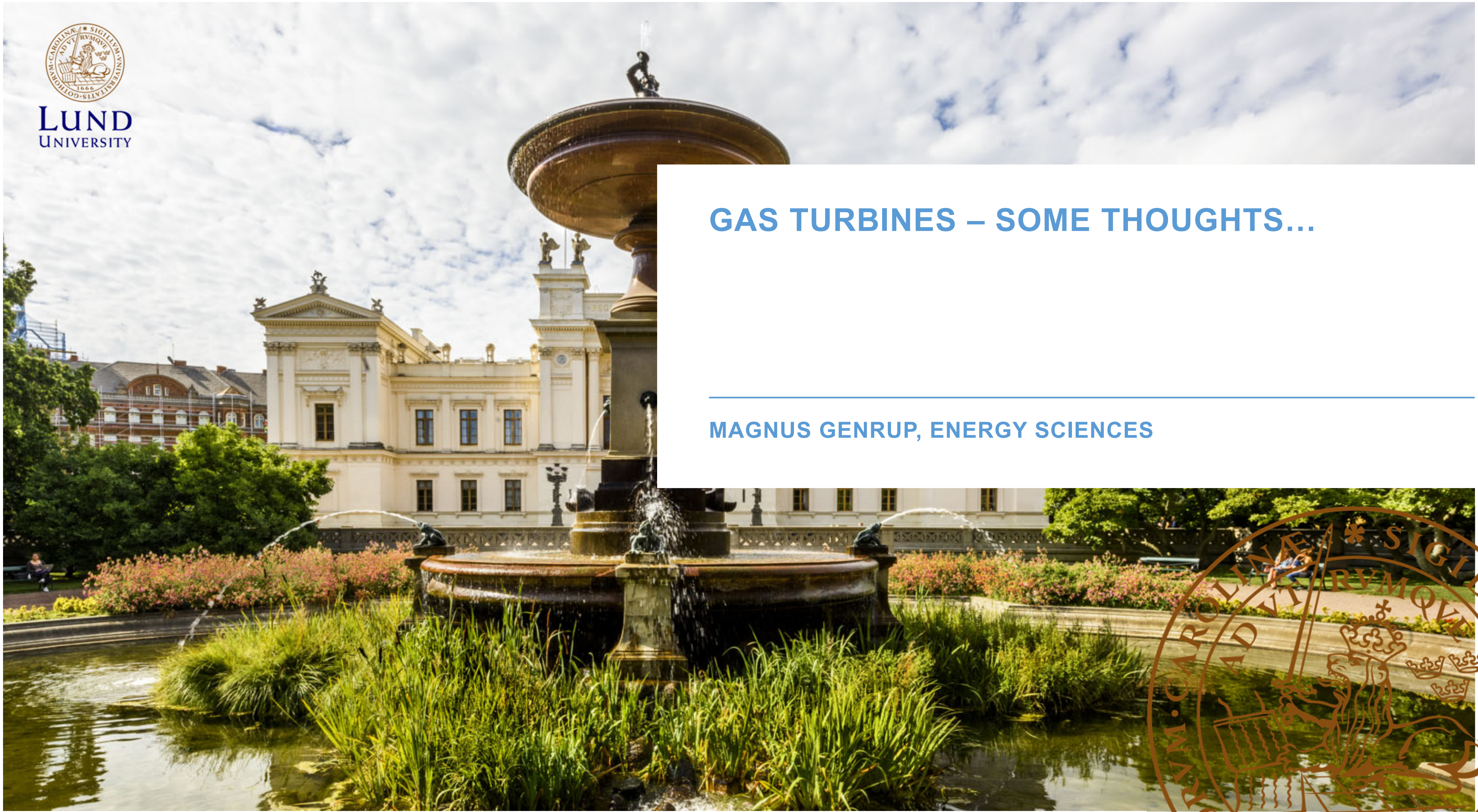
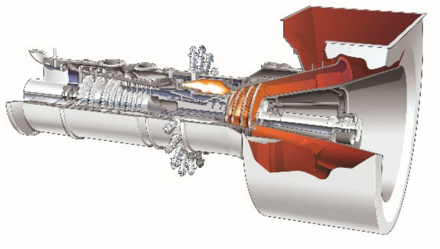


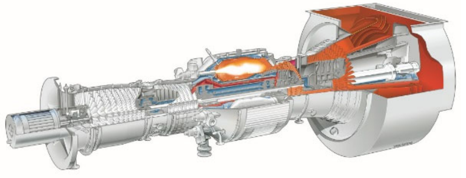
GAS TURBINES – SOME THOUGHTS…

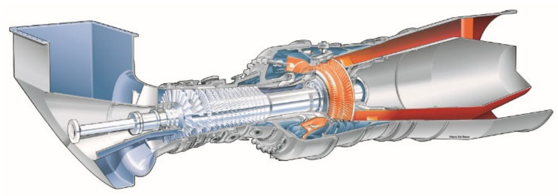
MAGNUS GENRUP, ENERGY SCIENCES

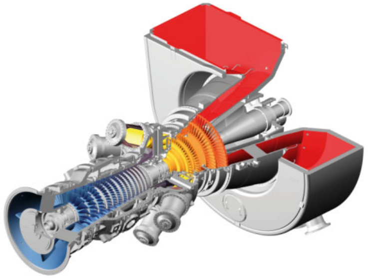
Magnus Genrup, PhD

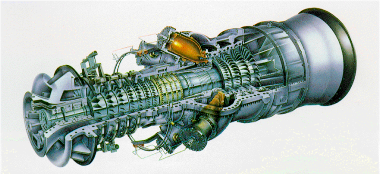
- Professor Thermal Power Engineering
  - ✓ Aerodynamics
  - ✓ Process
- Siemens/Alstom/ABB Stal 1994-2008

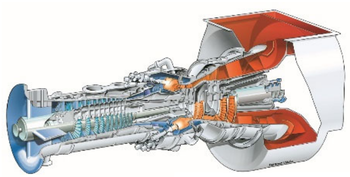


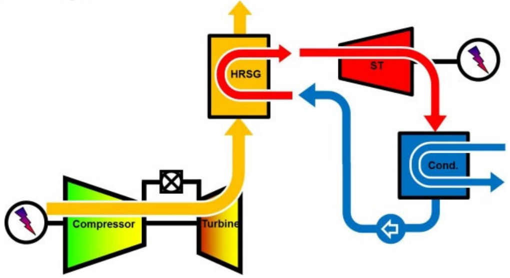


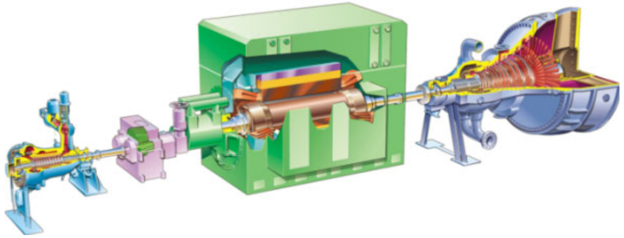






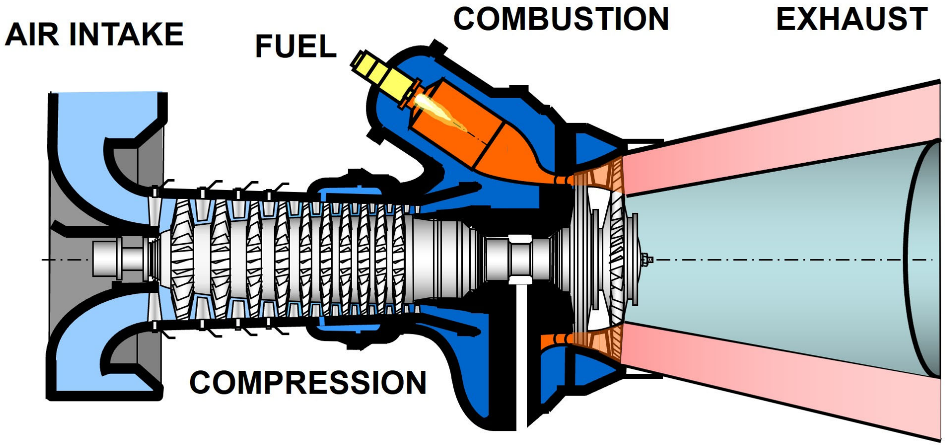


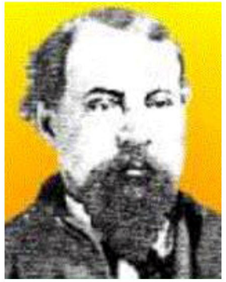




Gas turbine vs. reciprocating…

Continuous

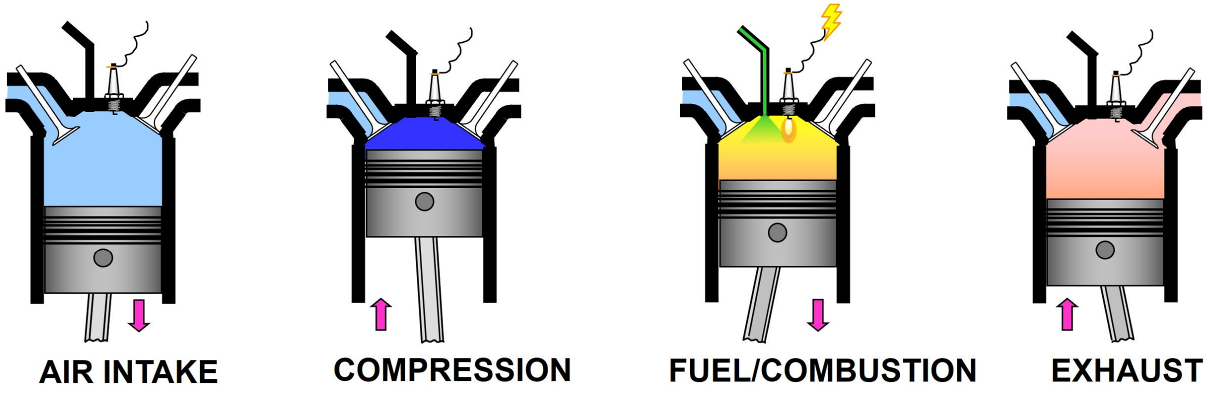




George Brayton
1830-1892

James Joule
1818-1889

Intermittent



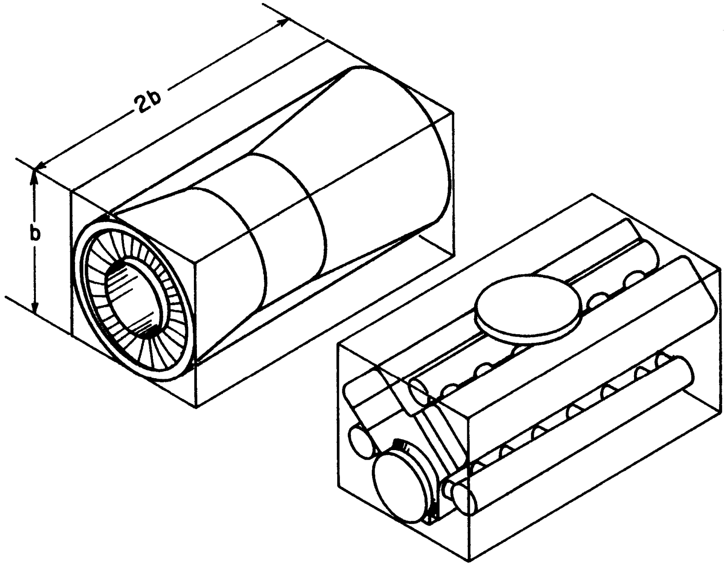
Swallowing capacity of turbomachinery
Gas turbine vs. turbocharged IC

Inlet volumetric flow can be expressed as:

$$\dot{V}_{GT} = \frac{\pi}{4}(0.9b)^2\left(1-0.5^2\right)0.7a = 0.334\,a\,b^2$$

$$\dot{V}_{ICE} = \frac{\pi}{4}(0.2b)^2\,0.8a = 0.025\,a\,b^2$$

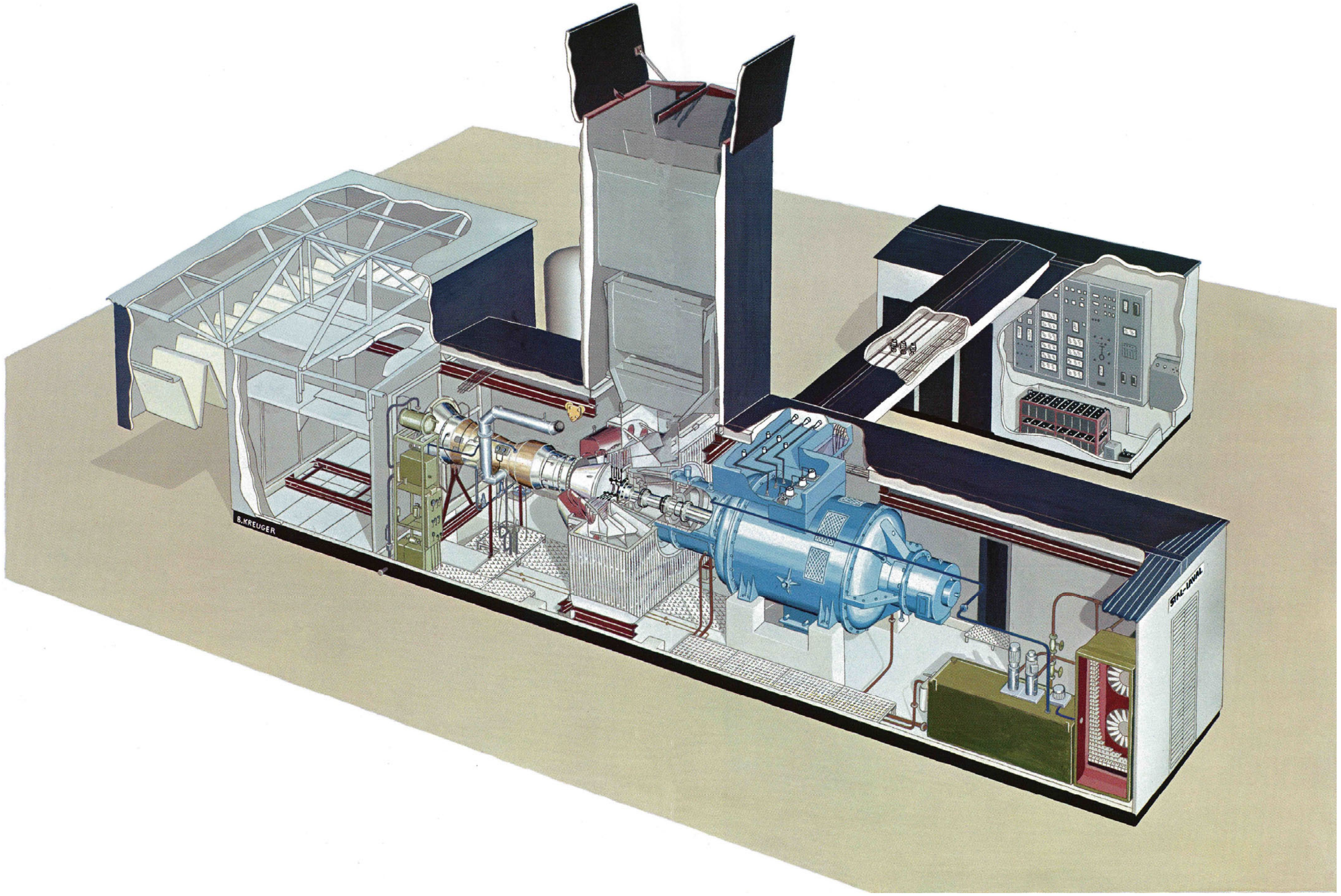
$$\frac{\dot{V}_{GT}}{\dot{V}_{ICE}} = \frac{0.334\,a\,b^2}{0.025\,a\,b^2} \approx 13.4$$

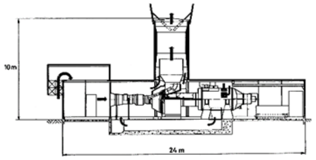


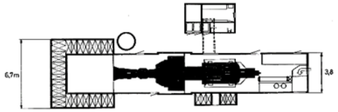
The gas turbine can handle higher air flow (~13 times), and thus producing far higher output.

