normal demand

Combined heat and power

Industrial back-pressure

Price, €/MWh

Hydro

Nuclear

Fossil

LOAD, MWh/h

Figure based on Energimarknadsinspektionen

- No wind/PV displays production curve to the left
- Low dam levels may cause a swap between hydro and nuclear!

Cost of Electricity – COE

COE = CAPEX + OPEX

$$COE = \underbrace{\frac{\beta \cdot CAPEX}{P \cdot H}}_{\text{Capital}} + \underbrace{\underbrace{\frac{f}{\eta}}_{\text{Fuel}} + \underbrace{\left\{ \frac{OM_{fix}}{P \cdot H} + \mu \cdot OM_{var} \right\}}_{\text{Maintenance}}}_{\text{Operation}} \quad \left[\frac{money\ unit}{kWh} \right]$$

$$COE = \frac{\beta \cdot CAPEX}{P_{eff} \cdot H_{eff}} + \frac{f}{\eta_{eff}} + \left\{ \frac{OM_{fix}}{P \cdot H} + \mu \cdot OM_{var} \right\} + \underbrace{\sum_{i=1}^{n} \left(c_i \cdot m_{p,i} \right)}_{\text{Emissions}} + \underbrace{\frac{S_c \cdot \Delta P + S_e \cdot \Delta E}{P_{eff} \cdot H_{eff}}}_{\text{Replacement capacity}}$$

Where:

$$\beta(i,N) = \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right]$$

10 percent interest rate (i) and 25 years (N) gives β = 0.11

$$f = \underbrace{f_0 \cdot k}_{USD/MMBtu} \cdot \underbrace{0.947817 \cdot 10^{-3}}_{[MMBtu/MJ]} \cdot \underbrace{3.6}_{[MJ/kWh]} = \frac{f_0 \cdot k}{293.071} \quad [USD/kWh]$$

$$\frac{CAPEX}{P} \approx (1.6 \ldots \mathbf{1.8} \ldots 2.0) \cdot \begin{cases} S/C : 3968 \cdot P^{-0.077} - 1313 & [USD/kW] \\ GTCC : 265 + 5.19 \cdot 10^4 \cdot P^{-0.36} \end{cases}$$

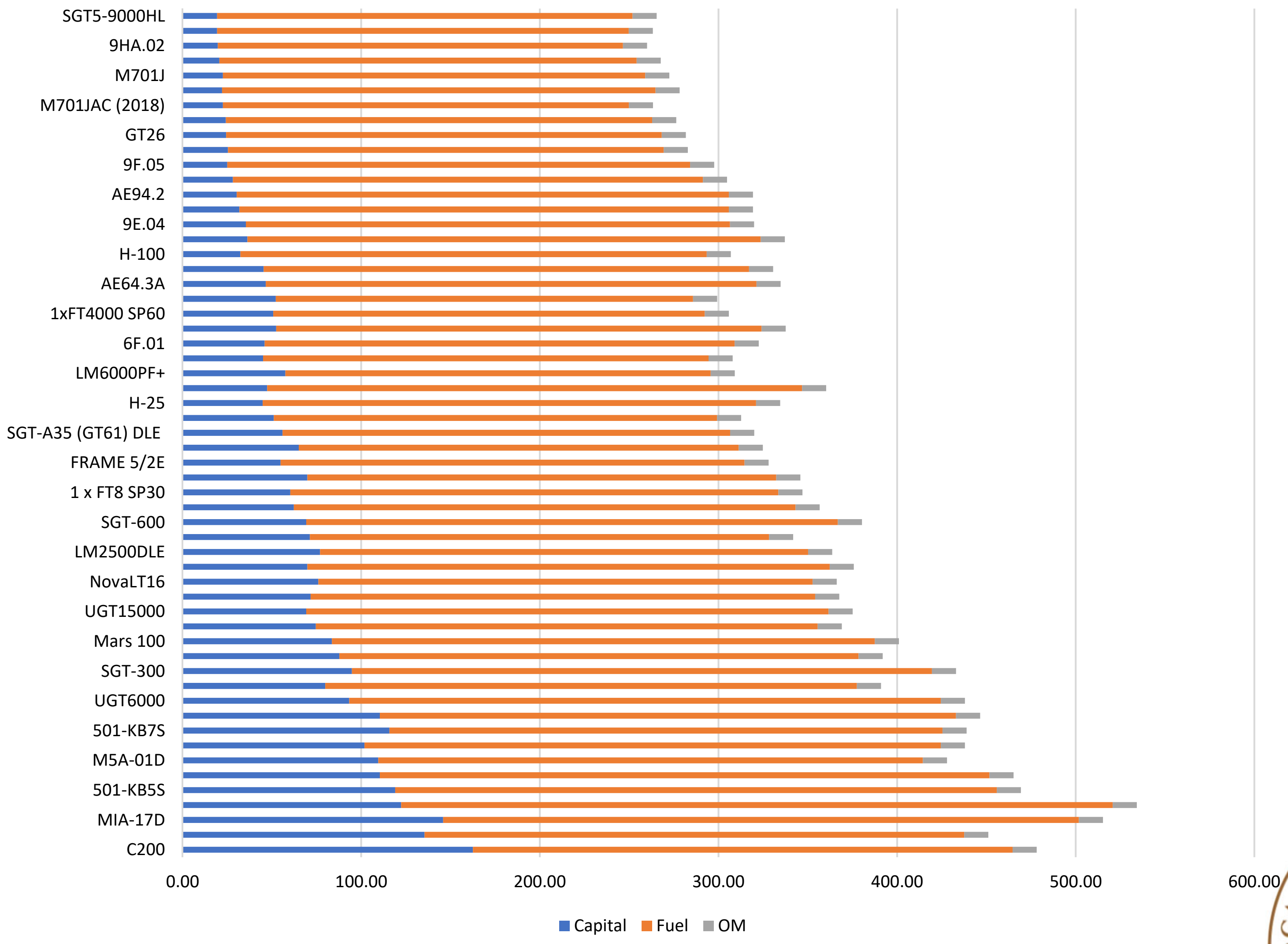
$$OM_{var} \approx (3.0 \ldots 3.5 \ldots 5.0) \cdot 10^{-3} \quad [USD/kWh]$$

$$OM = \underbrace{10 \ldots 16 \quad [USD/kW_{installed}]}_{per\ annum} + (3.5 \ldots 5.0) \cdot 10^{-3} \quad [USD/kWh]$$

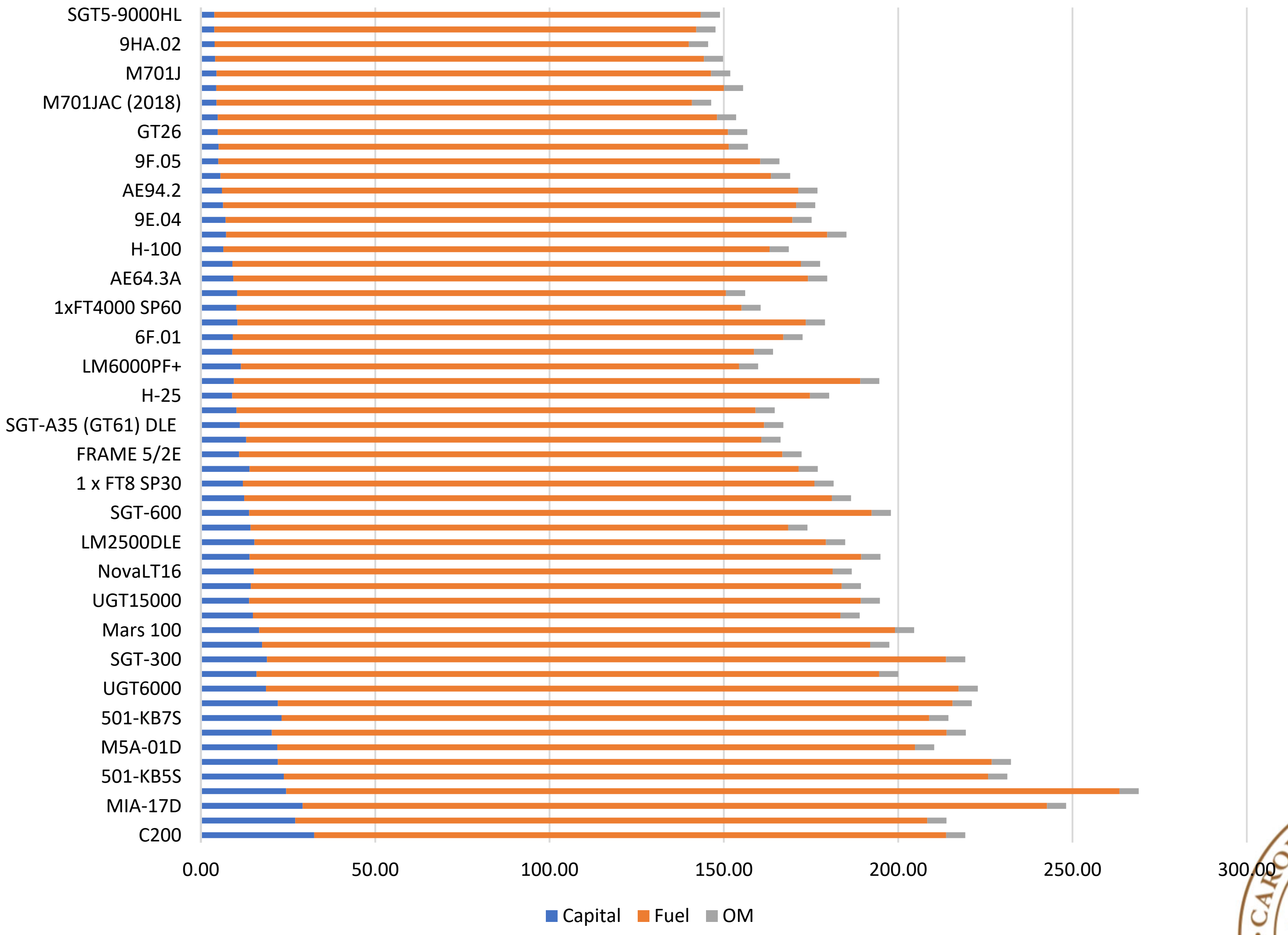
CAPEX	Capital Expenditure
β	Annuity factor
P	Power
H	Annual operating hours
f	Fuel cost [USD/kWh]
i	Interest rate
N	Number of years
OM_{fix}	Fixed OM-spending [USD]
OM_{var}	Variable OM-spending [USD/kWh]