- The gas turbine has a significantly lower weight per unit of power. Typically 1 tonne/MW (aero-derivatives), whilst the diesel engine is some 5 times higher.
- The gas turbine has a significantly lower volume per unit of power. It is typically 50 % of that of the diesel and increases with output

Power Pack – PP3

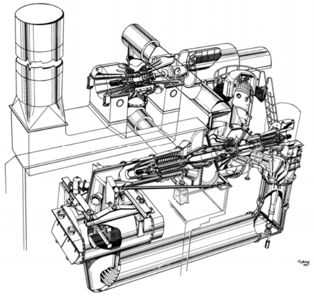


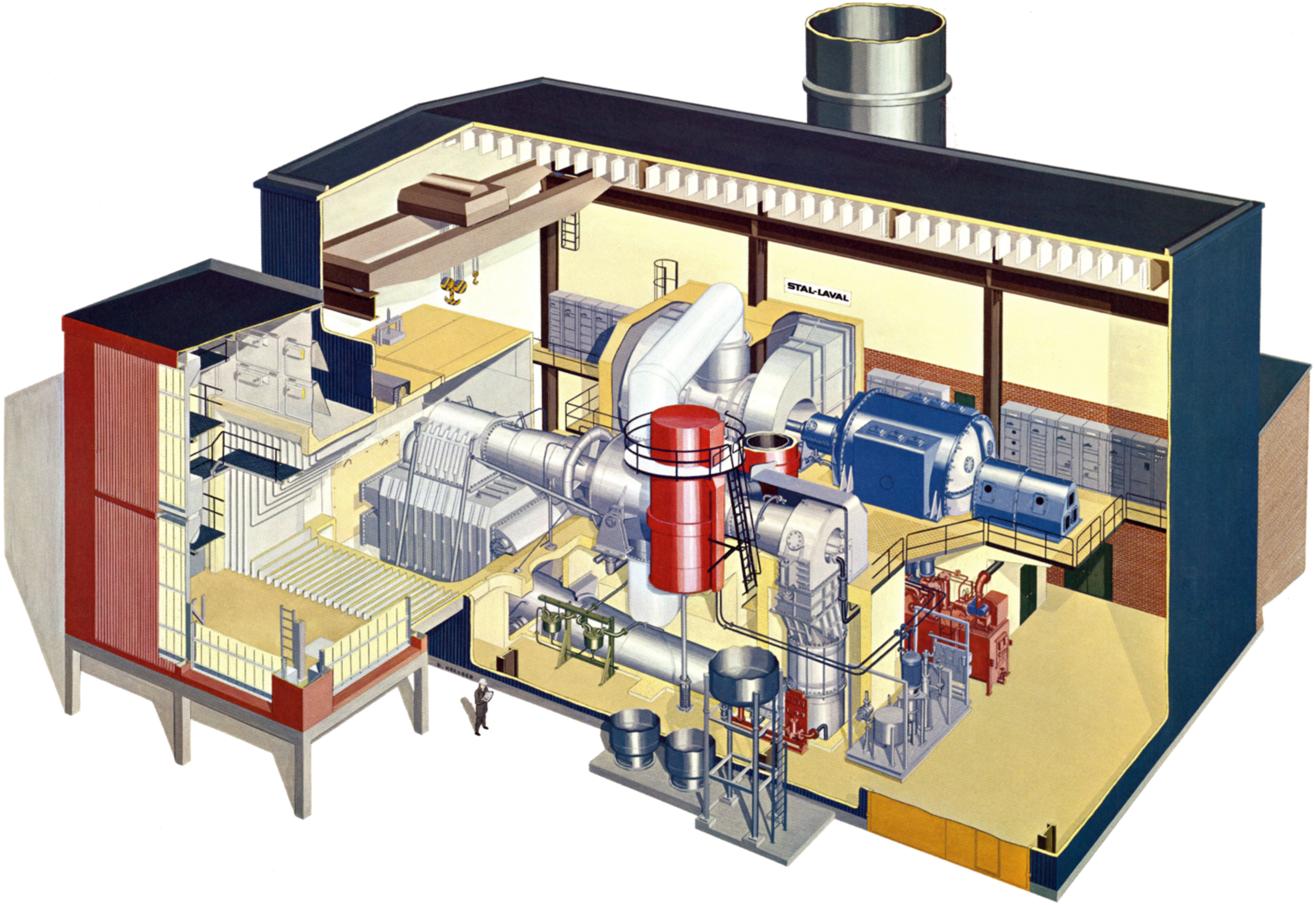




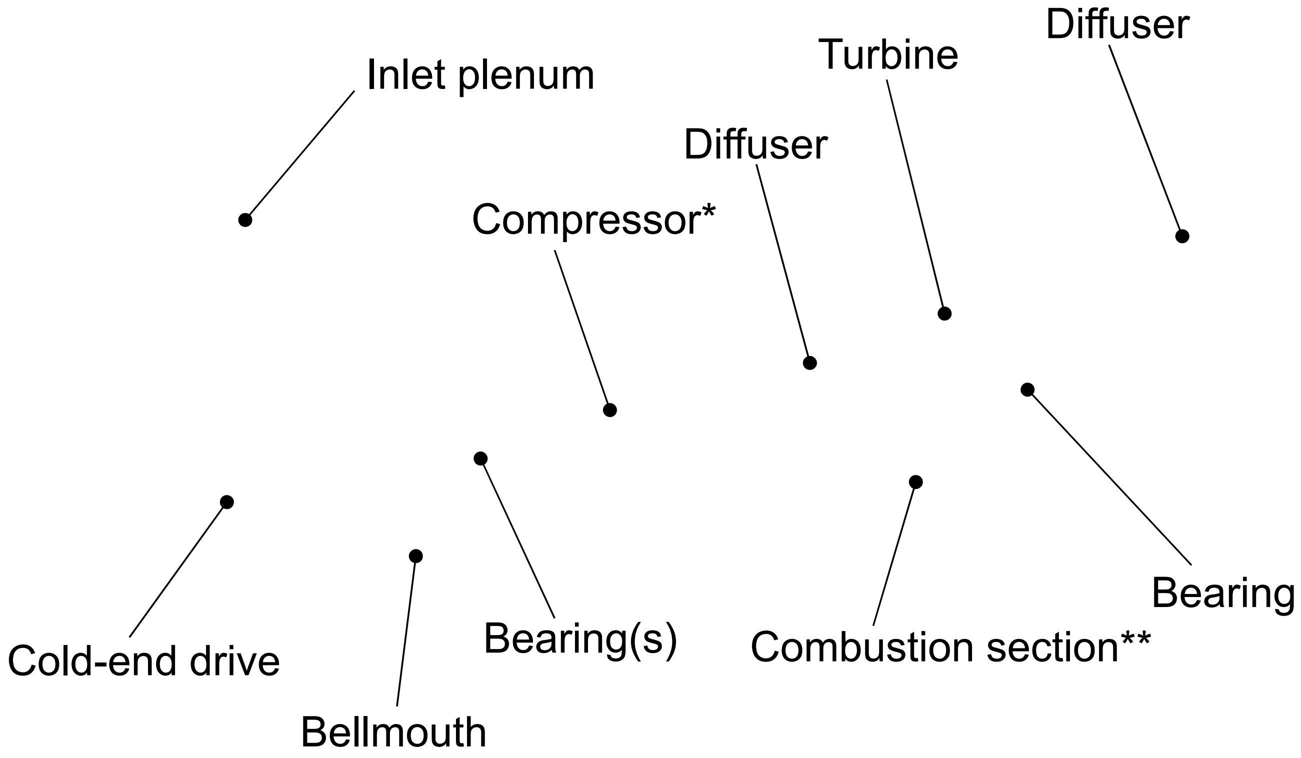
STAL-LAVAL GT-120

Late 50s 40…70 MW class, **21 units**





Siemens SGT-800 – main parts

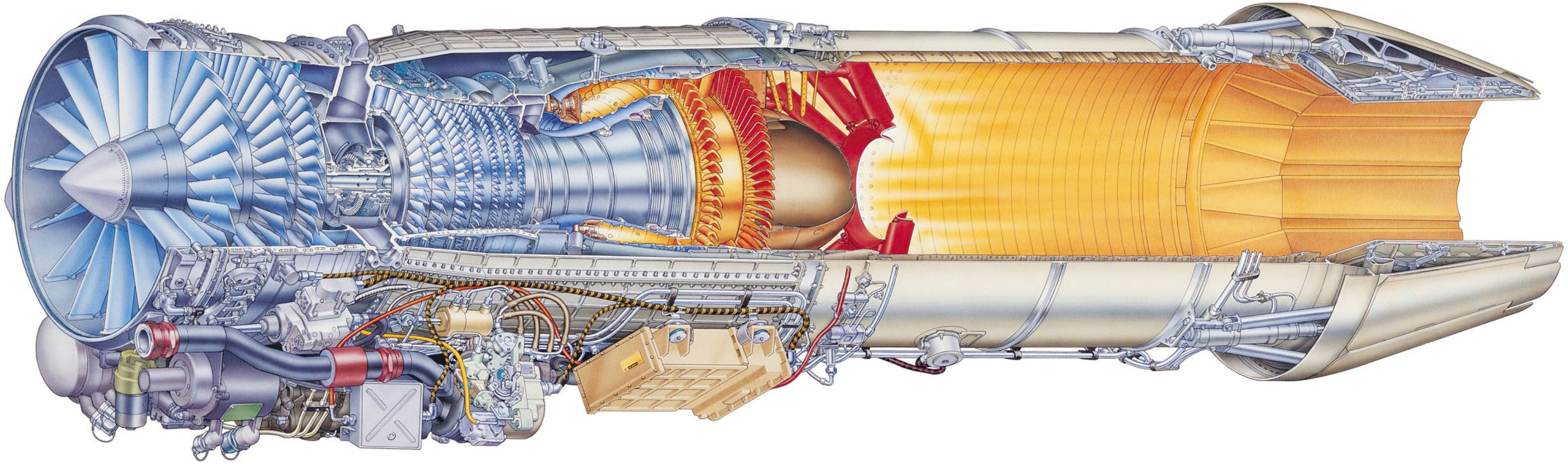


*15 stages PR ≈ 22, 3 variable
**Annular with 30 burners

Courtesy to Siemens

JAS Gripen engine - RM12

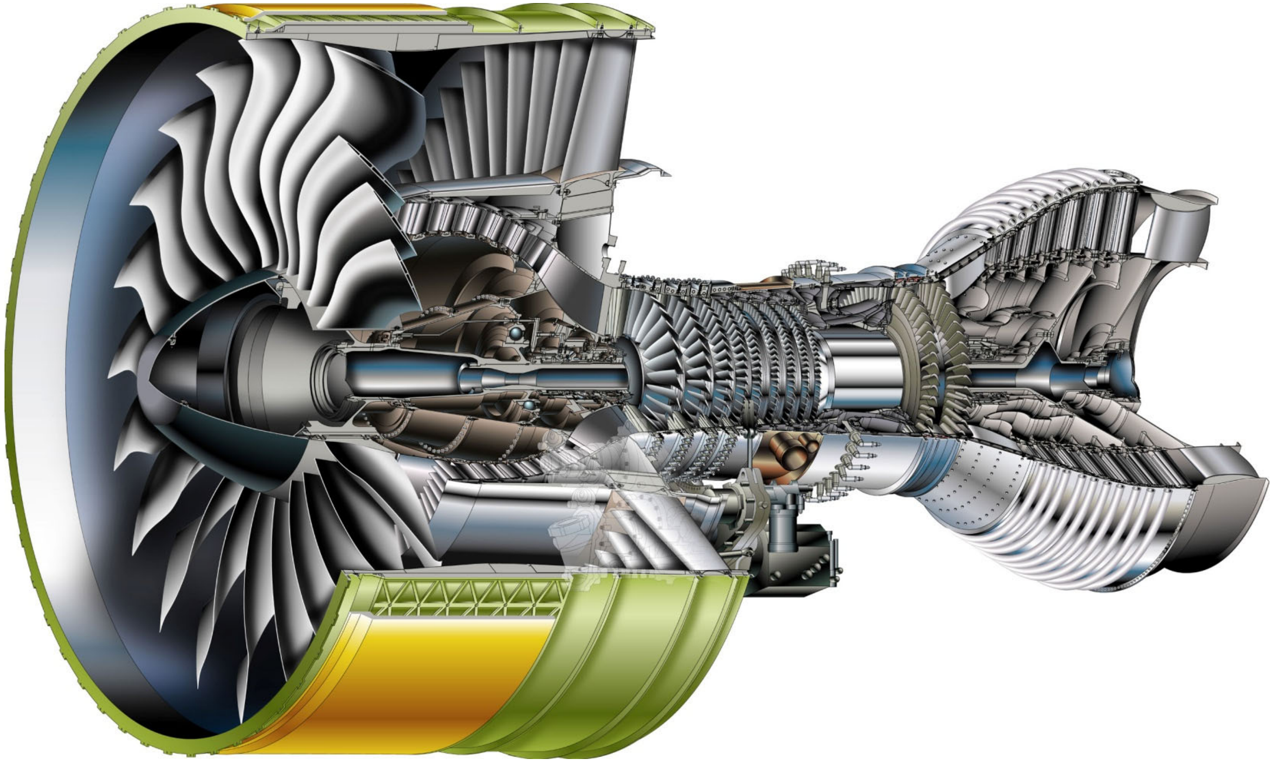
General Electric F404



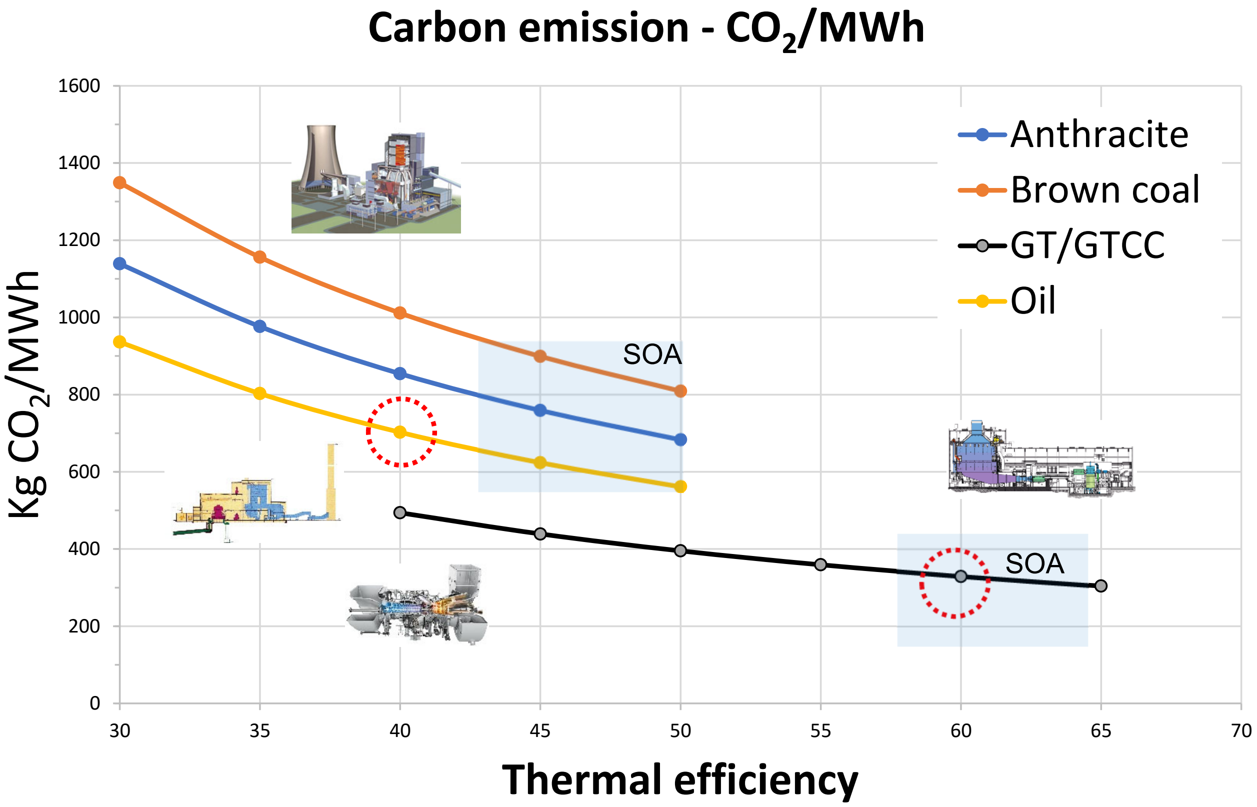
Thrust	54/80.5 kN
TSFC	23.9/50.1 g/kN·s)
PR	≈ 27.5:1
BPR	≈ 0.31:1
Flow	≈ 68 kg/s
Weight	≈ 1000 kg
Inlet diameter	≈ 0.79 m