N.B. All OM costs are engine dependent! One may (typically) expect a service cost equivalent to a new engine during 80,000 operating hours. The total service market will exceed 41 BUSD 2025!

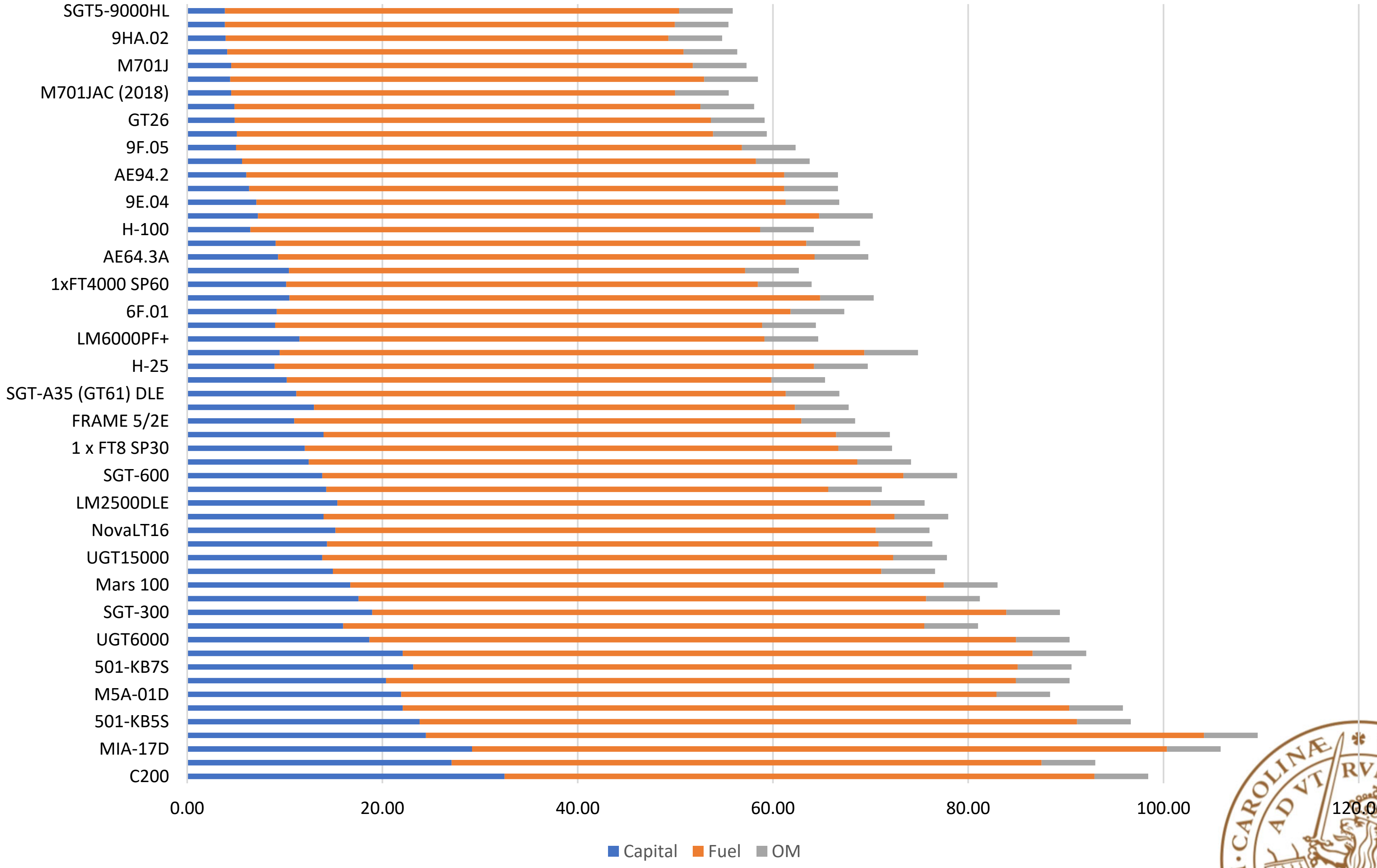
LCOE – 1000 h/a, 25 years, 100 USD/MWh



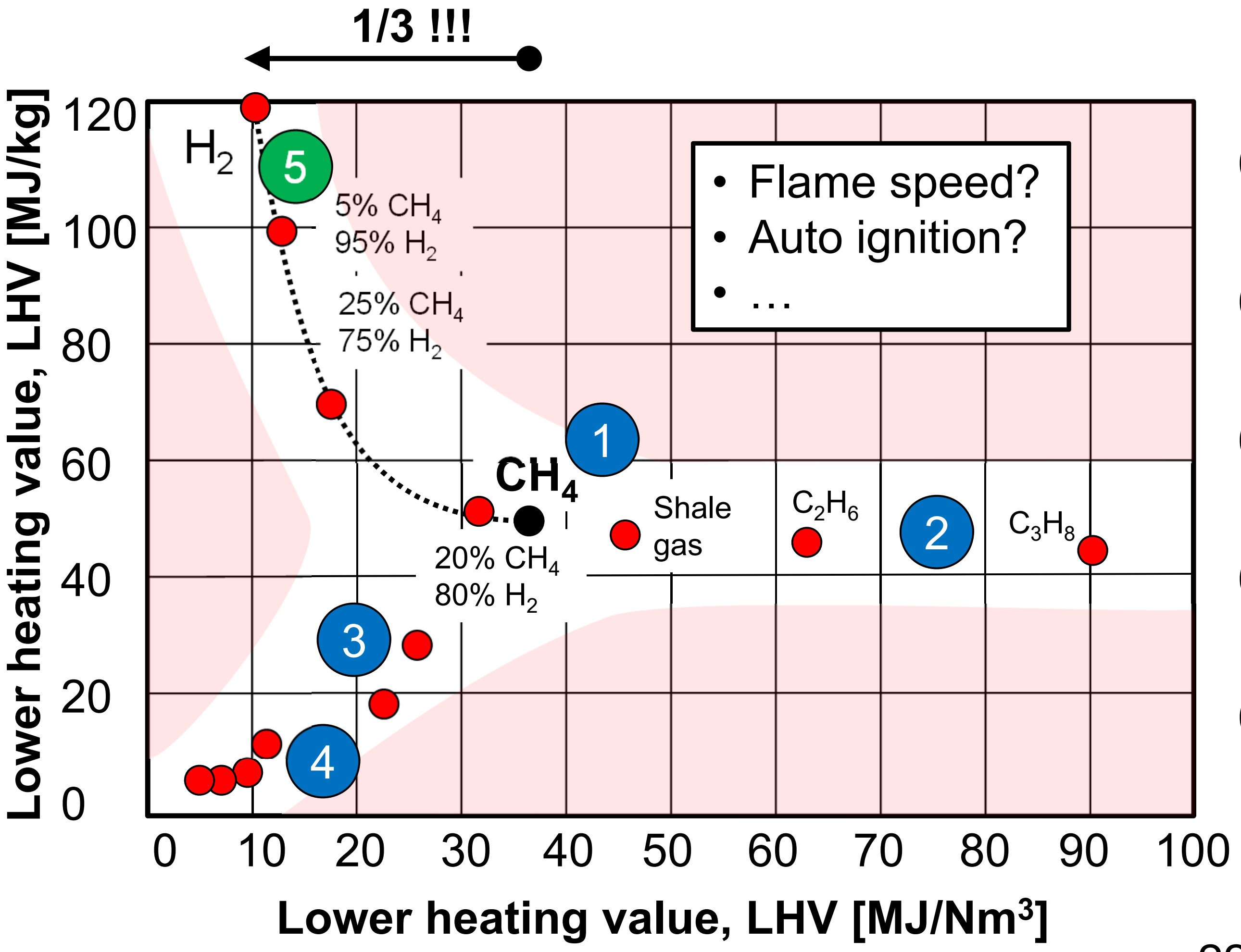
LCOE – 5000 h/a, 25 years, 60 USD/MWh



LCOE – 5000 h/a, 25 years, 20 USD/MWh



Fuel properties – gaseous fules



① Natural gas, LNG, Shale

② Higher hydro carbons, $C_nH_{2+2 \cdot n}$

③ Less methane fuels

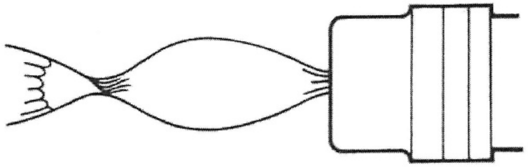
④ Low-LHV, syngas, steel mill, etc.

⑤ Hydrogen and blends

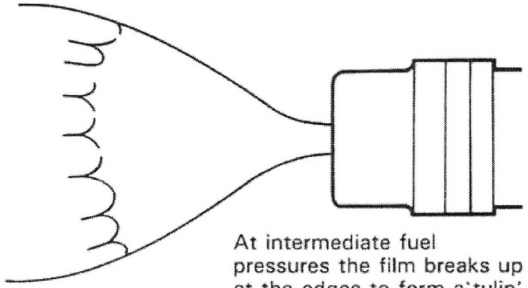
22.7 MJ/kg

Basic liquid burner

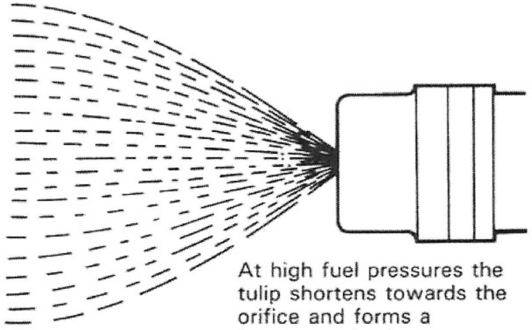
Simplex



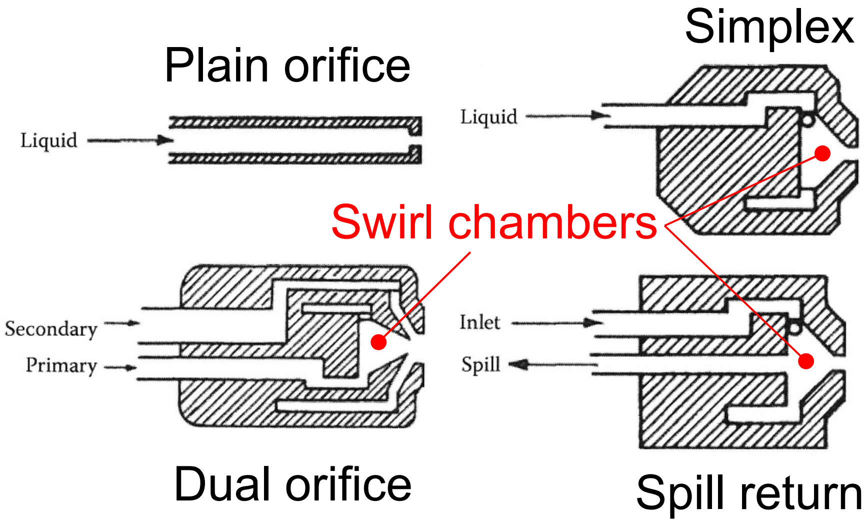
At low fuel pressures a continuous film of fuel is formed known as a 'bubble'