Courtesy to Volvo Aero

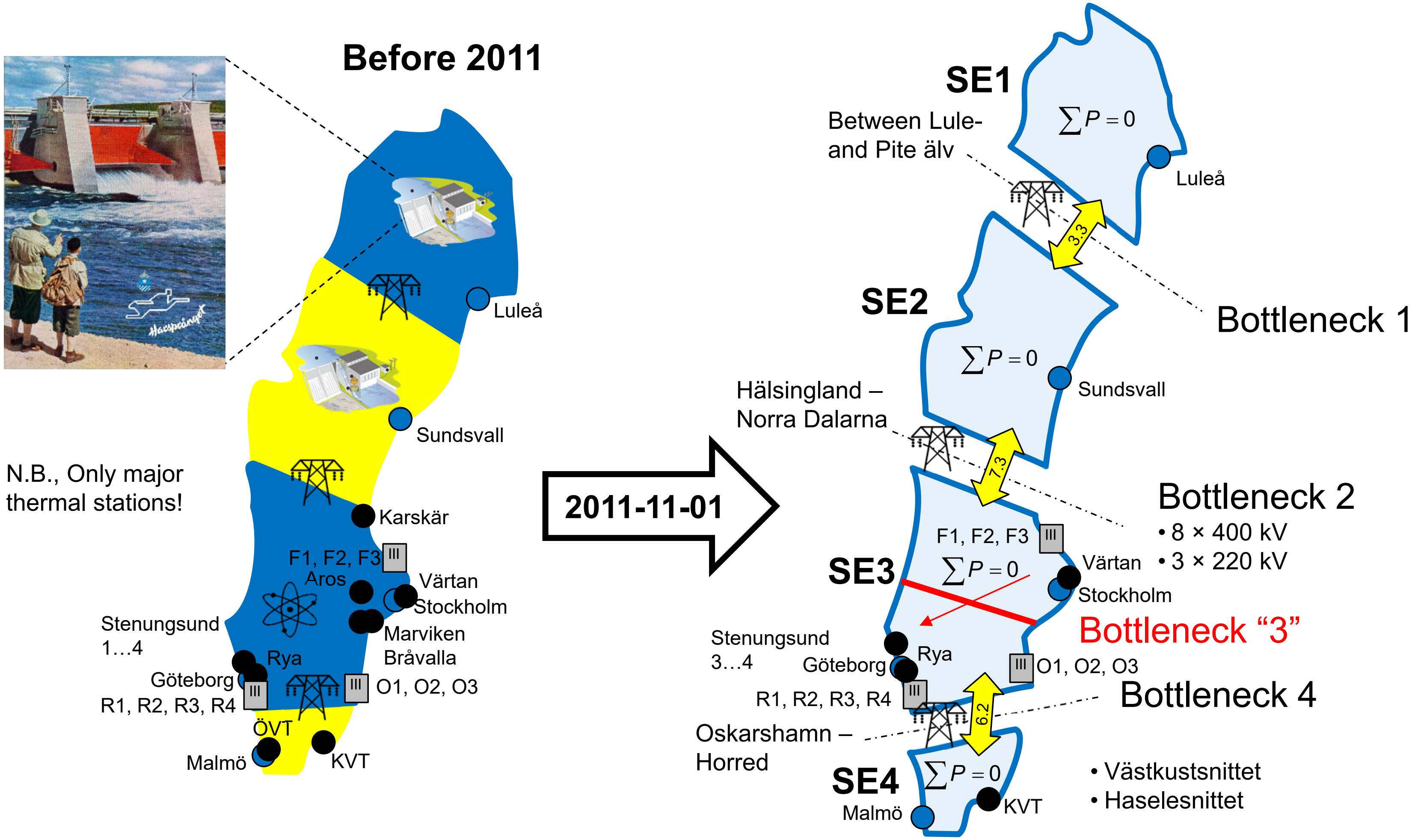
GE and Pratt & Whitney 7000-series (A380)



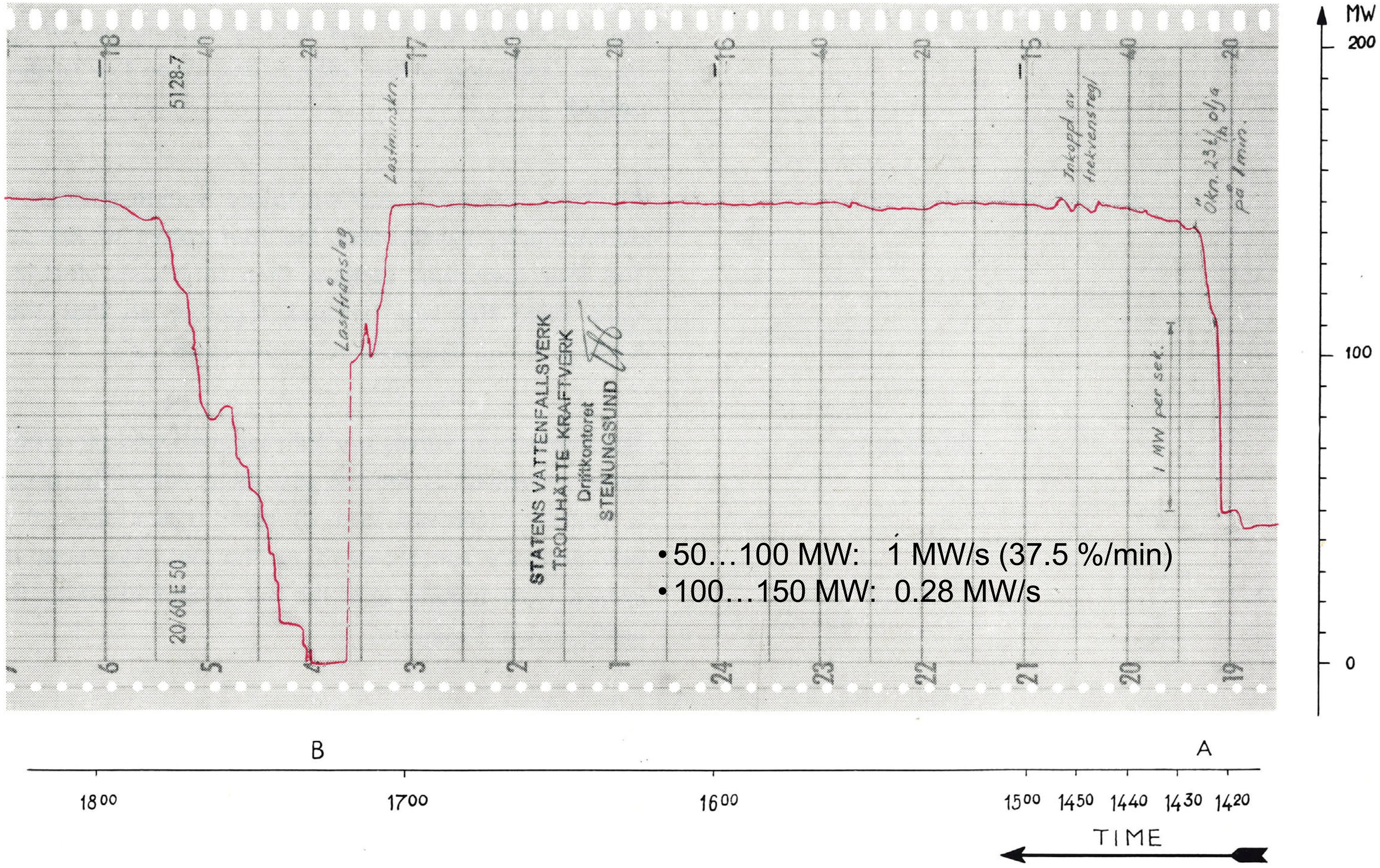
Emissions – CO_2



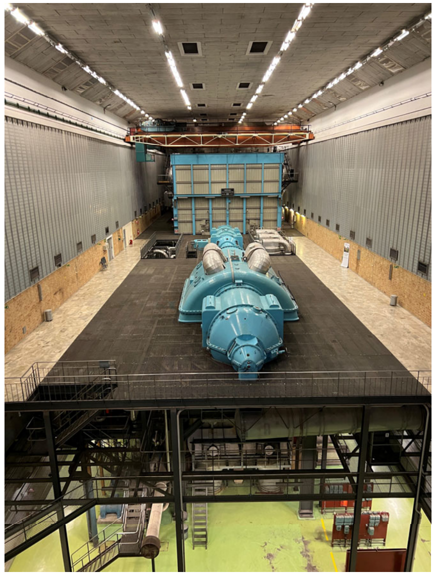
Production and transfer capacity – then and now…



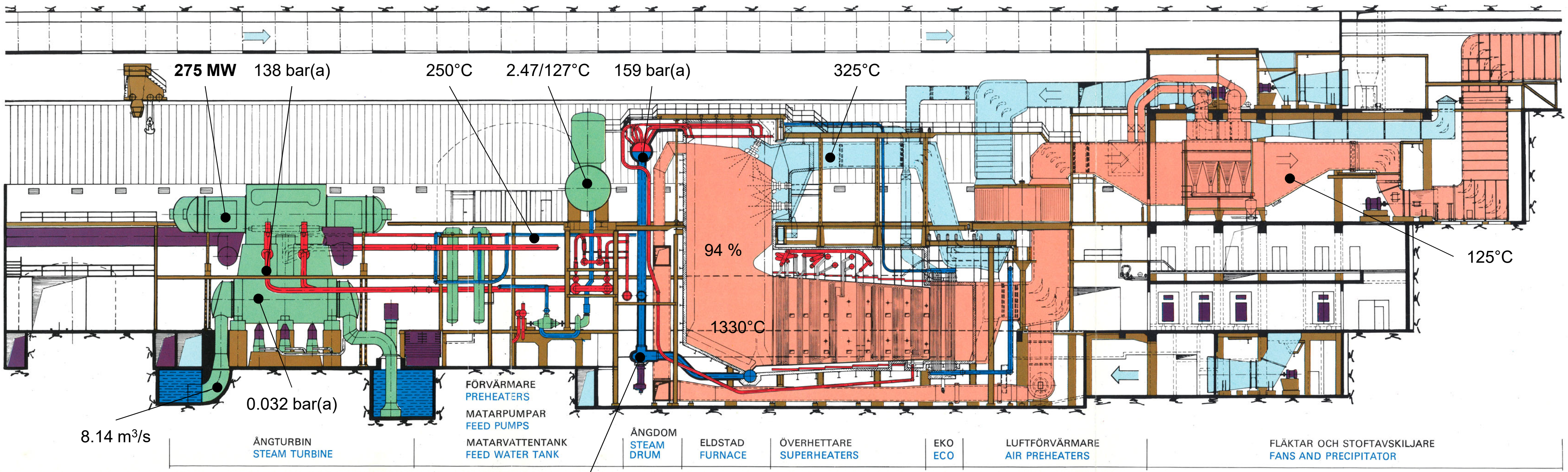
Stenungsund unit 2 - 1960



- 50…100 MW: 1 MW/s (37.5 %/min)
- 100…150 MW: 0.28 MW/s



Stenungsund QUAD-units 3 and 4 (1966-)



275 MW

138 bar(a)

250°C

2.47/127°C

159 bar(a)

325°C

94 %

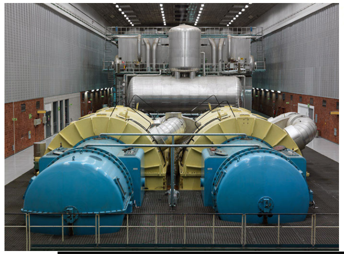
1330°C

125°C

0.032 bar(a)

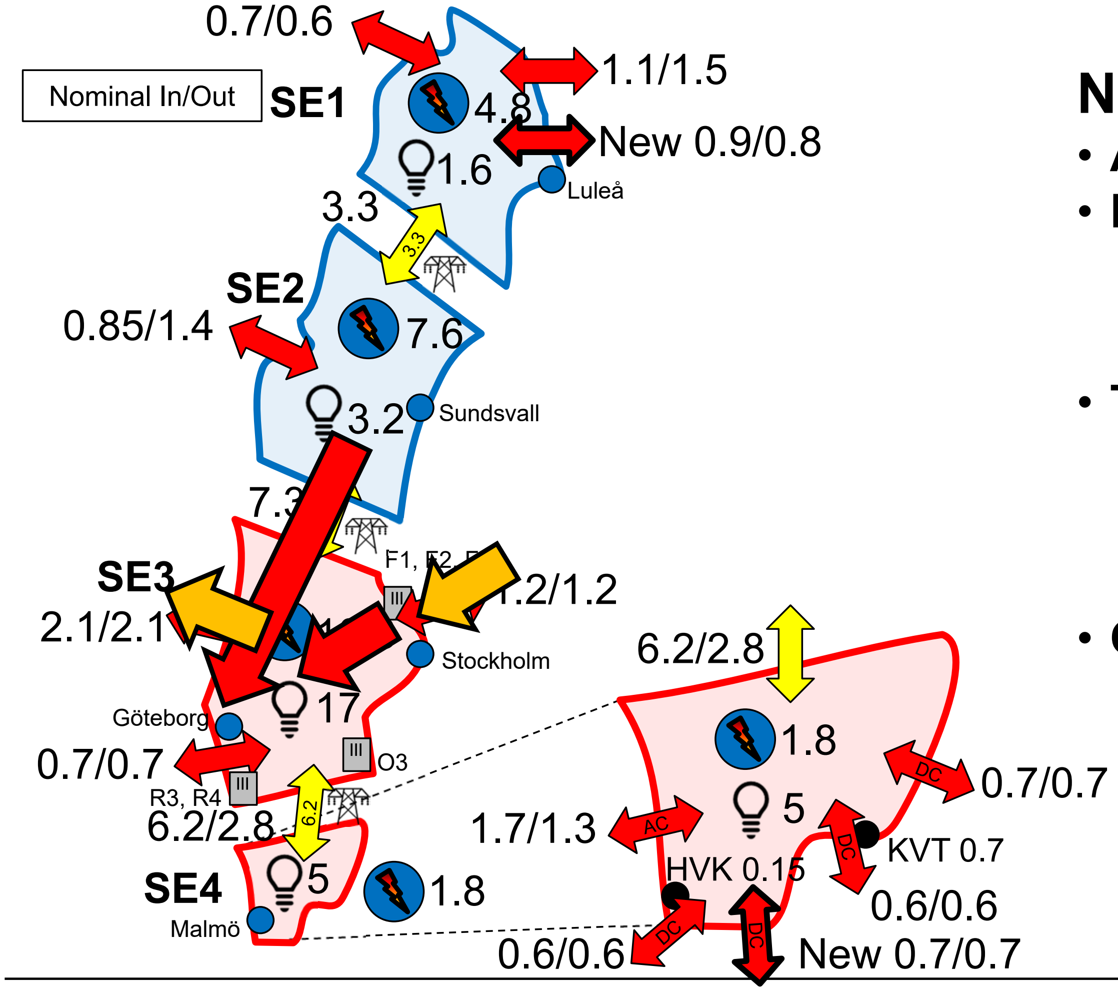
8.14 m^3/s

Δp = 2.65 bar
Flow = 3·400 kg/s
CR ≈ 5.3 –
P = 450 kW



- 270 MW, 41.3 %
- Adm 145/25.2 bar(a)/530/540°C, 227 kg/s
- p_{cond} = 0.032 bar(a)
- 4×5 m^2
- T_{FW} = 250°C
- Fuel = 16.1 kg/s

The current situation…



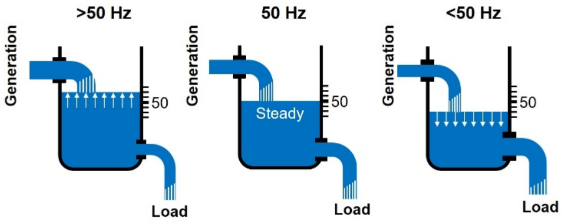
New flow patterns and scenarios!