At intermediate fuel pressures the film breaks up at the edges to form a 'tulip'



At high fuel pressures the tulip shortens towards the orifice and forms a finely atomized spray



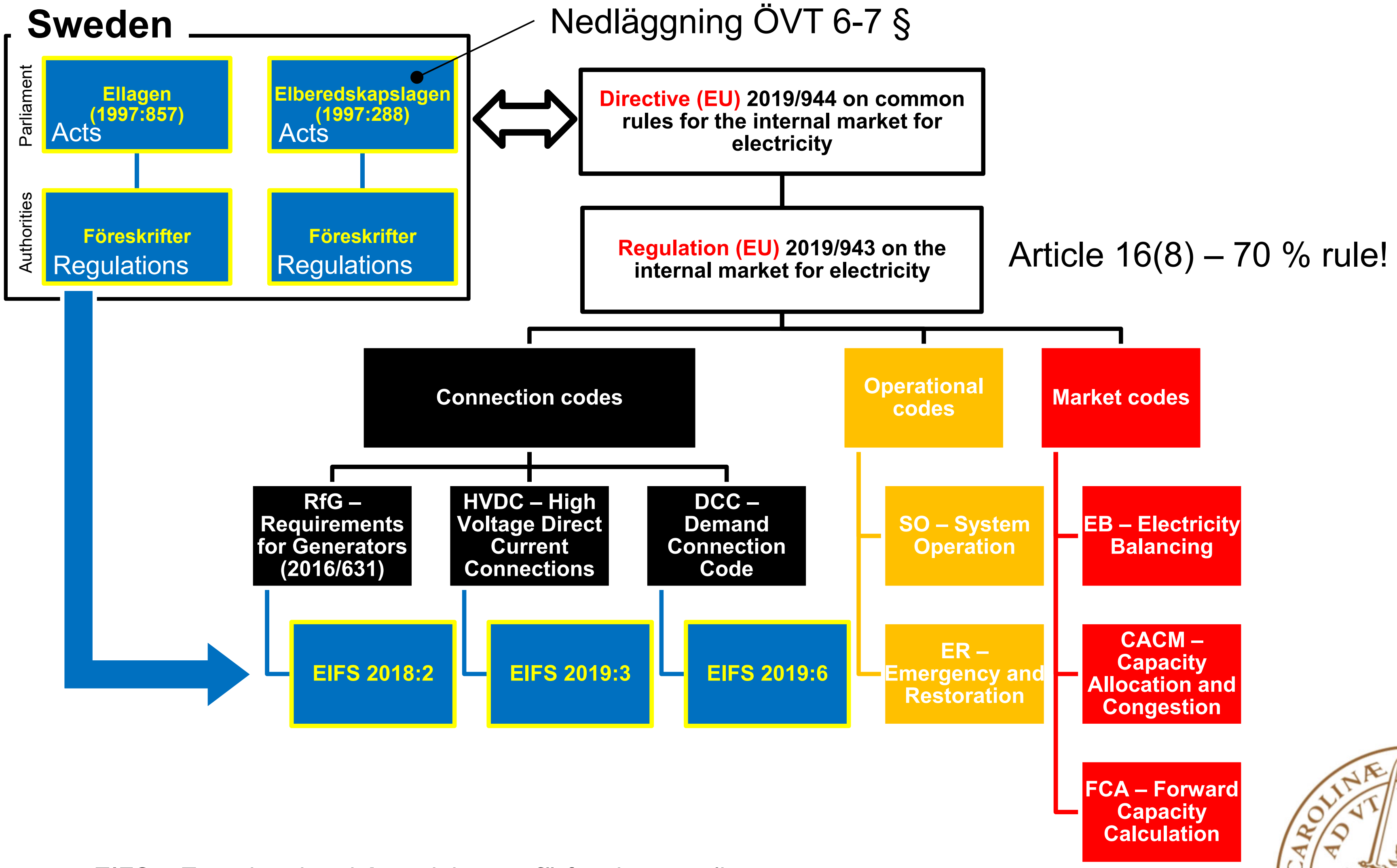
$$v \cong \varphi \cdot \sqrt{2 \cdot \frac{\Delta p}{\rho}}$$

$$\dot{m}_F \cong \sqrt{\rho \cdot 2 \cdot \Delta p} \cdot C_D \cdot A_{eff} =$$

$$= 1.11 \cdot \sqrt{\rho \cdot 2 \cdot \Delta p} \cdot C_D \cdot d_0^2$$

$$\frac{\Delta \dot{m}_F}{\dot{m}_F} \cong \frac{1}{2}\frac{\Delta p}{p} + 2\frac{\Delta d_0}{d_0} + \ldots$$

Regulatory framework – EU and Sweden



Sweden

Nedläggning ÖVT 6-7 §

Parliament

Ellagen (1997:857)
Acts

Elberedskapslagen (1997:288)
Acts

Authorities

Föreskrifter
Regulations

Föreskrifter
Regulations

Directive (EU) 2019/944 on common rules for the internal market for electricity

Regulation (EU) 2019/943 on the internal market for electricity

Article 16(8) – 70 % rule!

Connection codes

RfG – Requirements for Generators (2016/631)

HVDC – High Voltage Direct Current Connections

DCC – Demand Connection Code

EIFS 2018:2

EIFS 2019:3

EIFS 2019:6

Operational codes

SO – System Operation

ER – Emergency and Restoration

Market codes

EB – Electricity Balancing

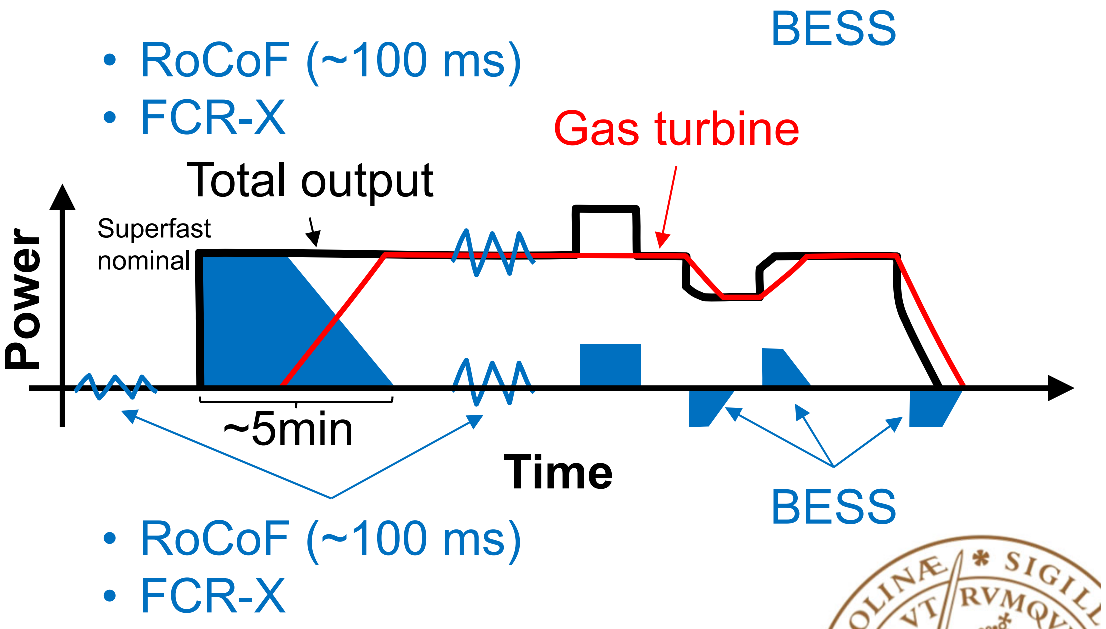
CACM – Capacity Allocation and Congestion

FCA – Forward Capacity Calculation

EIFS – **E**nergimarknads**i**nspektionens **f**örfattnings**s**amling

Gas turbine + BESS

- Combines FFR, FCR-X, and FRR
- Offers fast response (FFR) and persistent continuous operation (FRR)
- Fast hit 'n' runs without firing the gas turbine
- Size of battery?
- All aero derivatives and twin shafts have low H-values:
    - ✓ Can we use load banks or even the battery to prevent stepping out of phase?
    - ✓ Typically 40 kg·m^2 for a 1000 kg two-stage power turbine
- Lazard (-21) indicates 172…250 DC + 20…83 AC USD/kWh