- **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…
- **On hold Hansa PowerBridge - HPB (SE4)**

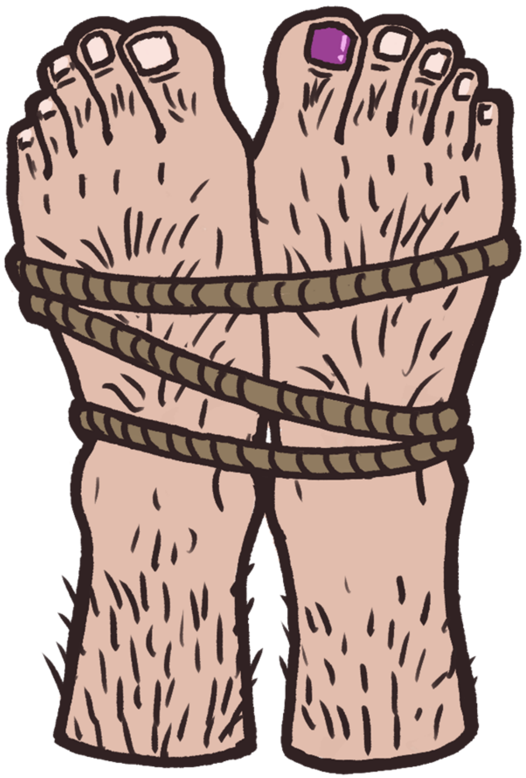
$$\frac{\sum \text{Export}_{@SE4}}{\text{Produktion}_{@SE4}} = \frac{3.2}{1.8} \approx 1.8$$

What is of utmost importance?

- **Frequency stability**
  - ✓ 50 Hz (FCR-X, FRR, …)
  - ✓ Inertia…

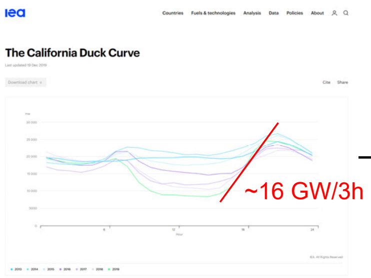


- **Rotor angle stability**
  - ✓ The ability of interconnected machines of a power system to remain in synchronism during a disturbance
  - ✓ The load angle and dynamic stability (cf. the equal area criteria)
  - ✓ Inertia… $\Delta\varphi \sim 1/H$
  - ✓ Power system stabilizer – PSS during normal operation
- **Voltage stability**
  - ✓ The ability to maintain steady acceptable voltage at all buses in the system under normal operation – and after being subjected to a disturbance
  - ✓ The main factor causing instability is the inability of the power system to meet the demand for reactive power. **The heart of the problem is usually the voltage drop that occurs when active- and reactive power through the inductive reactance associated with the transmission network**
  - ✓ In recent years, voltage instability has been responsible for several major network collapses, such as New York (1970), Florida (1982), France (1978 and 1987), Belgium (1982), Sweden (1983 and 2003), and Japan (1987)



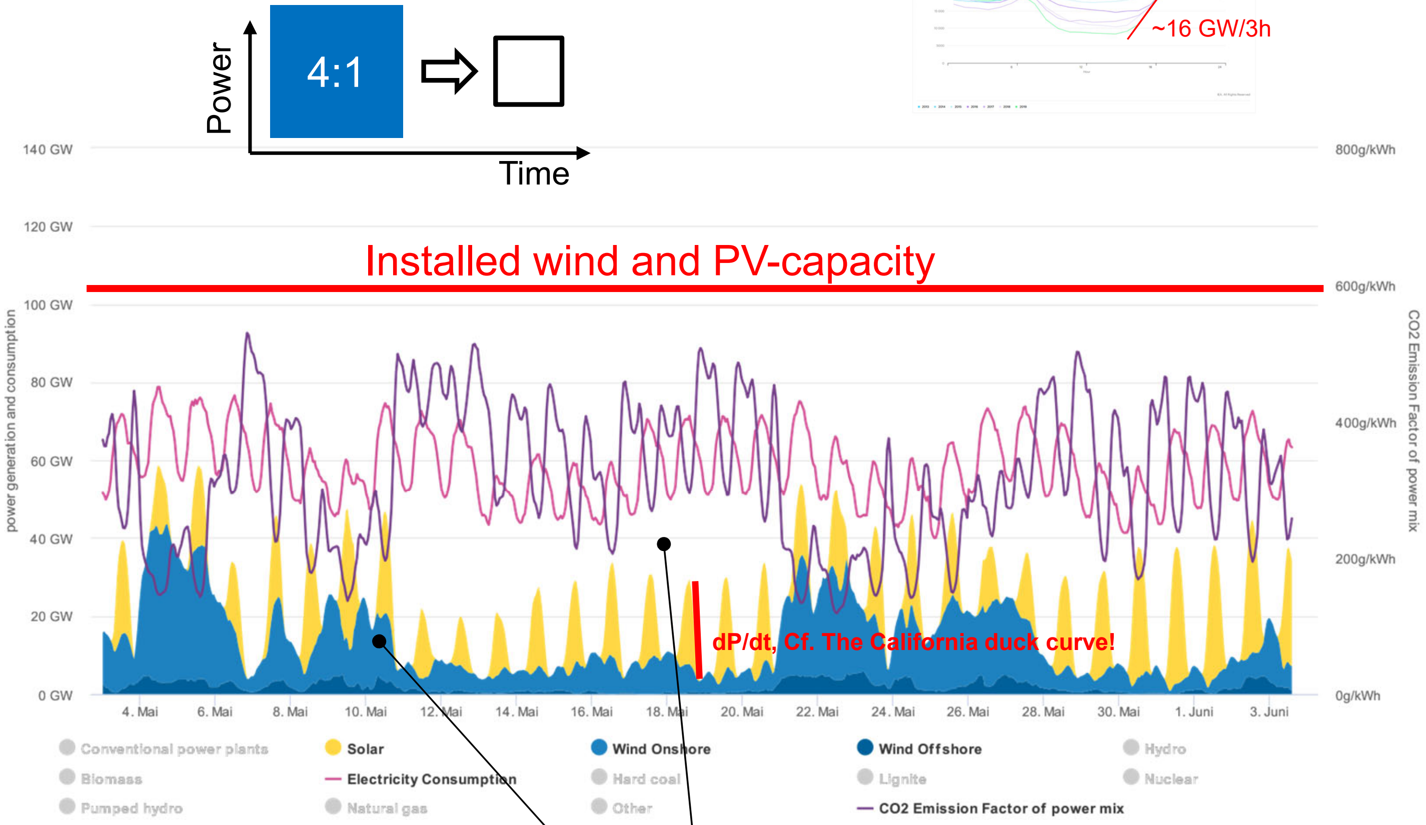
N.B., Study Kundur for an exhaustive treatment!

Germany May -21



The California Duck Curve

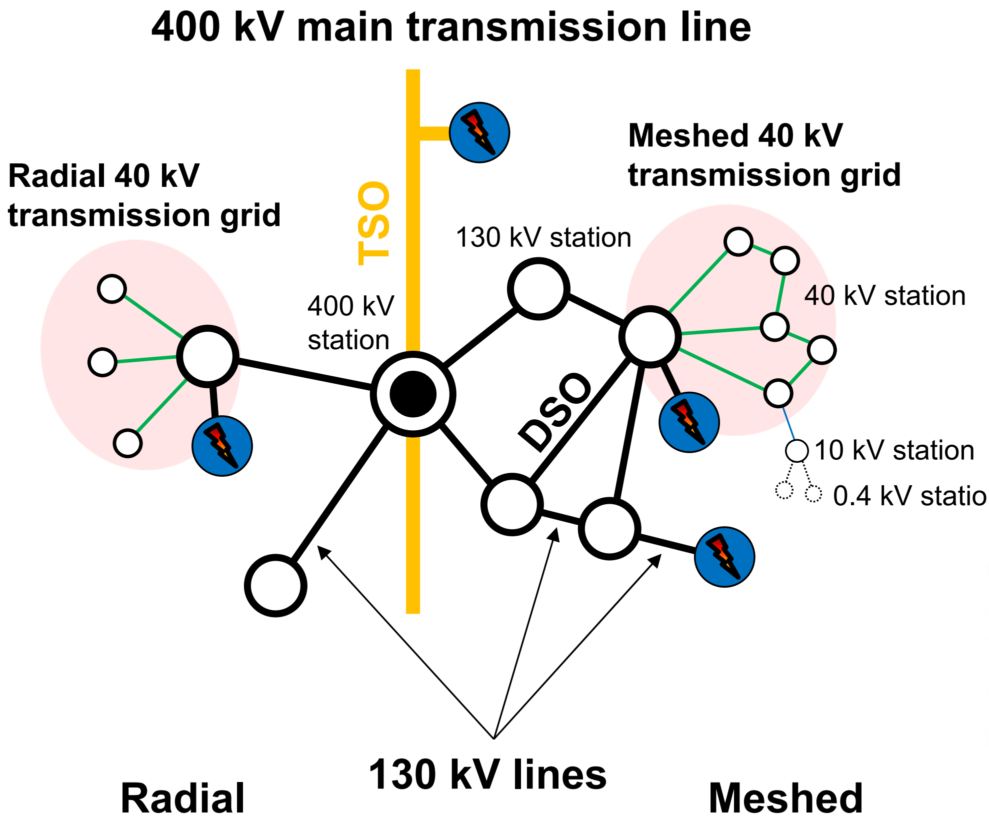
Last updated 19 Dec 2019

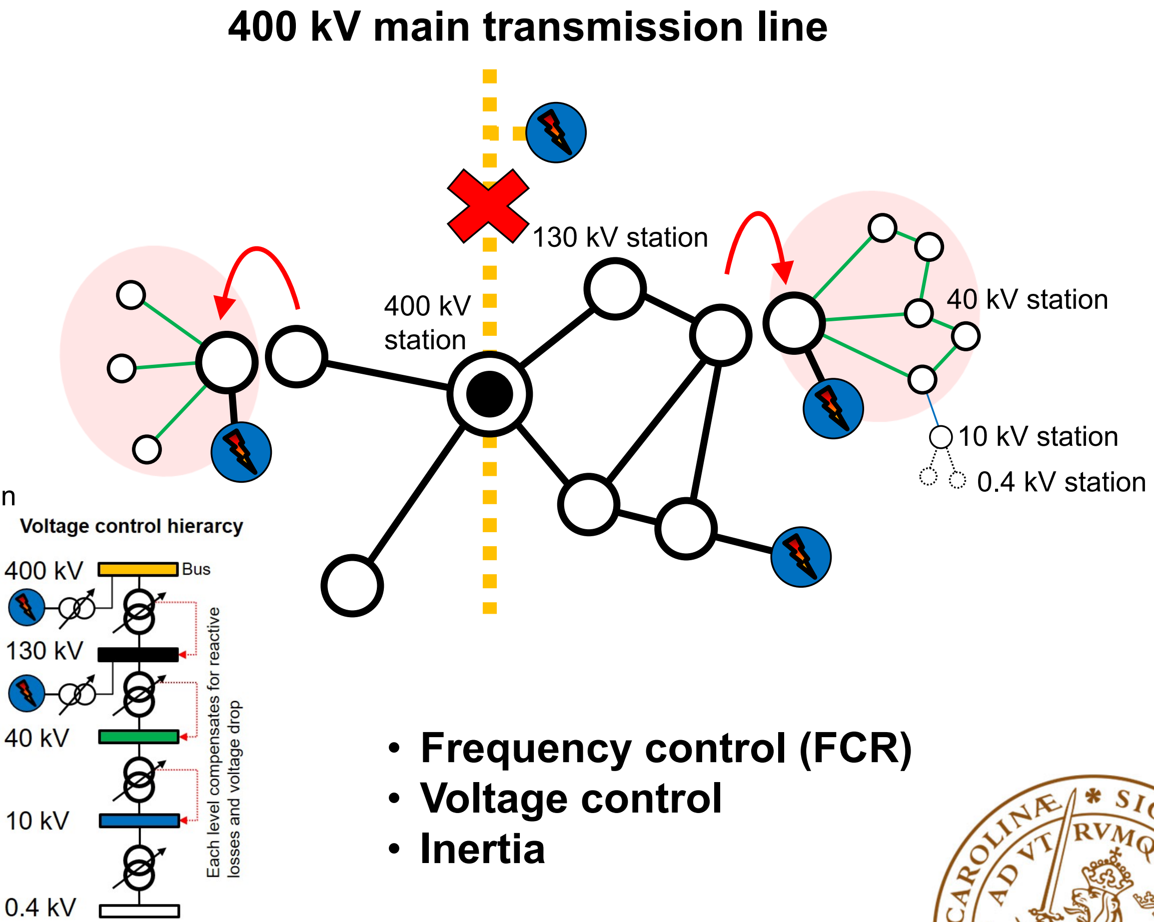


$$P\text{-}ratio = \frac{1}{LHV/HHV\prod_i(\eta_i)} \qquad E_{Wind} = \int_0^{8760} P_{Wind}\,dt \approx 2.4\ldots3.9\int_0^{8760} P_{GT}\,dt$$

Agora Energiewende; Current to: 03.06.2021, 15:45

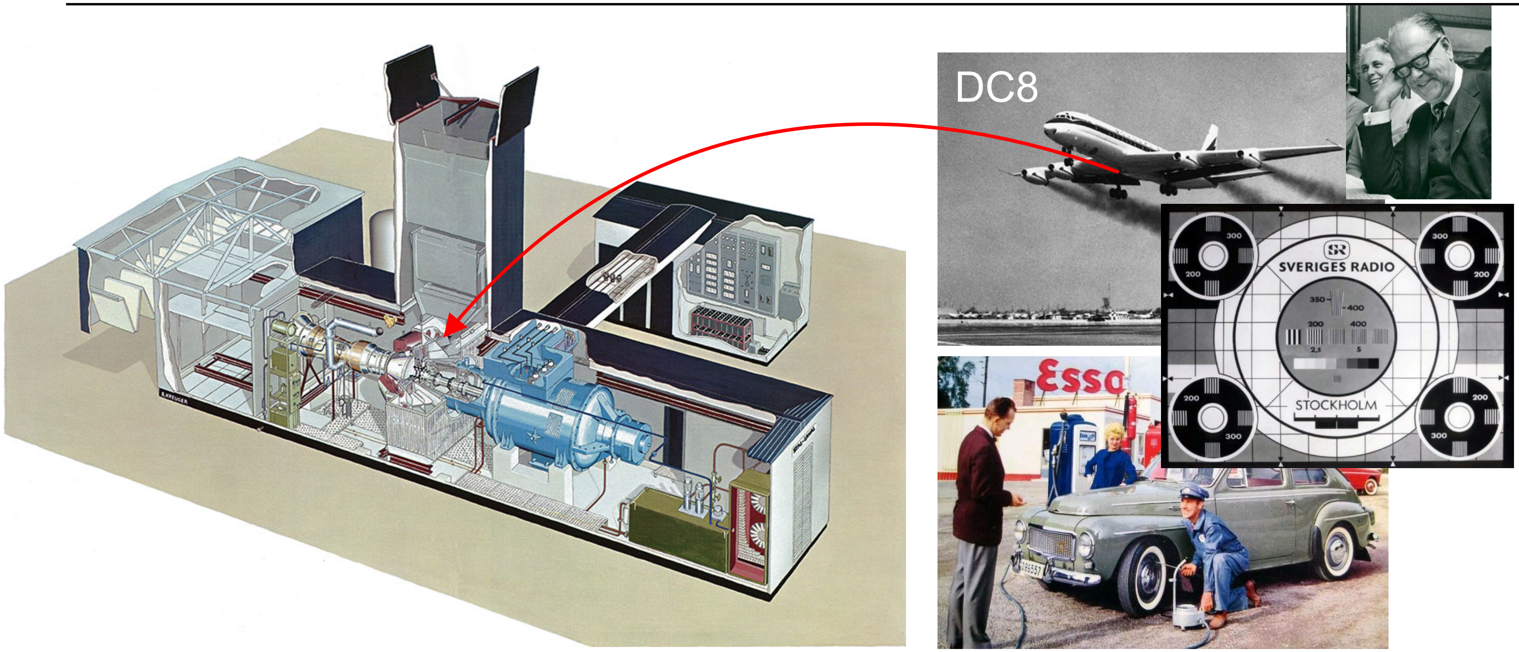
Black start and island mode – handling crisis and conflict





- **Frequency control (FCR)**
- **Voltage control**
- **Inertia**

Power plants – PP3 and PP4



The current fleet:

- Modern single-shaft
- Old single-shaft
- Old multi-shaft
- Old aero-derivatives

Beyond 2025:

- Market
- All xFRR
- RfG-rules for FRT (5 min rule)?