BESS

- RoCoF (~100 ms)
- FCR-X

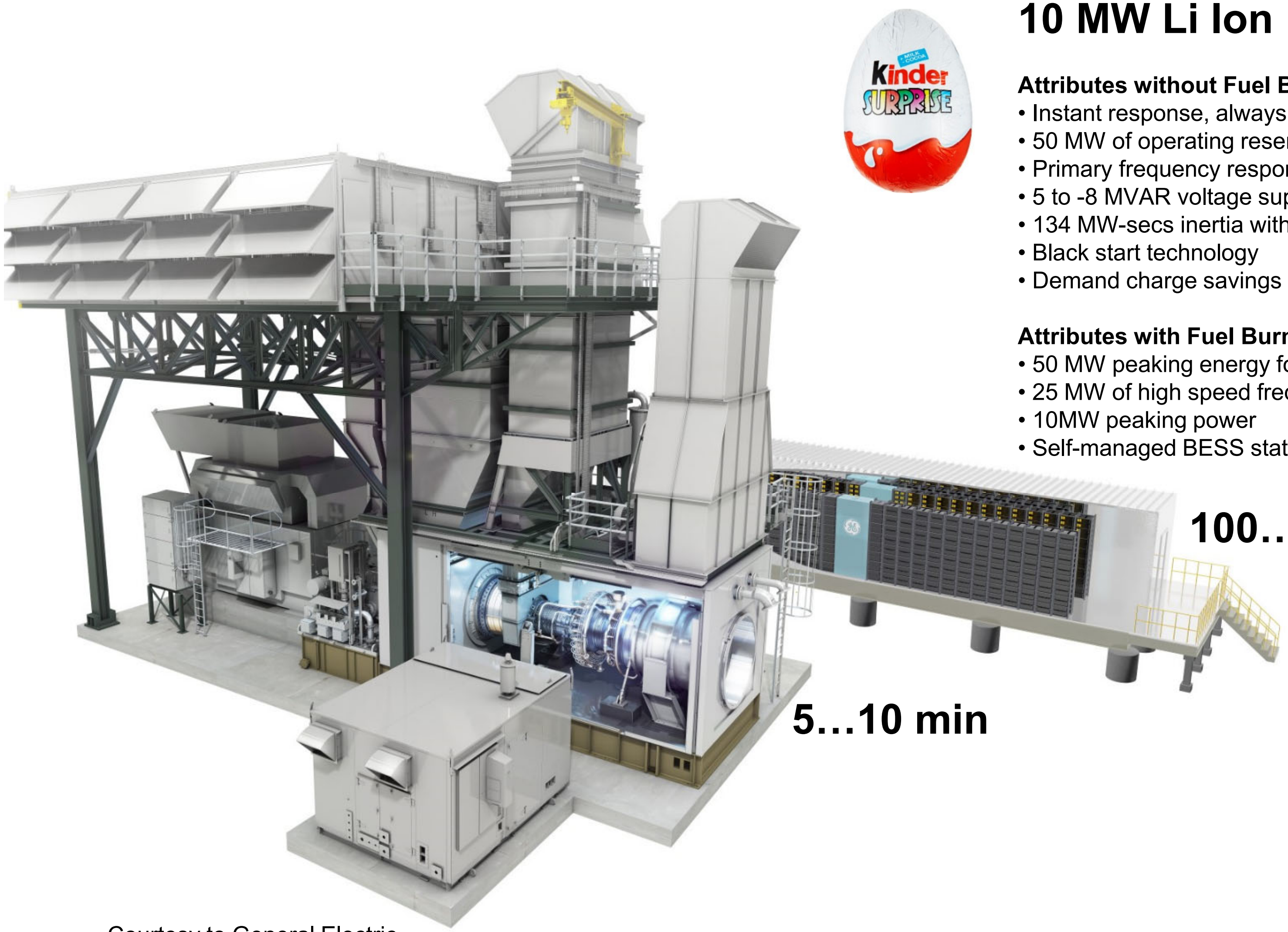
Gas turbine

Total output

BESS

- RoCoF (~100 ms)
- FCR-X

GE LM6000 Hybrid EGT



5…10 min

100…250 ms

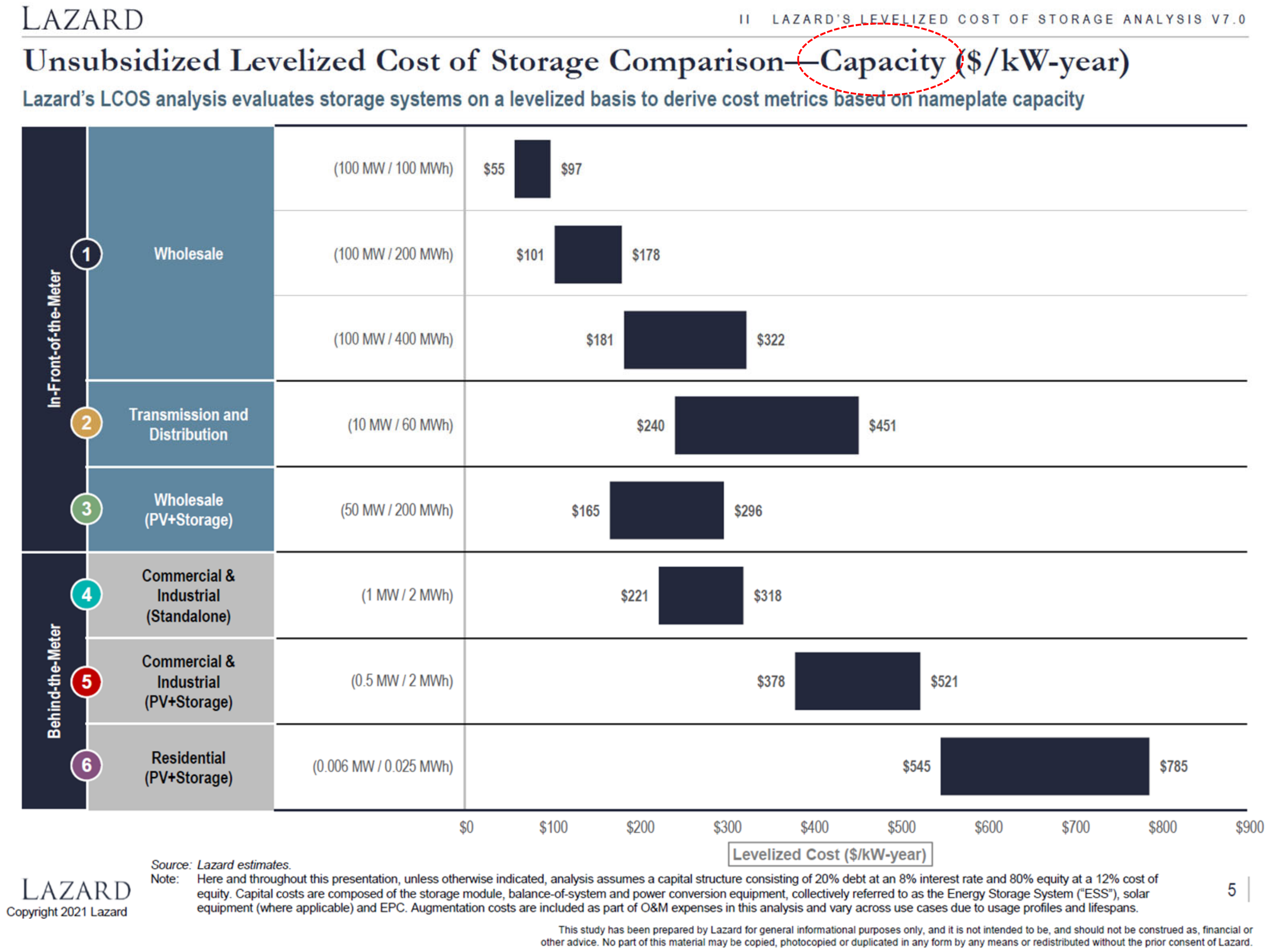
Courtesy to General Electric

10 MW Li Ion Battery

Attributes without Fuel Burn
- Instant response, always ready technology
- 50 MW of operating reserve
- Primary frequency response
- 5 to -8 MVAR voltage support
- 134 MW-secs inertia with synchronous condensing
- Black start technology
- Demand charge savings

Attributes with Fuel Burn
- 50 MW peaking energy for local contingency
- 25 MW of high speed frequency regulation
- 10MW peaking power
- Self-managed BESS state of charge

What does it cost – Lazard



LAZARD

II LAZARD'S LEVELIZED COST OF STORAGE ANALYSIS V7.0

Unsubsidized Levelized Cost of Storage Comparison—Capacity ($/kW-year)

Lazard's LCOS analysis evaluates storage systems on a levelized basis to derive cost metrics based on nameplate capacity

Source: *Lazard estimates.*

Note: Here and throughout this presentation, unless otherwise indicated, analysis assumes a capital structure consisting of 20% debt at an 8% interest rate and 80% equity at a 12% cost of equity. Capital costs are composed of the storage module, balance-of-system and power conversion equipment, collectively referred to as the Energy Storage System ("ESS"), solar equipment (where applicable) and EPC. Augmentation costs are included as part of O&M expenses in this analysis and vary across use cases due to usage profiles and lifespans.

LAZARD

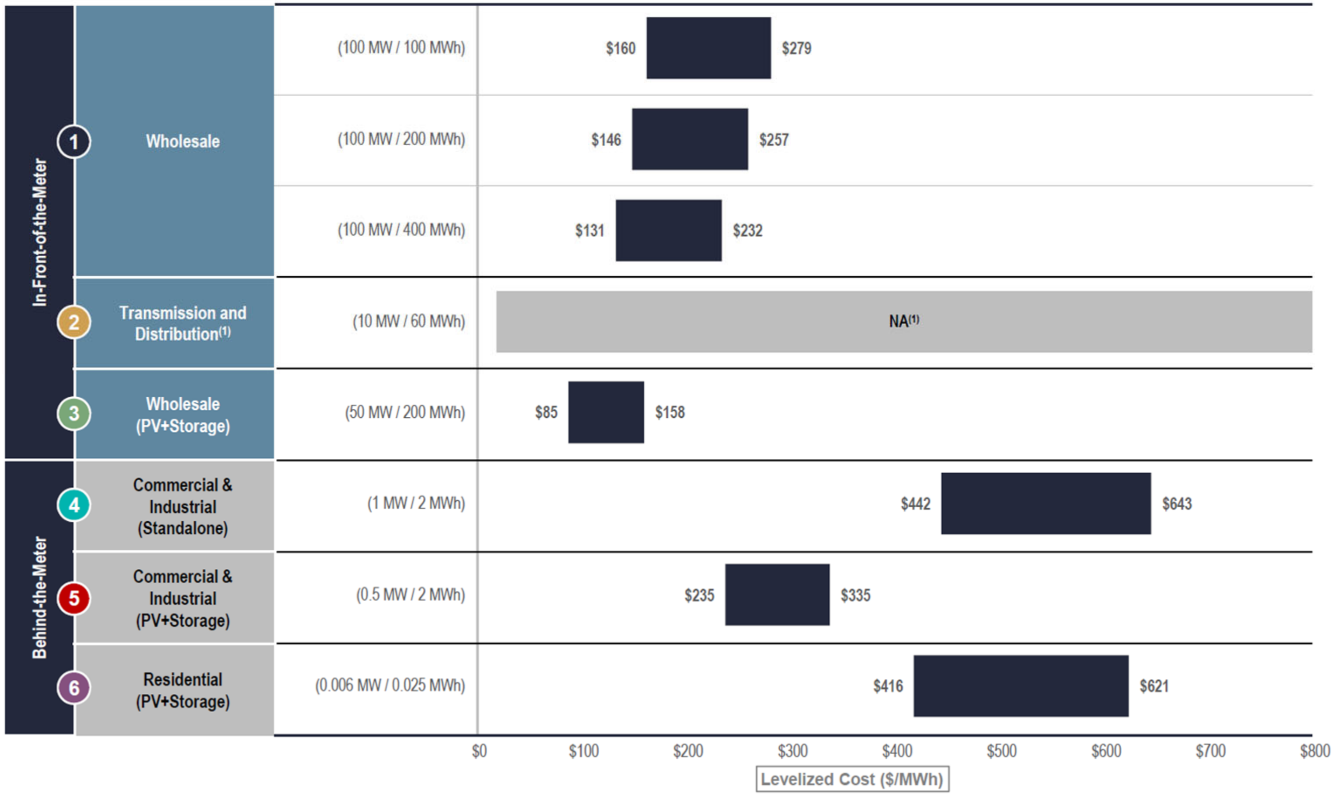
What does it cost – Lazard

LAZARD

II LAZARD'S LEVELIZED COST OF STORAGE ANALYSIS V7.0

Unsubsidized Levelized Cost of Storage Comparison—Energy ($/MWh)

Lazard's LCOS analysis evaluates storage systems on a levelized basis to derive cost metrics based on annual energy output



LAZARD

Source: Lazard estimates.

(1) Given the operational parameters for the Transmission and Distribution use case (i.e., 25 cycles per year), certain levelized metrics are not comparable between this and other use cases presented in Lazard's Levelized Cost of Storage report. The corresponding levelized cost of storage for this case would be $1,613/MWh – $3,034/MWh.

Basic principles – inertia constant

$$\boxed{J = \frac{T_m(t) - T_e(t)}{\frac{d\omega}{dt}} \quad \left[kg\, m^2\right]}$$

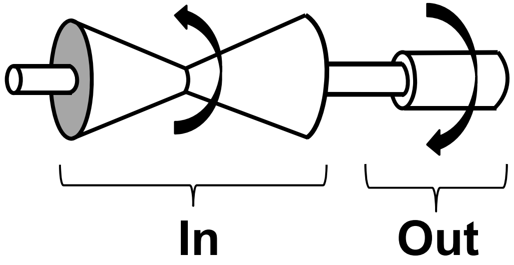
Newton second law:

$$F = m \cdot a = m \frac{dv}{dt}$$

Recast to yield:

$$Torque\ in - Torque\ out = Inertia \cdot accelration = T_m(t) - T_e(t) = J \cdot \frac{d\omega}{dt} \quad [Nm]$$

Or more convenient, introduce:



$$E_{kin} = \frac{1}{2} \cdot J \cdot \omega^2 \quad [Nm]$$

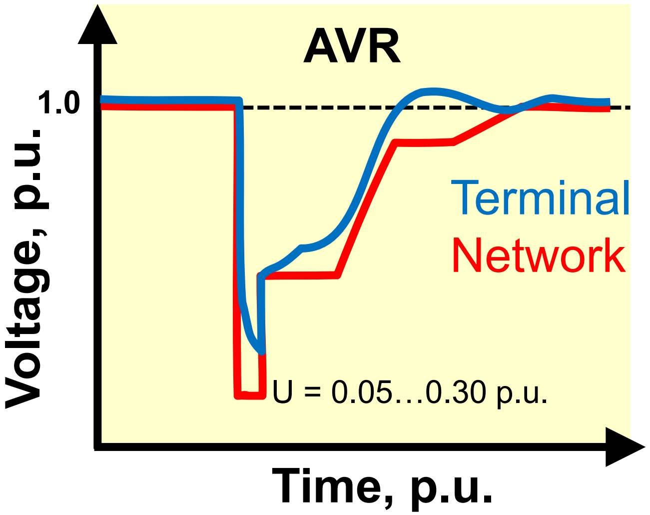
$$\left.\begin{aligned} & P_m(t) - P_e(t) = \frac{dE_{kin}}{dt} = \omega \cdot J \cdot \frac{d\omega}{dt} \\ & H = \frac{E_{kin}}{S_{nom}} = \frac{J \cdot \omega^2}{2 \cdot S} \\ & \omega = 2 \cdot \pi \cdot f \end{aligned}\right\} \therefore P_m(t) - P_e(t) = \frac{2 \cdot S_{nom} \cdot H}{f} \cdot \frac{df}{dt} \quad \left[\frac{Nm}{s} = W\right]$$

$$p_m(t) - p_e(t) = \frac{2 \cdot H}{(2 \cdot \pi \cdot f)} \cdot \frac{d\omega}{dt} = \frac{2 \cdot H}{f} \cdot \frac{df}{dt} \quad [p.u.]$$

$$H = \frac{E_{kin}}{S} = \frac{J \cdot (2 \cdot \pi \cdot f)^2}{2 \cdot S_{nom}} [s]$$

FRT – Fault Ride Through capability

- Physical rotor angle at short circuit
  - Δφ ~ 1/H
- Load angle
  - Always below 90°
  - AVR response
- Fast breaking
  - Resistors (~500 ms)
  - Cf. Kundur p. 1106 (ed 1) or 881 (ed 2)



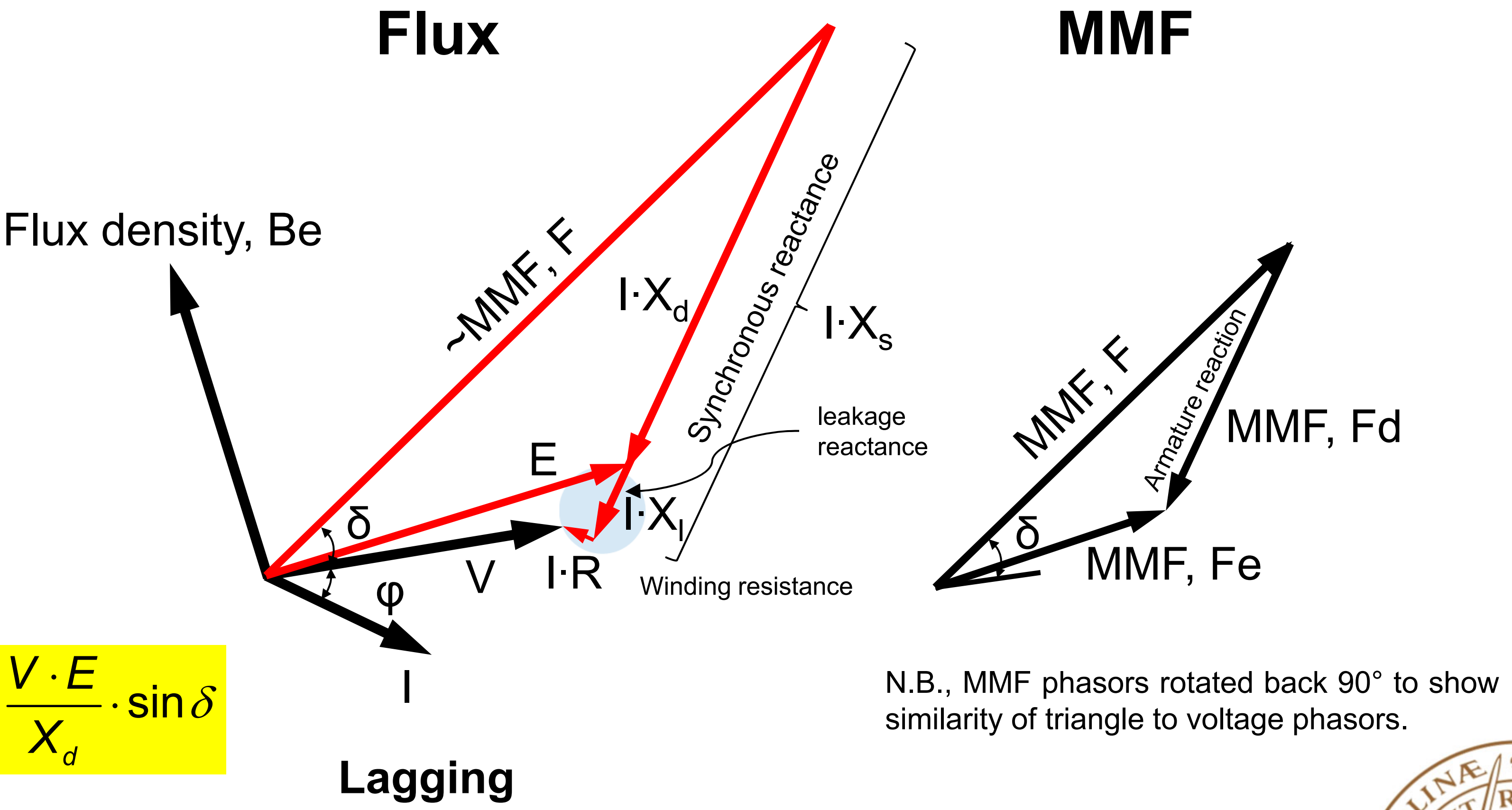
$$\left.\begin{array}{l}\dfrac{df}{dt}=\dfrac{\Delta P}{2\cdot H\cdot P_{nom}}\cdot f_{nom}\\ \omega=2\cdot\pi\cdot f\end{array}\right\}\therefore\ \frac{d\omega}{dt}=\frac{\pi\cdot\Delta P}{H\cdot P_{nom}}\cdot f_{nom}$$

$$\Delta\omega=\frac{\pi\cdot\Delta P}{H\cdot P_{nom}}\cdot f_{nom}\cdot t\quad\Rightarrow\quad\Delta\varphi_{rtr}=\frac{\pi\cdot\Delta P}{2\cdot H\cdot P_{nom}}\cdot f_{nom}\cdot t^2\quad\xrightarrow[\Delta P=P_{nom}]{\text{Loss of power}}\quad\Delta\varphi_{rtr}=\frac{90}{H}\cdot f_{nom}\cdot t^2\,[^\circ]$$

- Caveat! The load angle “δ” must also be taken into consideration (≤90°). Cf. the literature on generators!
- Short-circuit torque variation – factor of 10! (miss-synchronization on the order of 20.)