Plant	Noff	Installed	Power	Firing	GG	A/C*	Vintage
STAL PP3	**8**	65…71	7…15	≤ 850°C	JT3C-6	B707/DC8	1950
STAL PP4	**14**	73…74	15…21	≤ 850°C	JT4A	B707/DC8	1955

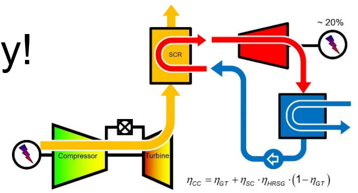
JT3C 1950 → JT3D (T-fan) 1958
JT4A 1955 → GG4/FT4

- JT3: B-52, KC-135,F-101, F-100, Sabre, F-8
- JT4: F-106, U-2, F-105

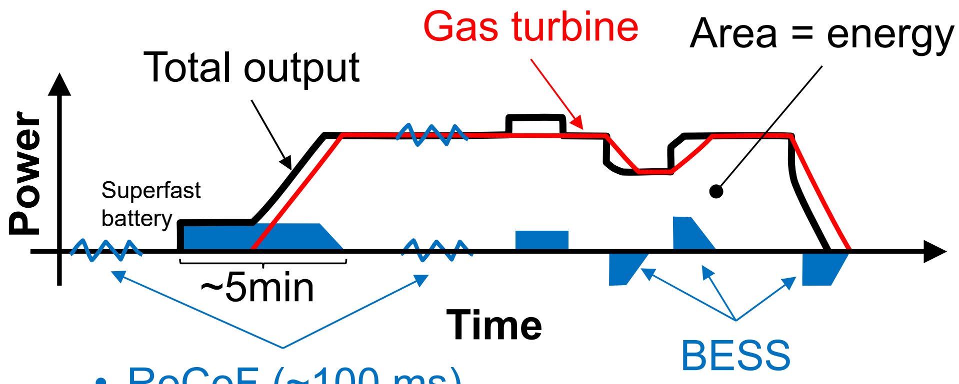
Gas turbines for SE3 and SE4?

- **Renewable fuels**
  - Hydrogen
  - e-Methanol
  - Ammonia
  - HVO
  - Bio-gas

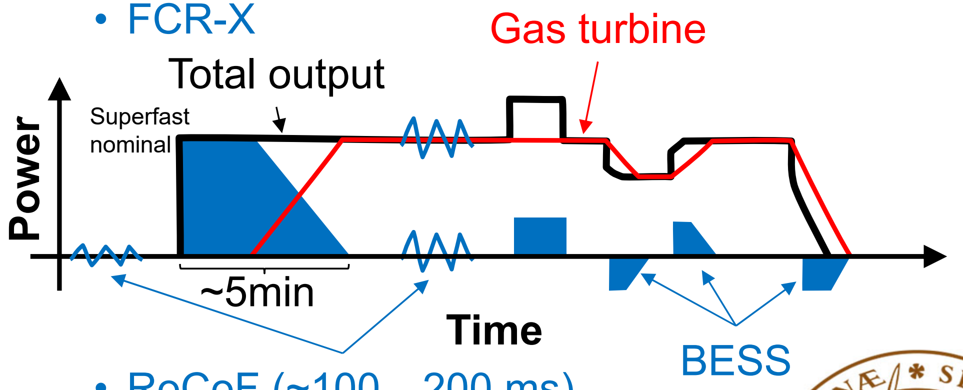
@64 % Efficiency!



- **5…10 minutes start**
  - GTCC within 30 min
  - Future hot start capability 2 min for GT and 15 for GTCC
- **A plethora of grid support**
  - FCR-N/FCR-D
  - aFRR/mFRR (i.e., secondary and tertiary)
  - Synchronous compensation (voltage/reactive power)
  - Black start and island operation
  - Inertia 1…3 and 5…~9 seconds (FRT)
  - Short-circuit current
- **Combine with battery and SSS-clutch**
  - FFR (~100…200 ms), FCR-D, xFRR, … from the battery
  - Voltage/reactive/short-circuit/inertia (24/7)
  - No emissions!!! Hydrogen produces NOx!

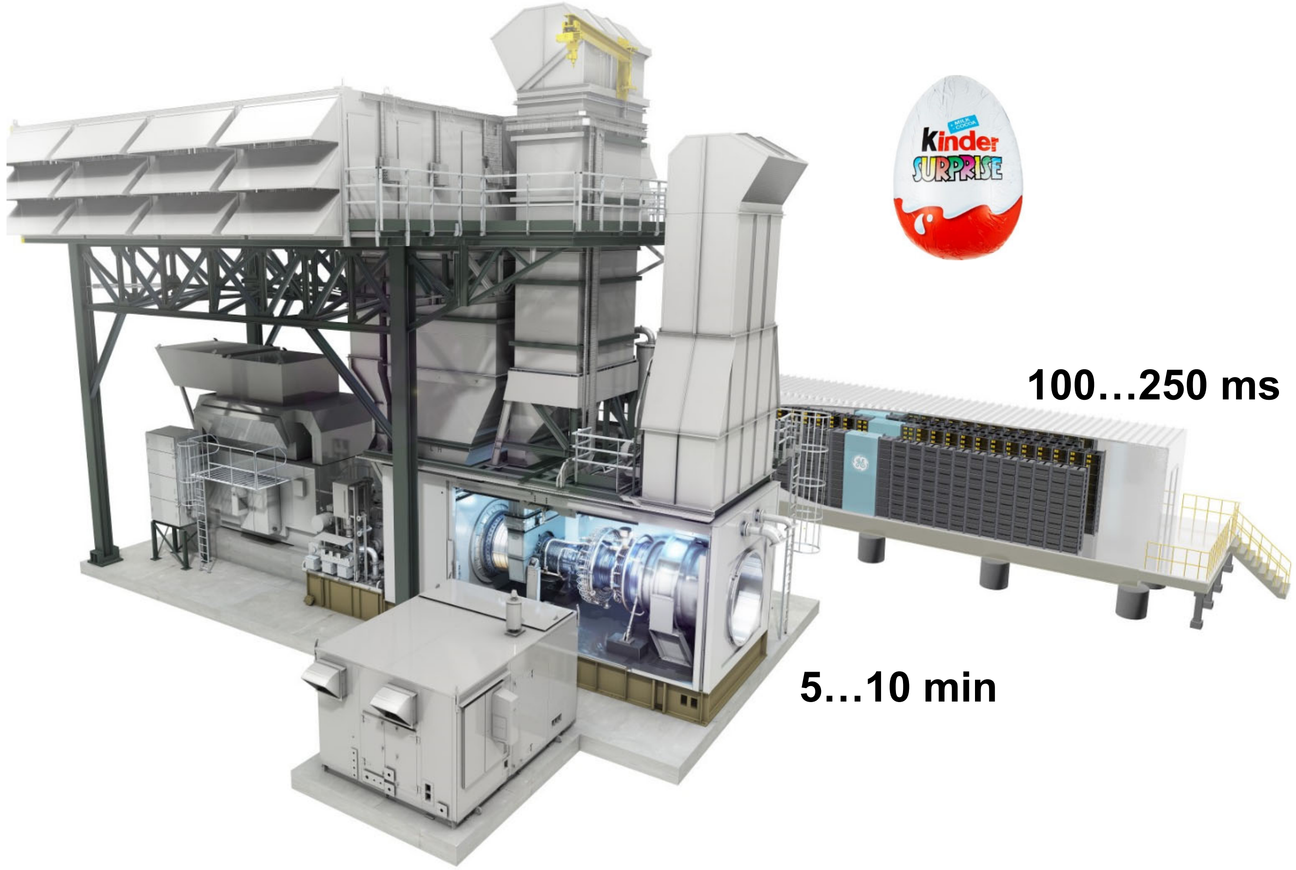


- RoCoF (~100 ms)
- FCR-X



- RoCoF (~100…200 ms)
- FCR-X

Gas turbine + BESS



100…250 ms

5…10 min

Courtesy to General Electric

10 MW Li Ion Battery

Attributes without Fuel Burn

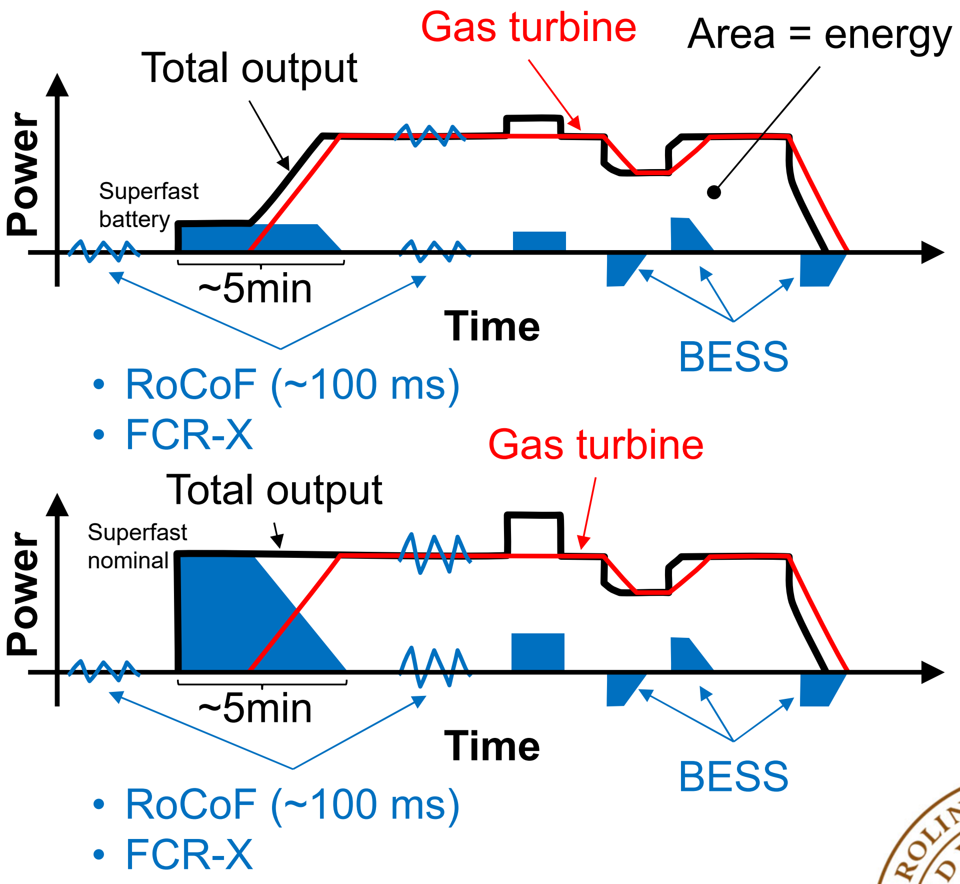
- Instant response, always ready technology
- 50 MW of operating reserve
- Primary frequency response
- 5 to -8 MVAR voltage support
- 134 MW-secs inertia with synchronous condensing
- Black start technology
- Demand charge savings

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

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

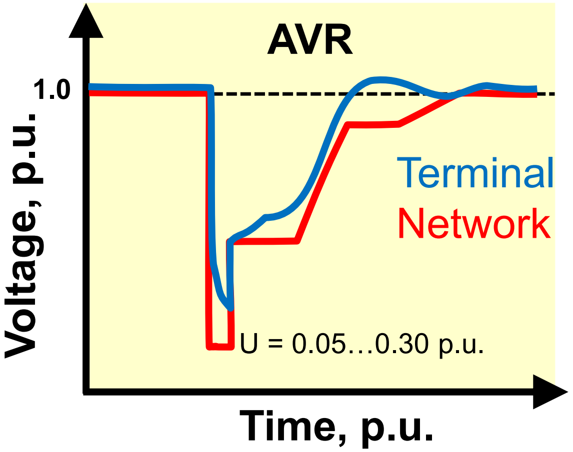


- RoCoF (~100 ms)
- FCR-X

- RoCoF (~100 ms)
- FCR-X

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)

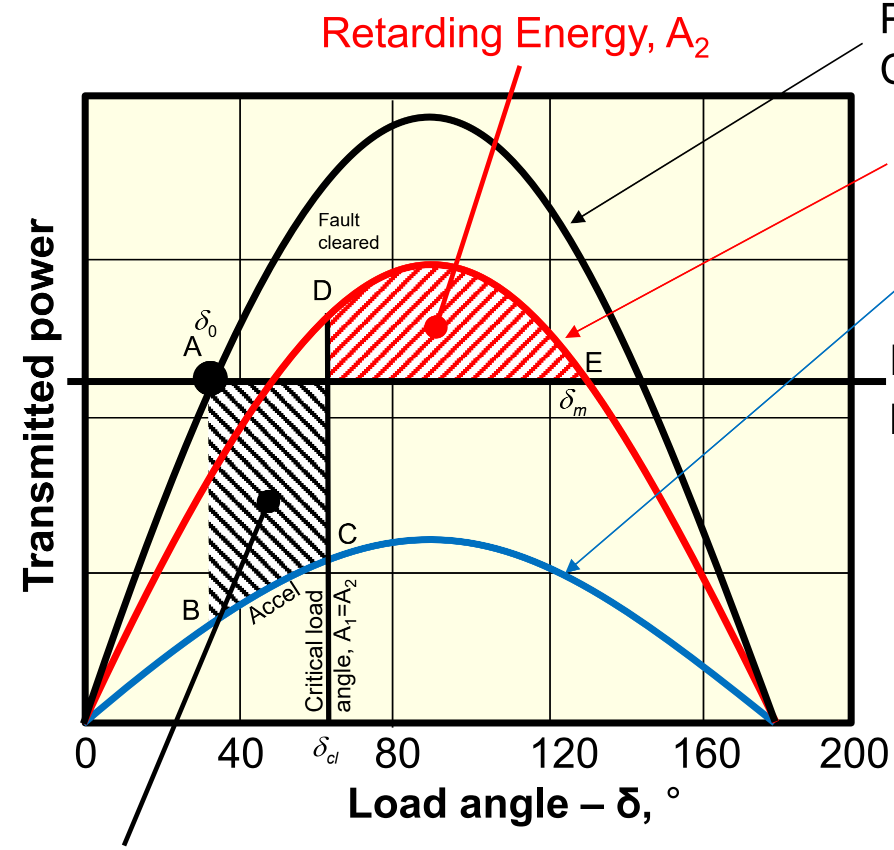


$$\left.\begin{aligned}\frac{df}{dt}&=\frac{\Delta P}{2\cdot H\cdot P_{nom}}\cdot f_{nom}\\ \omega&=2\cdot\pi\cdot f\end{aligned}\right\}\therefore\frac{d\omega}{dt}=\frac{\pi\cdot\Delta P}{H\cdot P_{nom}}\cdot f_{nom}$$

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

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

The equal area criteria



Retarding Energy, A_2

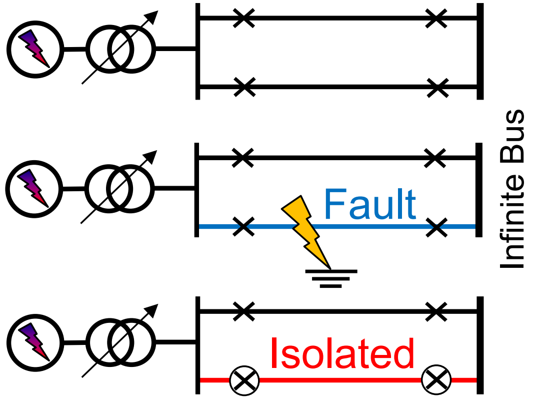
Power Angle Curve – Healthy Condition

Power Angle Curve – One Circuit Lost (weaker grid)

Power Angle Curve – Curve During Fault

Prefault power

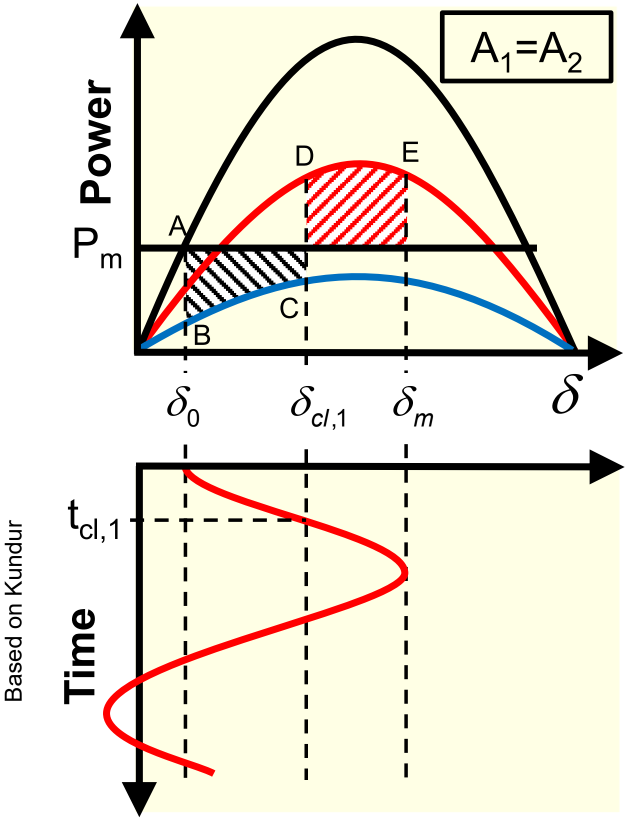
Accelerating Energy, A_1



The system is stable if the area $\mathbf{A_1}$ is smaller than the area $\mathbf{A_2}$.