MMF, flux and the magnetic circuit

The design load angle (δ) is typically
in the range of 45…55°



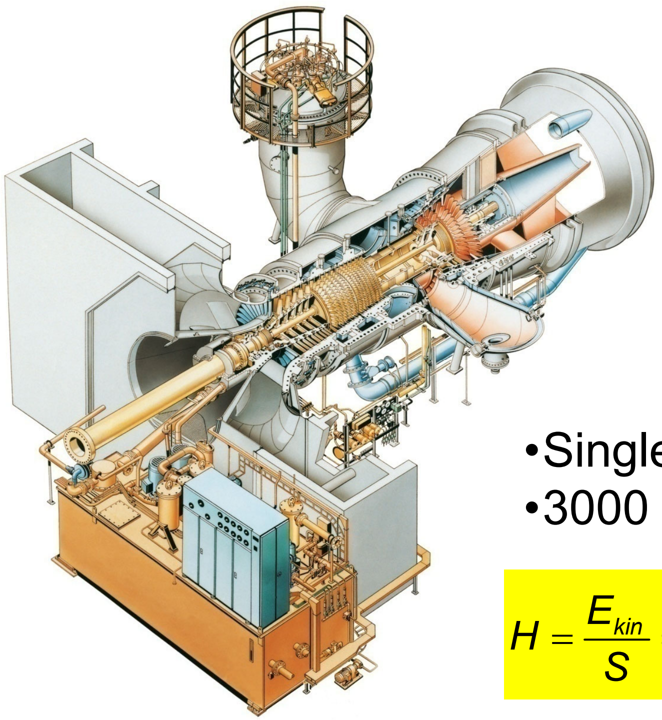
$$P = \frac{V \cdot E}{X_d} \cdot \sin\delta$$

N.B., MMF phasors rotated back 90° to show similarity of triangle to voltage phasors.

Figure based on C.E.G.B

Inertia – Example V94.2/SGT5-2000E

Turboset	
Power rating, [MW]	200
RfG-class	D
H-value, kJ/kVa [s]	**5.14***
Inertia, J [kg·m^2]	**21200**
Generator	
Rated output, [MW]	203.5
Power factor, [-]	0.85
Voltage, [kV]	10.5
Current, [kA]	11.19
Transient reactance, X_d' [p.u.]	0.3527
Synchronous reactance, X_d [p.u.]	2.988
Inertia, J [kg·m^2]	**5063**
Turbine	
Power, MW	210
Inertia, J [kg·m^2]	**16137**
Step-up	
Rating, [MVA]	202
Reactance, [p.u.]	0.123



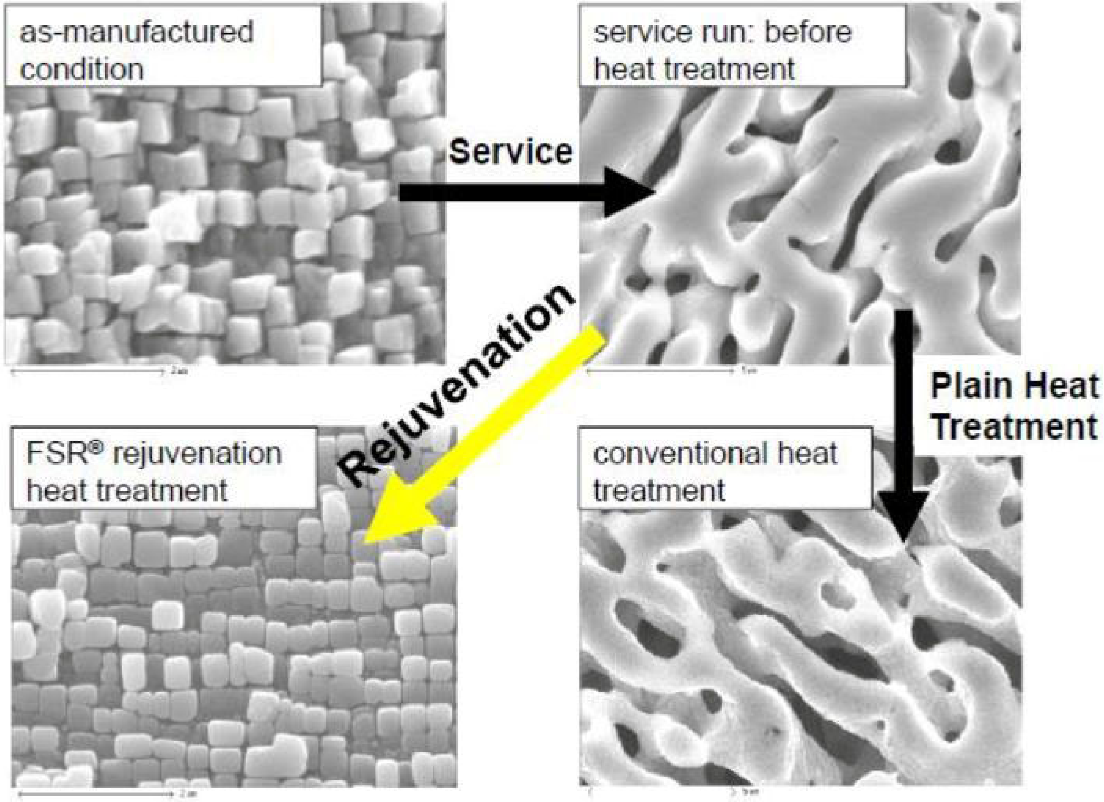
- Single-shaft
- 3000 rpm

$$H = \frac{E_{kin}}{S} = \frac{J \cdot (2 \cdot \pi \cdot f)^2}{2 \cdot S_{nom}} [s]$$

Resulting FRT capability** is ~0.2 s
- Stepping out of phase…
- AVR (load angle)

*GE LM2500 H~1.2 s
**Gränsbryttid

Service

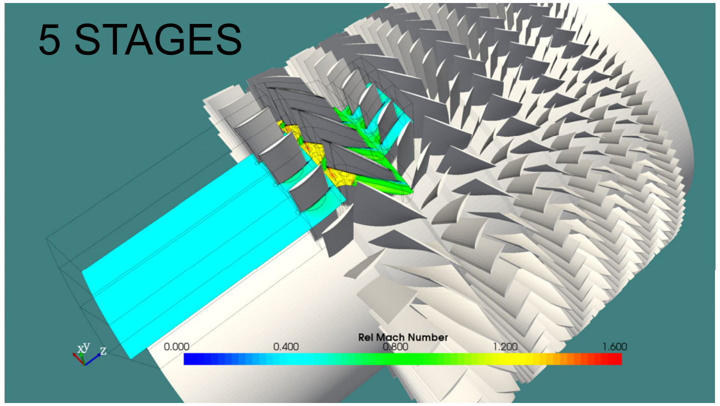

as-manufactured condition
Service
service run: before heat treatment
Rejuvenation
Plain Heat Treatment
FSR® rejuvenation heat treatment
conventional heat treatment

Three-stage filtration – 28,000 hours

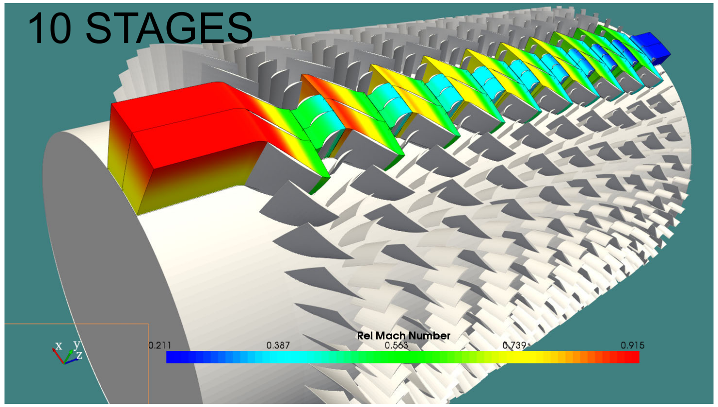
CCS – what options are at hand?