Based on C.E.G.B

The equal area criteria cont'd



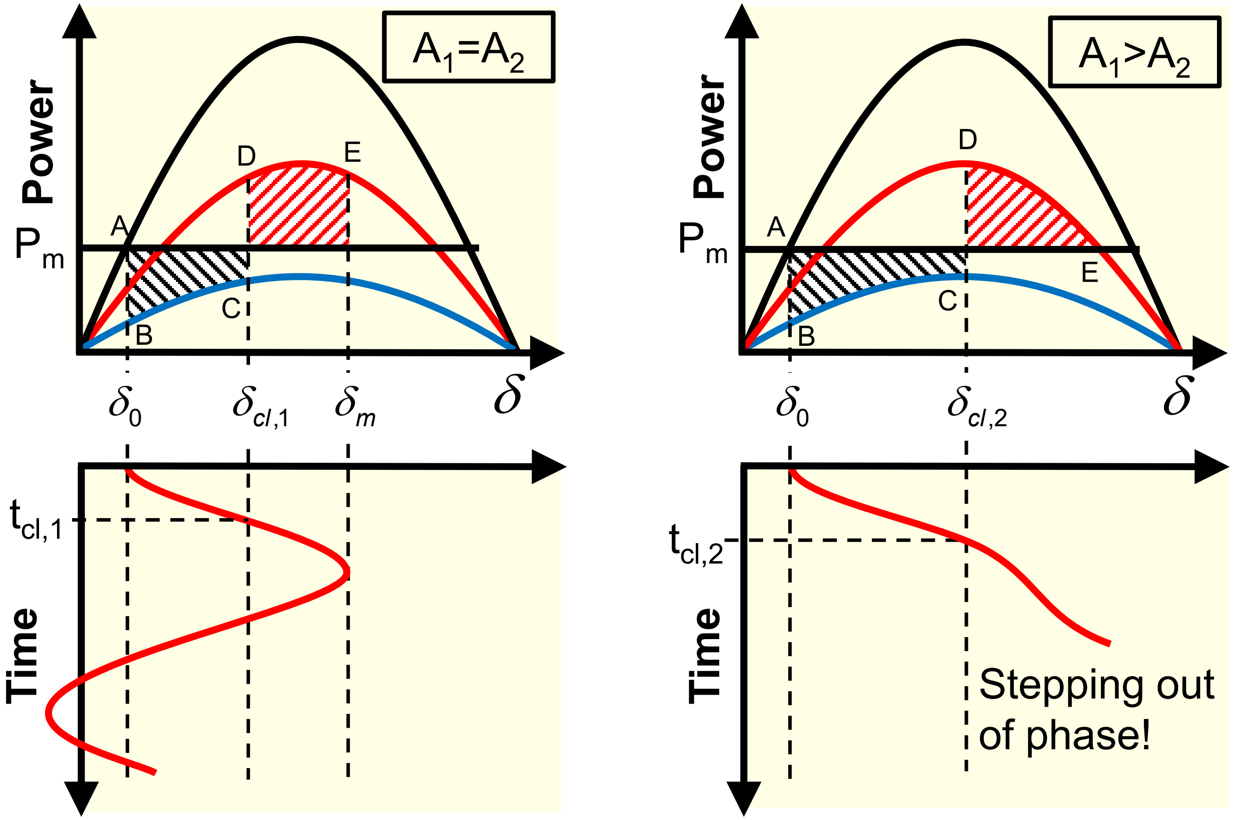
Stable case

1. When the fault occurs, the operating point suddenly changes from "A" to "B". Owing to inertia, the load angle cannot change directly
2. The shaft power is larger than the electric power, and the rotor accelerates to "C".
3. When the fault is cleared (by isolating line 2 from the system), the operating point suddenly shifts to "D". **Now the electric power is higher than the shaft ditto, eventually causing deceleration**. The rotor speed is still higher than the nominal!
4. The rotor speed will continue to increase until the gained energy (i.e., A_1) is consumed, and we will reach point "E" at nominal speed – hence, A_2 equals A_1!
5. Since the electric power is higher than the shaft power, the rotor decelerates below nominal ("E" to "D" and further down), and the load angle drops.
6. There will now be a new minimum load angle, which depends on the post-fault equal area criteria…
7. In the absence of **damping**[1], the system will continue to oscillate with constant amplitude!

[1] Fast load reduction and exciter response (PSS)

The equal area criteria cont’d

Based on Kundur



Stable case

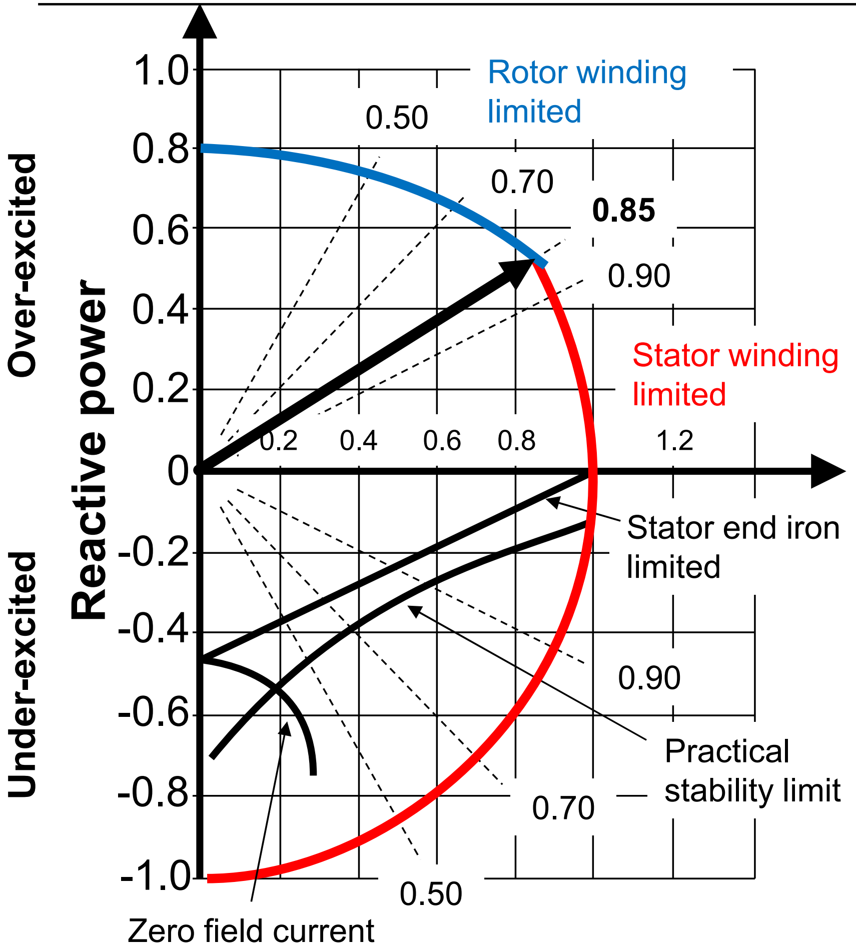
Instability

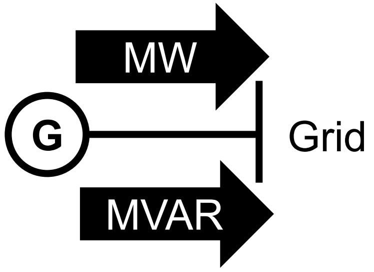
Fault ride-through (FRT) capability – important factors

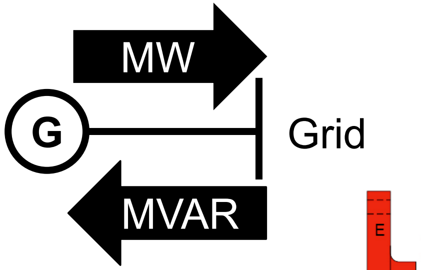
- The generator load before the fault
- The generator load during the fault – depends on the fault location and type.
  - For example, a meshed or radial grid
- The fault-clearing time
- The post-fault transmission system reactance
- The generator reactance, where lower increases peak power and reduces the initial load angle
- **The turbo-set inertia. The higher the inertia, the slower the rotor angle change rate. This reduces the gained kinetic energy during the fault – i.e., lower A_1!**
- The generator’s internal voltage, i.e., the exciter
- The infinite bus voltage magnitude

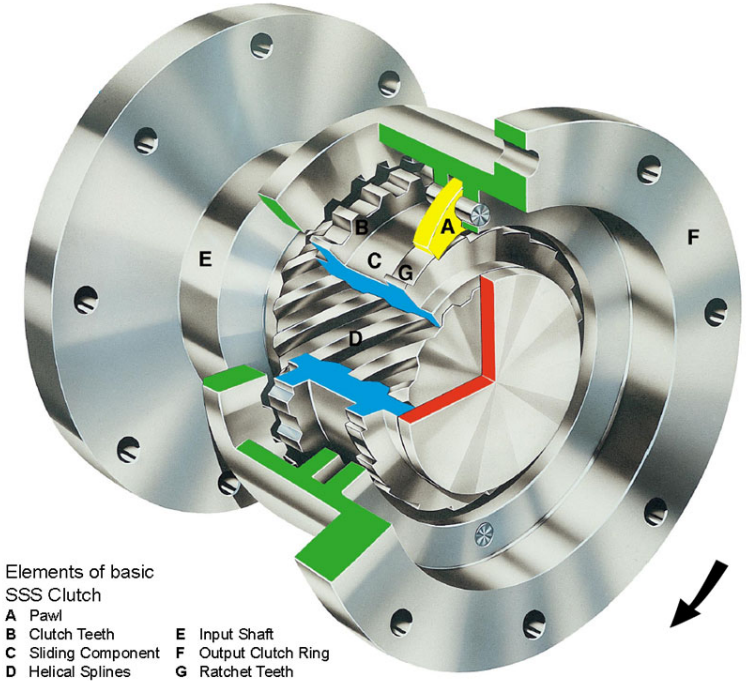
N.B., Study Kundur for an exhaustive treatment!

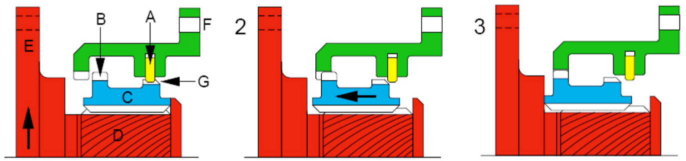
Alternator capability and SSS-clutch











SSS-clutches in Sweden – more than 43!

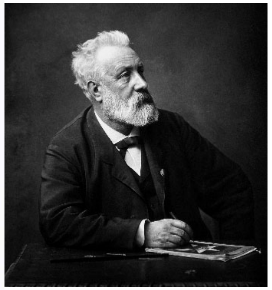
Year	Power – rating	Number of	Site	Engine
~~1969~~	~~50~~	~~1~~	~~Värtan~~	~~SL GT120~~
1969	20	2	Nondisclosed	SL PP3/PP4
1970	65	1	-”-	V93
1970	65	1	-”-	V93
1970	20	1	-”-	SL PP3
1971 (1972)	70	3	-”-	SL GT120
1971	30	6	-”-	RR Avon
1971	30	2	-”-	RR Avon
1971	30	2	-”-	RR Avon
1971	20	4	-”-	SL PP4
1972	20	2	-”-	SL PP3
1973	20	4	-”-	SL PP4
1974	80	2	-”-	SL GT120
1974	30	4	-”-	RR Avon
1975	35	4	-”-	RR Avon

Synchronous condensation:

- Sweden has more than 43 SSS clutches installed
- Total installed SSS clutches in 2012 exceeded 550 units

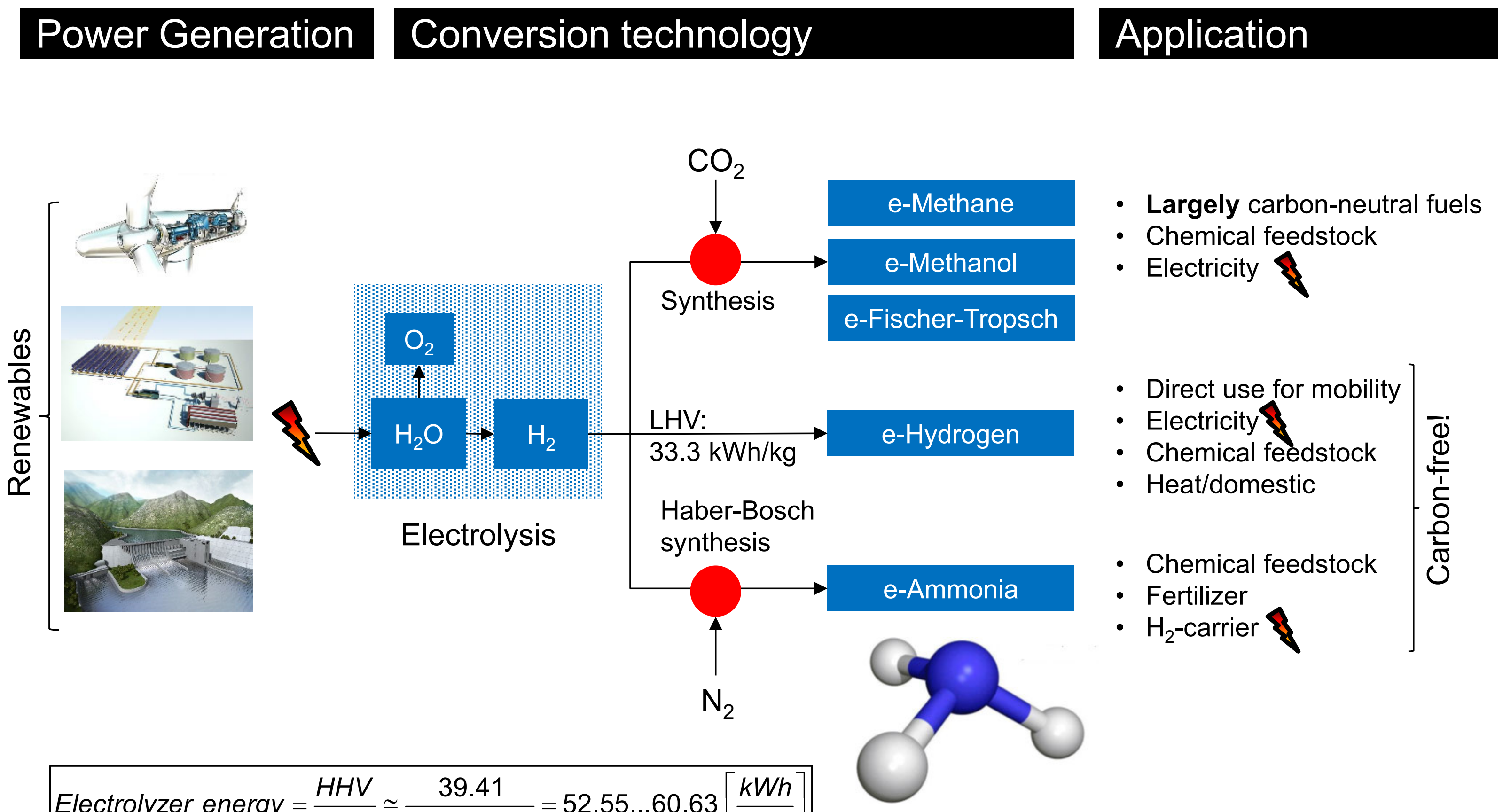
Hydrogen

"…I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable…"



Jules Verne – The Mysterious Island (L'Île mystérieuse), 1874

Power-to-Hydrogen and e-fuels



Power Generation | **Conversion technology** | **Application**

- **Largely** carbon-neutral fuels
- Chemical feedstock
- Electricity

- Direct use for mobility
- Electricity
- Chemical feedstock
- Heat/domestic

- Chemical feedstock
- Fertilizer
- H_2-carrier

$$Electrolyzer\ energy = \frac{HHV}{\eta} \cong \frac{39.41}{0.65...0.75} = 52.55...60.63 \left[\frac{kWh}{kg}\right]$$

Ammonia – the flip side…

PREMIUM - FÖR DIG SOM PRENUMERERAR

KÄVLINGE 18 april 2021 10:00

25 år sedan ammoniakolyckan i Kävlinge: ”Det var som en krigszon”

Under några dygn i april 1996 vändes allas blickar mot Kävlinge. Ett godståg spårade ur i en kurva mellan Kävlinge och Furulund och två vagnar lastade med 85 ton ammoniak välte. Det blev början på ett pådrag som varade i tre dygn och tvingade 9 000 människor att lämna sina hem.