- Novel advanced cycles
  - Allam-Fetvedt
- Post-combustion
  - Amine (MEA et al.)
  - HPC (~6…7 bar_a)
  - Extraction (i.e. lost power) vs. power…
- Oxy-fuel
- IGCC

~13000 RPM

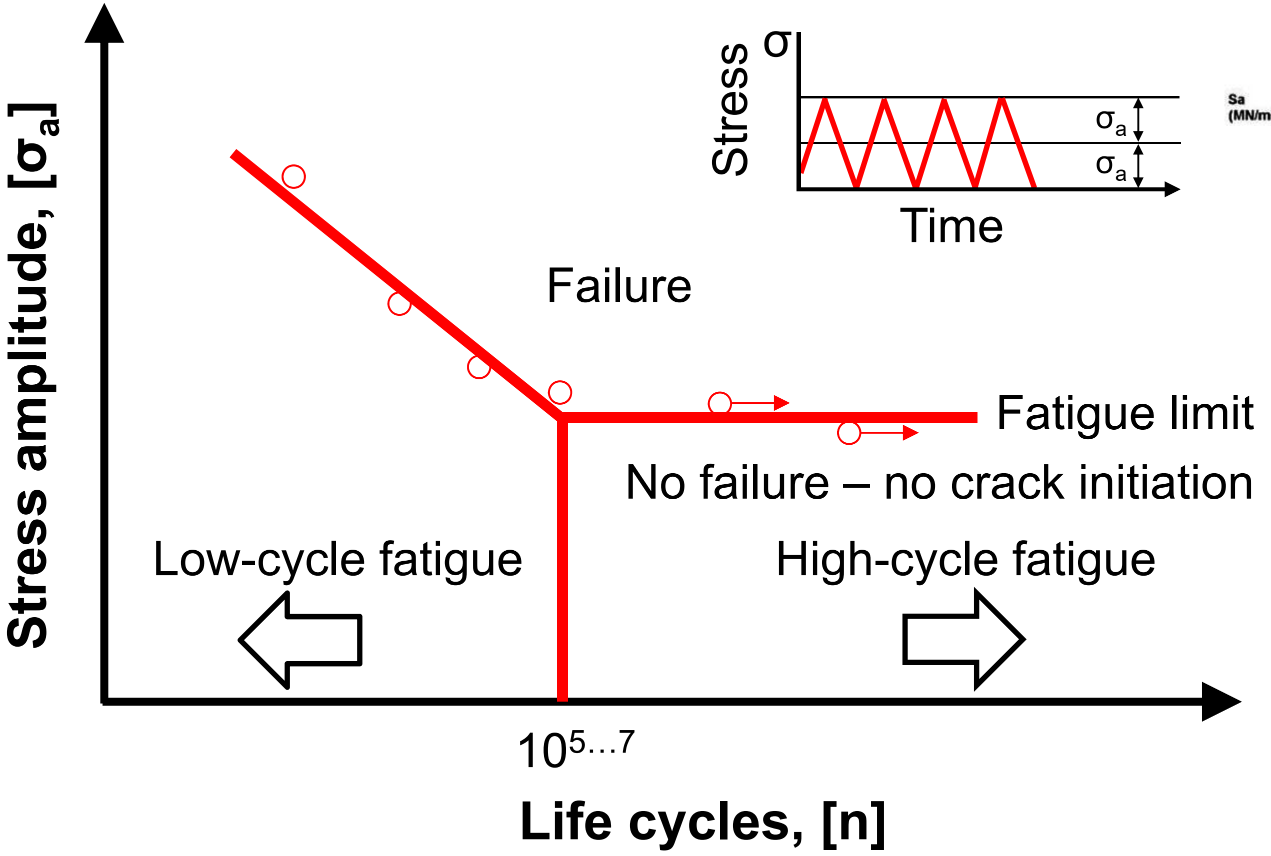


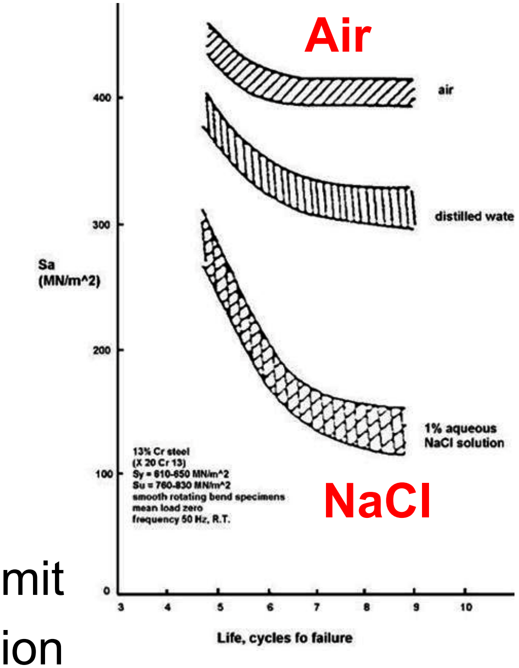
6000 RPM



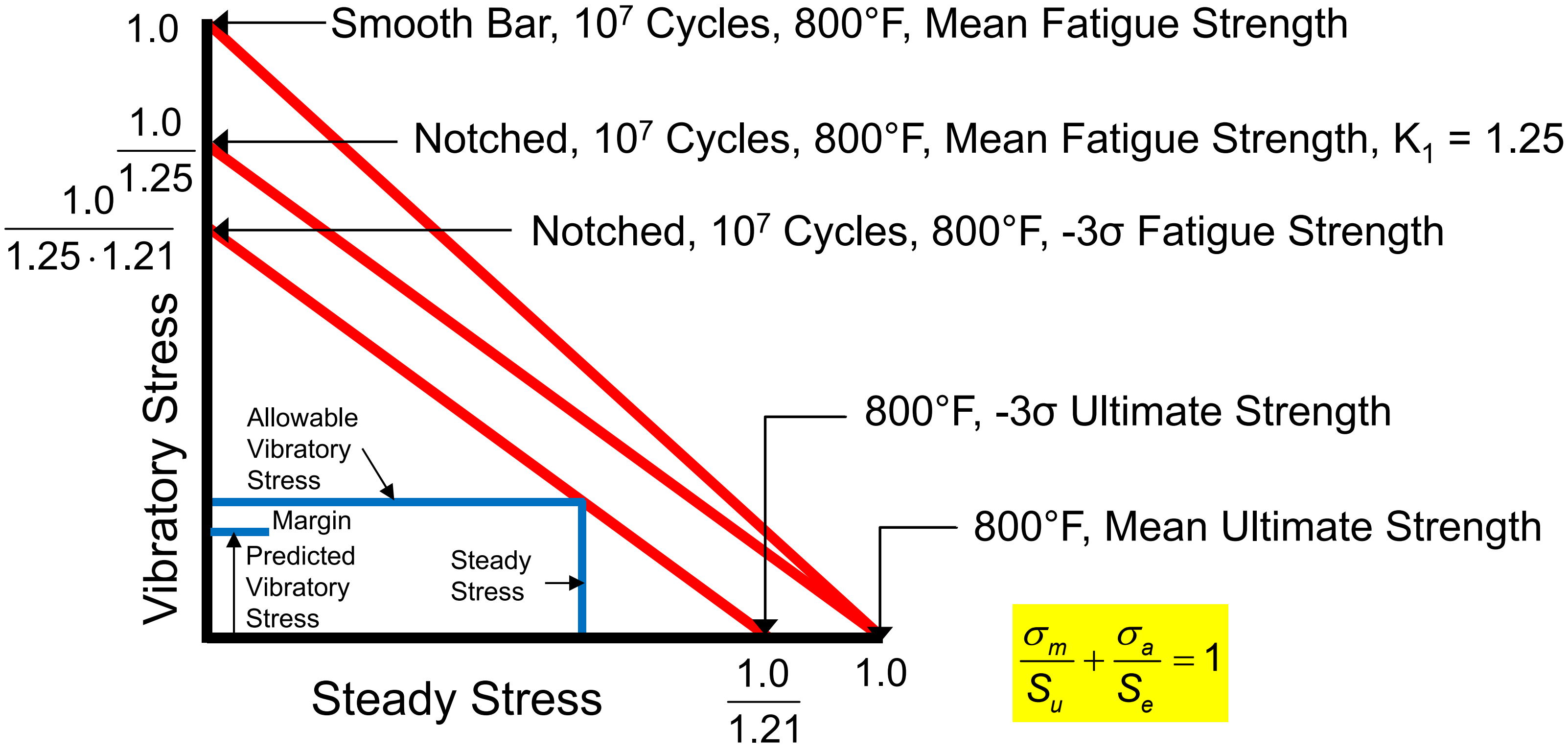
Fatigue – low or high?

Wöhler- or σ,N curve





Typical Modified Goodman Diagram



$$\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S_e} = 1$$

- Steady (mean) stress includes centrifugal, pressure, and thermal loads
- Using the steady stress, allowable vibratory stress (alternating stress) can be determined from the Goodman diagram
- That allowable vibratory stress must be greater than 50% of the steady stress.