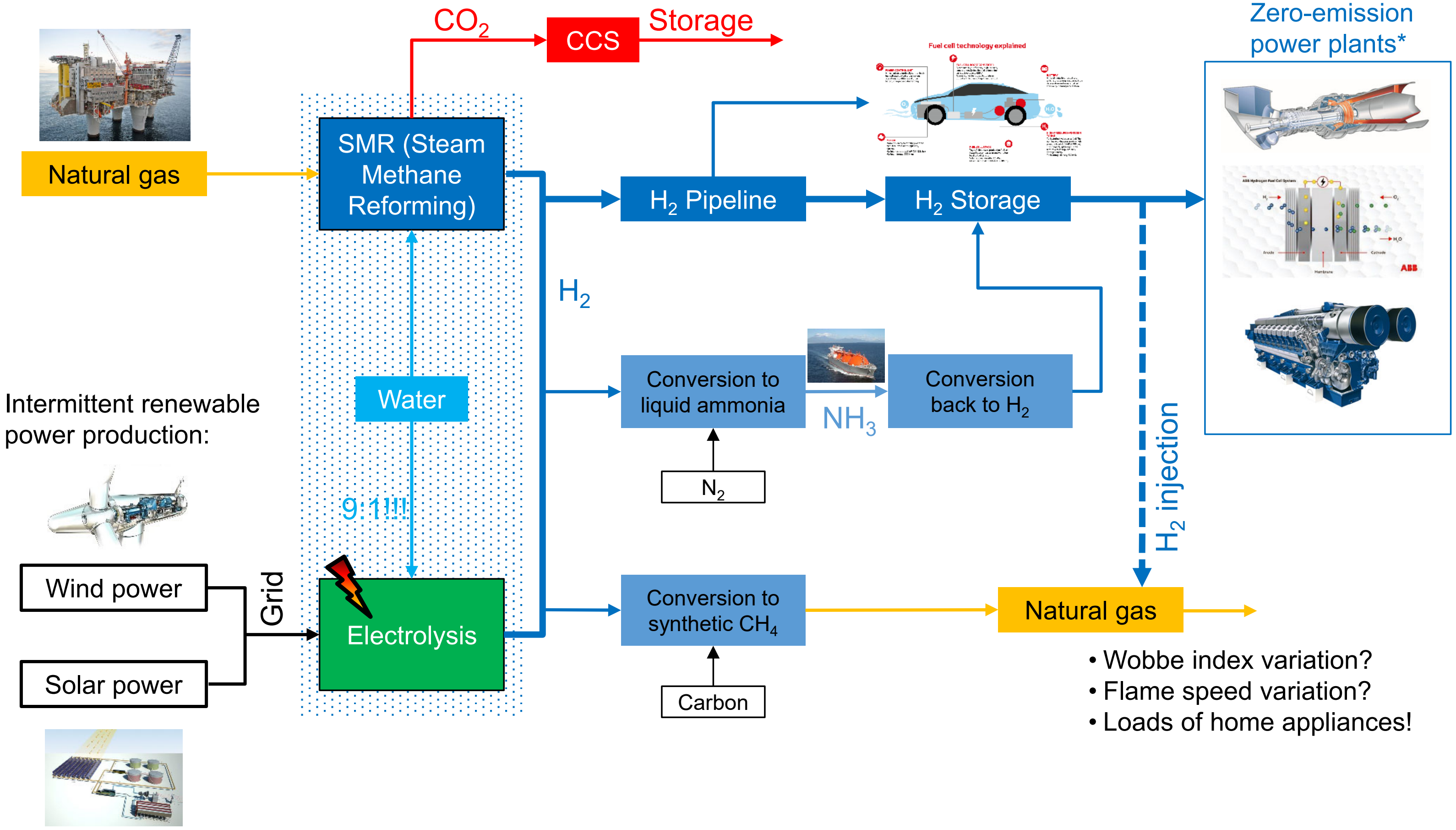
Emelie Malmros

Maria Sehlin

Vid olyckan spårade nio vagnar ur. De två välta tankvagnarna innehöll 45 respektive 40 ton ammoniak, vilket krävde ett stort säkerhetspådrag.

Bild: Peter Kroon

Hydrogen – possibilities for power



Natural gas

SMR (Steam Methane Reforming)

CO_2

CCS

Storage

Water

9:1!!!

Electrolysis

Intermittent renewable power production:

Wind power

Solar power

Grid

H_2

H_2 Pipeline

H_2 Storage

Conversion to liquid ammonia

NH_3

Conversion back to H_2

N_2

Conversion to synthetic CH_4

Carbon

H_2 injection

Natural gas

Zero-emission power plants*

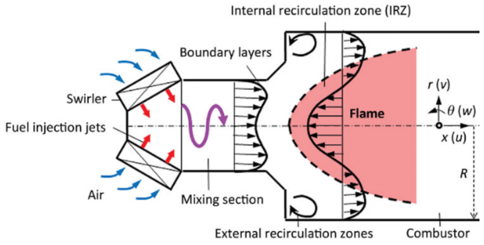
- Wobbe index variation?
- Flame speed variation?
- Loads of home appliances!

*64% (+) efficiency for GTCC

Hydrogen – key fuel characteristics

	H_2-blend in pipeline natural gas					
H_2-blend (%-vol)	**0**	5	10	20	30	**100**
Laminar flame speed[1] [cm/s]	**124**	127	130	139	150	**749**
Autoignition delay time[2] [ms]	**124**	112	107	104	103	**76**
Rel Wobbe index	**1**	0.987	0.974	0.947	0.919	**0.855**
Flame temperature[3] [°C]	**2,319**	2,321	2,324	2,329	2,337	**2,488**
Flammability (%-vol LEL)	**4.88**	4.83	4.79	4.71	4.63	**4**
H_2-blend (%-vol)	**0**	5	10	20	30	**100**

[1] Calculated for equivalence ratio 1.0 @ 316°C/1 atm
[2] Calculated for equivalence ratio 0.4 @ 649°C/1 atm
[3] Adiabatic stoichiometric for a typical gas turbine



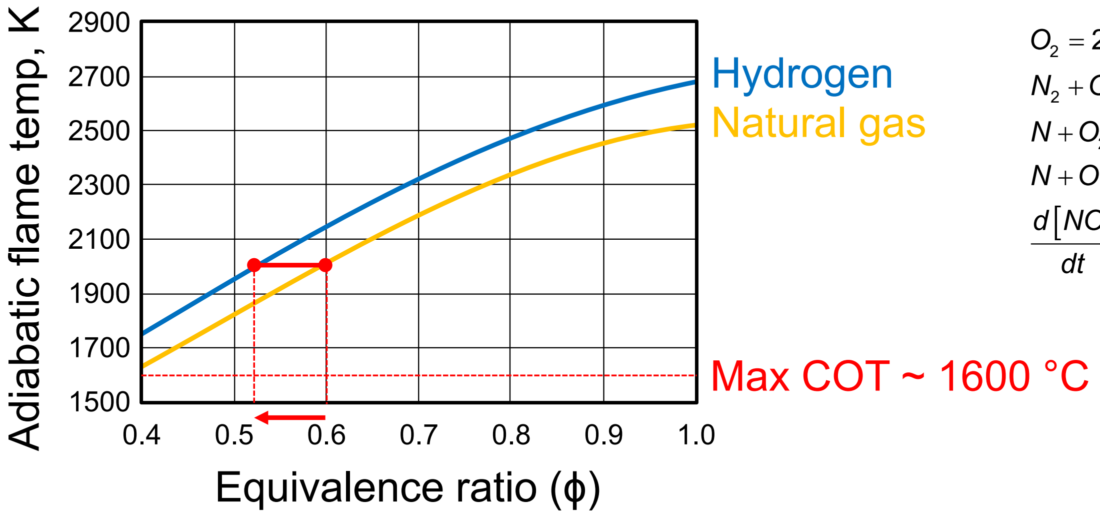
Benim & Syed: Flashback Mechanisms in Lean Premixed Gas Turbine Combustion

$$\frac{2\left[\frac{USD}{kg}\right]}{120\left[\frac{MJ}{kg}\right]}\cdot 3600\left[\frac{s}{h}\right]=60\left[\frac{USD}{MWh}\right]=30\cdot f\left[\frac{USD}{kg}\right]$$

$$Electrolyzer\ energy=\frac{HHV}{\eta}\cong\frac{39.41}{0.65...0.75}=52.55...60.63\left[\frac{kWh}{kg}\right]$$

Hydrogen storage:
- 39.2 kg/m^3@700 bar/25°C
- 67.7/2.5 kg/m^3@2bar/-250.2°C

Hydrogen – flame temperature



$$O_2 = 2 \cdot O$$

$$N_2 + O \leftrightarrow NO + N \quad (slowest)$$

$$N + O_2 \leftrightarrow NO + O$$

$$N + OH \leftrightarrow NO + H$$

$$\frac{d[NO]}{dt} = C_1 \cdot T^{-\frac{1}{2}} \cdot e^{-\frac{69090}{T}} \cdot [N_2] \cdot [O_2]^{\frac{1}{2}}$$

How do we fix the NOx-issue?

- Higher adiabatic flame temperature with hydrogen…
- Increasing NOx with increasing temperature – the rate roughly doubles (!) in magnitude for each 20°C a.k.a the “misery factor
- Two principal tings to do – more lean or/and reduced residence time

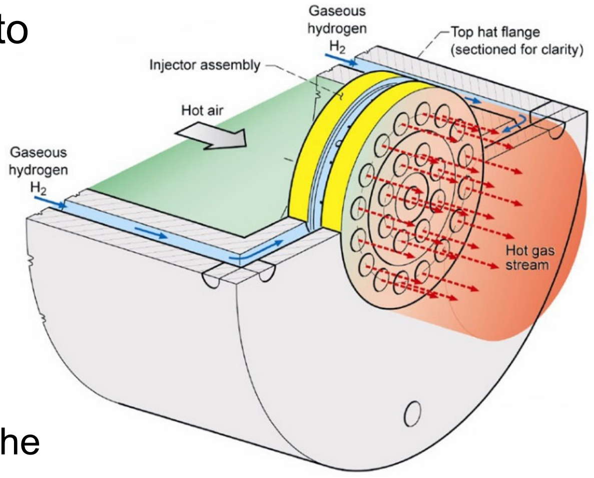
Hydrogen, Ammonia and Methane

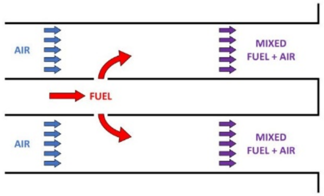
		Methane	Hydrogen	Ammonia
Molecule		CH_4	H_2	NH_3
Molecular weight	g/mol	16	2	17
Boiling temperature	°C	-161.5	-252.9	-33.3
Lower/upper flammability limits	%	4.4/17	4/75	15/28
Flame speed	cm/s	~30…40	~200…300	~6…7
Burner exit velocity	m/s	60…75	?	?
Adiabatic flame temperature	°C	1,963	2,204	1,799
Lower heating value	MJ/Nm^3	35.8	10.8	14.1
Lower heating value	MJ/kg	50.0	120.0	18.6
Lower heating value	kWh/kg	13.9	33.3	5.2
NOx impact (relative to CH_4)	-	1	~2×	~150×

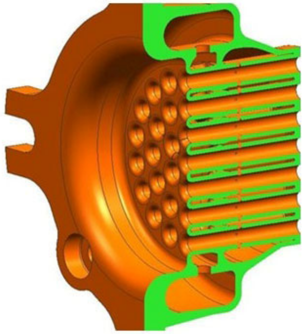
Critical swirl number is 0.5…0.6

NASA hydrogen combustor – LDI

- Normal “swirl-based” DLE-systems may run into severe issues:
  - ✓ Flashback
  - ✓ Flame holding
- **L**ean **D**irect **I**njection – LDI
  - ✓ Rapid mixing
  - ✓ Loads of small-scale mixers
  - ✓ Bulk velocity leaving the mixer is higher than the flame speed
  - ✓ Hole diameter less than the quench distance of the flame – little risk for flame holding within the tubes
- General Electric DLN2.6e



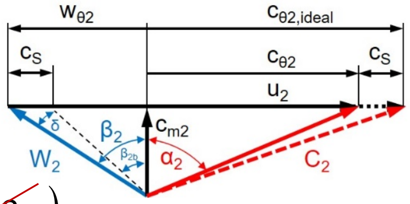




Hydrogen compression – a stress thing!

	NG	**H_2**
η_p [-]	0.87	0.87
$\gamma = c_p/c_v$ [-]	1.468	1.412
M [kg/kmol]	17.185	2.016
T_0 [K]	288.15	
a_0 [m/s]	452	1296
u_2 [m/s]	**700 (!!!) $\sigma \sim u^2$**	
$M_{u,2}$ [-]	1.55	**0.54**
$\beta_{2,b}$ [°]	-45 (0)	0
Z [-]	18	18
α_2 [°]	71*	
$\Delta h_0/u_2^2$ [-]	0.70 (0.87)	0.87
PR [-]	**4.82 (6.38)**	**1.34**
$Noff_{rel}$ [-]	1	5.3 (6.3)

*$\lambda \approx 2.9$



Basic equations:

$$\Delta h_0 = \omega\left(r_2 \cdot c_{\theta,2} - \cancel{r_1 \cdot c_{\theta,1}}\right)$$

$$c_{\theta,2} = u_2 + c_m \cdot \tan\beta_{2,b} - c_{slip}$$

$$\frac{\Delta h_0}{u_2^2} = \frac{\Delta c_\theta}{u} = \underbrace{1 - \frac{c_{slip}}{u_2}}_{\sigma} + \frac{c_{m,2}}{u_2}\tan\beta_{2,b} = \frac{\sigma}{1 - \frac{\tan\beta_{2,b}}{\lambda}}$$

Wiesner slip factor:

$$\sigma = 1 - \frac{\sqrt{\cos\beta_{2,b}}}{Z^{0.7}}$$

$$PR = \left[1 + (\gamma - 1)\frac{\Delta h_0}{u_2^2} M_{u2}^2\right]^{\eta_p \frac{\gamma}{(\gamma-1)}}$$

N.B., each stage must be inter-cooled!!!

Blade Mach number:

$$M_{u2} = \frac{u_2}{\sqrt{\gamma R T_{01}}}$$

Cost of Electricity – COE

COE = CAPEX + OPEX

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

$$H_2@2\left[\frac{USD}{kg}\right]:\frac{60\cdot 5}{2}=150\left[\frac{USD}{MWh}\right]$$

$$H_2@4\left[\frac{USD}{kg}\right]:\frac{120\cdot 5}{2}=300\left[\frac{USD}{MWh}\right]$$

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

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

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

$$\frac{CAPEX}{P} \approx (1.6 \ldots \mathbf{1.8} \ldots 2.0) \cdot \begin{cases} S/C: 4098 \cdot P^{-0.0843} - 1216 & [USD/kW] \\ GTCC: 337 + 6.58 \cdot 10^4 \cdot P^{-0.38} \end{cases}$$

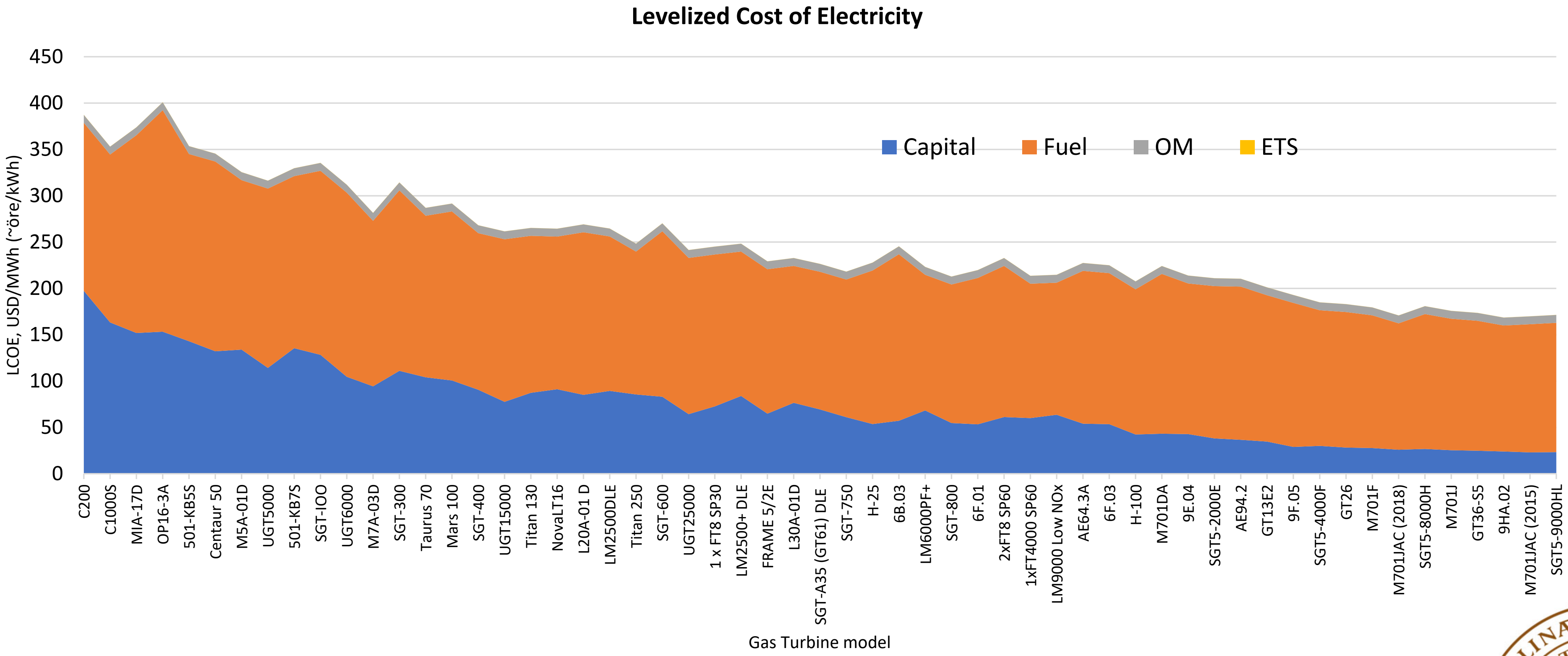
$$OM_{var} \approx (3.0 \ldots 3.5 \ldots 5.0) \cdot 10^{-3} \quad [USD/kWh]$$

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

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]

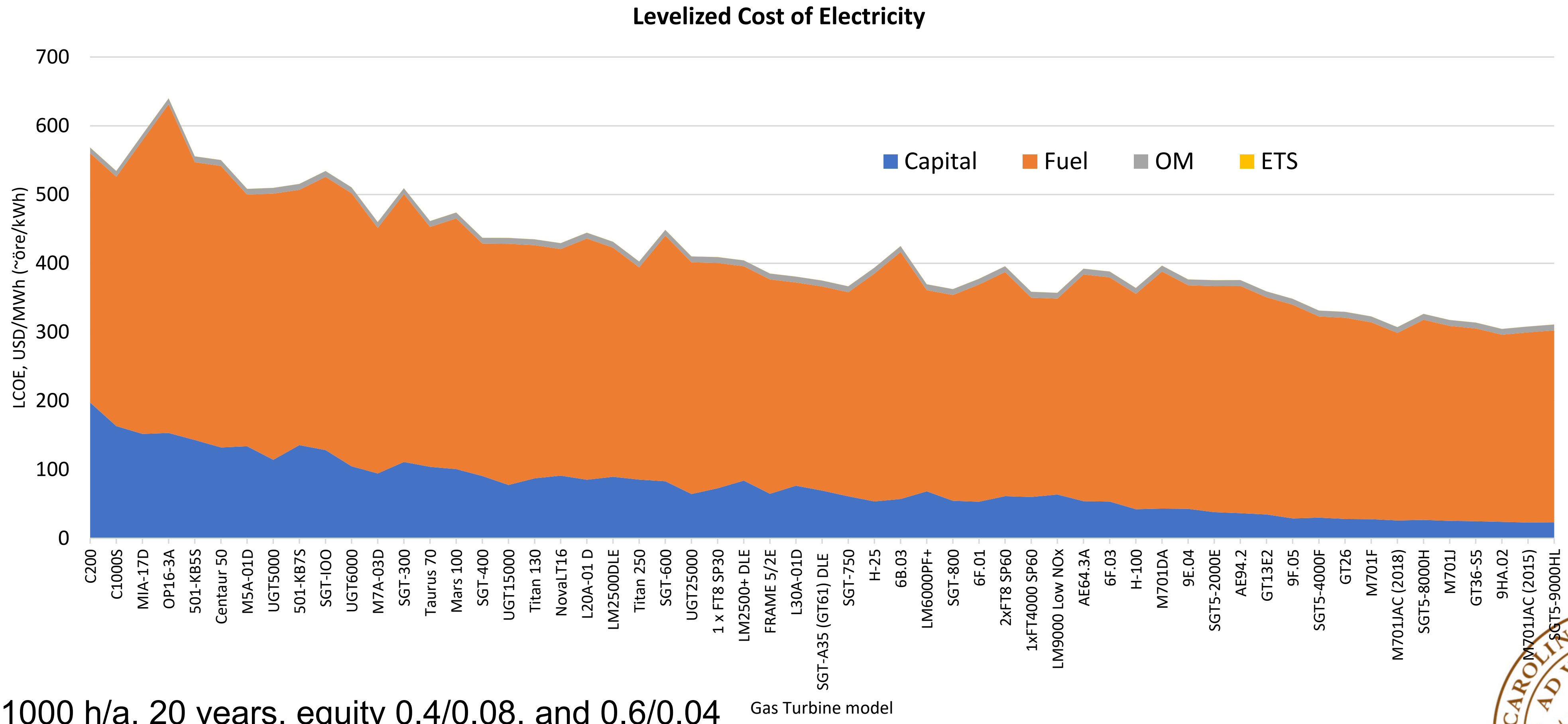
N.B. All OM costs are engine dependent! One may (typically) expect a service cost equivalent to a new engine during 80,000 operating hours. The total service market will exceed 41 BUSD 2025!

Hydrogen @ 60 USD/MWh – a feasible solution?



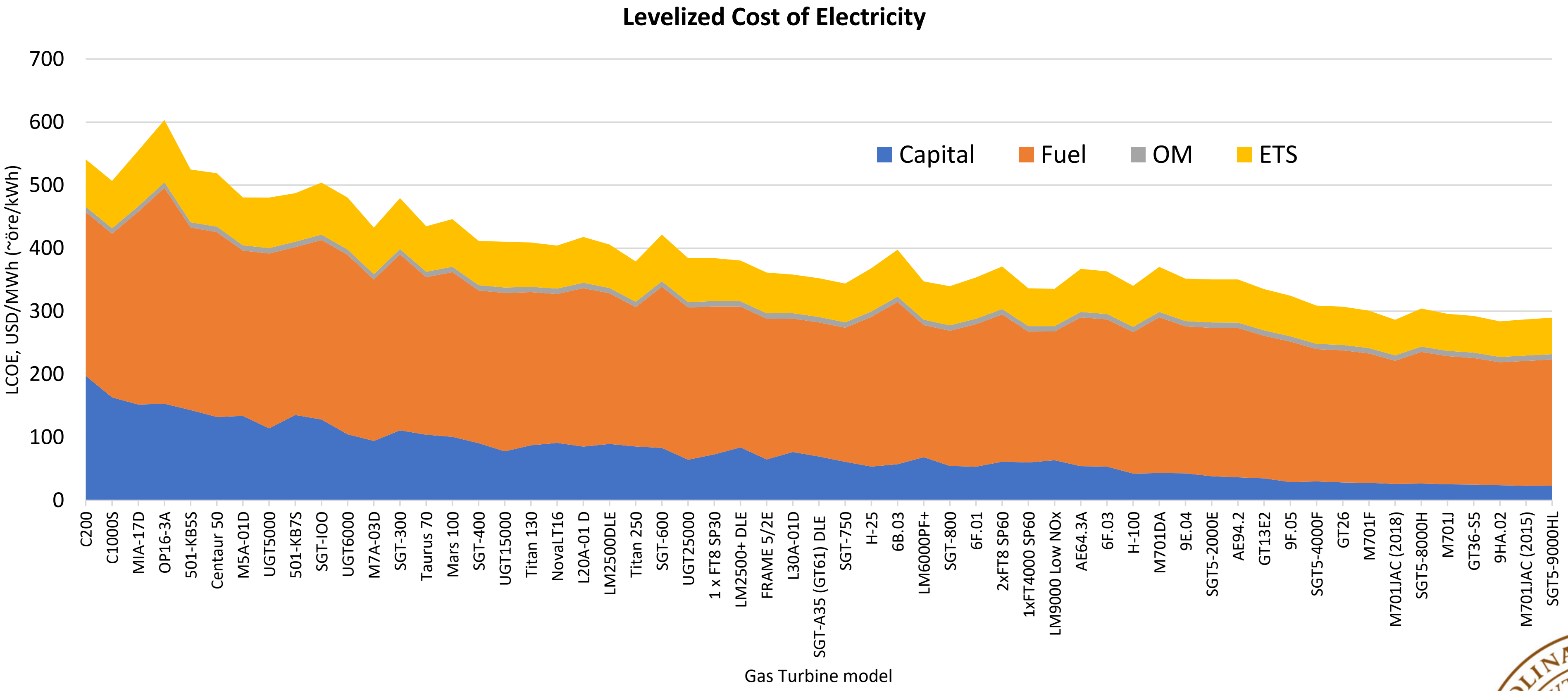
1000 h/a, 20 years, equity 0.4/0.08, and 0.6/0.04

Hydrogen @ 120 USD/MWh – a feasible solution?



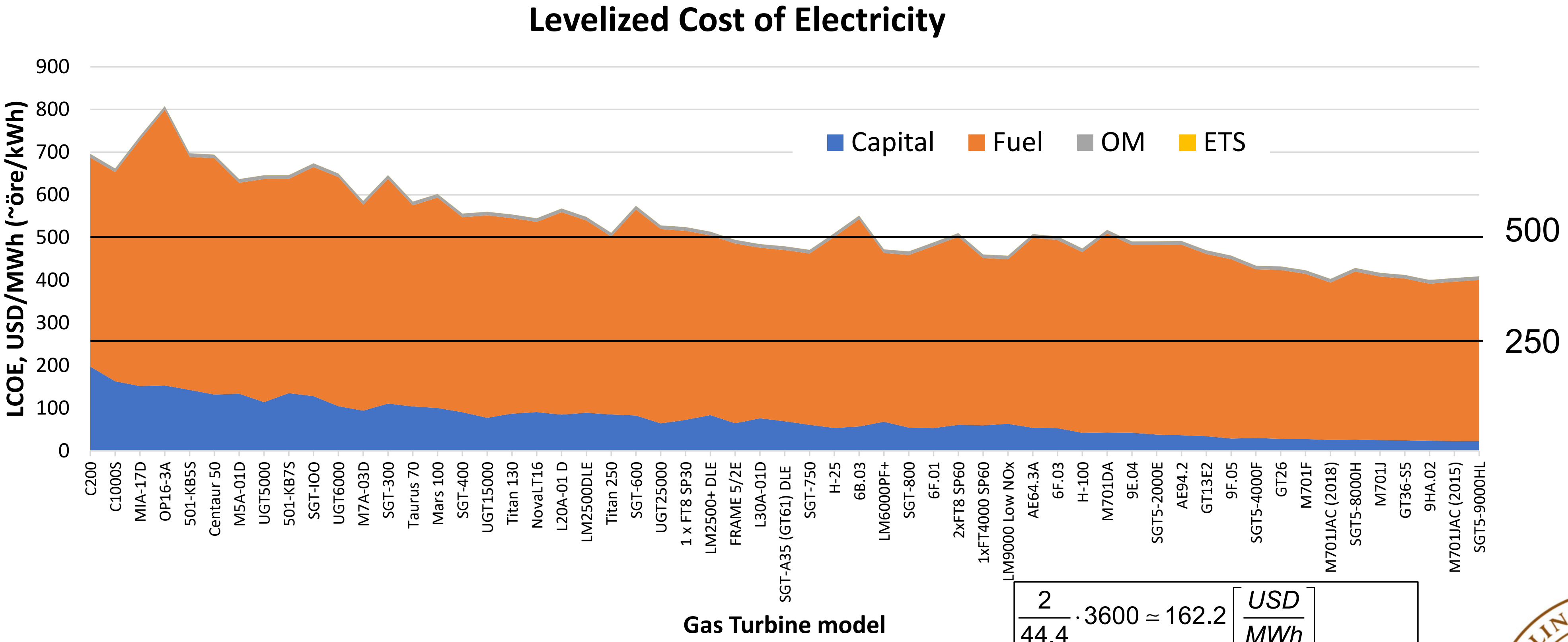
1000 h/a, 20 years, equity 0.4/0.08, and 0.6/0.04

Methanol @ 86 USD/MWh – a convenient solution?



1000 h/a, 20 years, equity 0.4/0.08, and 0.6/0.04

HVO @ 162.2 USD/MWh – a feasible solution?



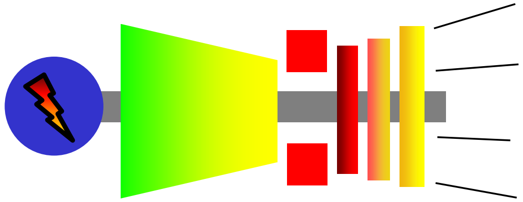
$$\frac{2}{44.4}\cdot 3600 \simeq 162.2\left[\frac{USD}{MWh}\right]$$

$$\therefore @40\%: \frac{162.2\cdot 5}{2} \simeq 406.25\left[\frac{USD}{MWh}\right]$$

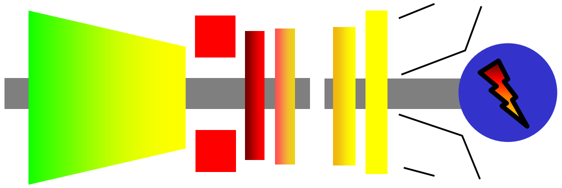
1000 h/a, 20 years, equity 0.4/0.08, and 0.6/0.04

Gas turbine technology – some features!

Single- vs. multi-shaft industrial I

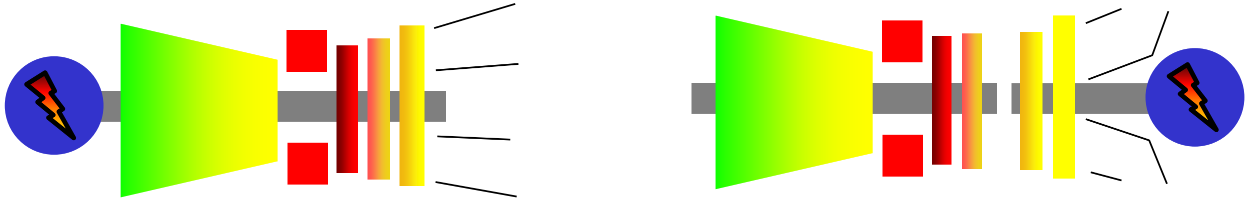


- Only power generation (torque issues)
- Part-load (pro's and con's) – effective way of controlling engine flow for high/constant exhaust temperature
- Exhaust size limitations (lower speed or high outlet velocity)
- Efficient exhaust
- 50/60 Hz direct drive for large units
- Beam rotor with two bearings



- Both power and driver
- Part-load (pros and cons)
- Lower starter power
- "Free" power turbine speed (lower outlet velocity level)
- Typically less efficient exhaust (lower recovery levels)
- Three-shaft aero-derivatives
- Low inertia (1…3 seconds)!
- PT over-speed risk at load rejection

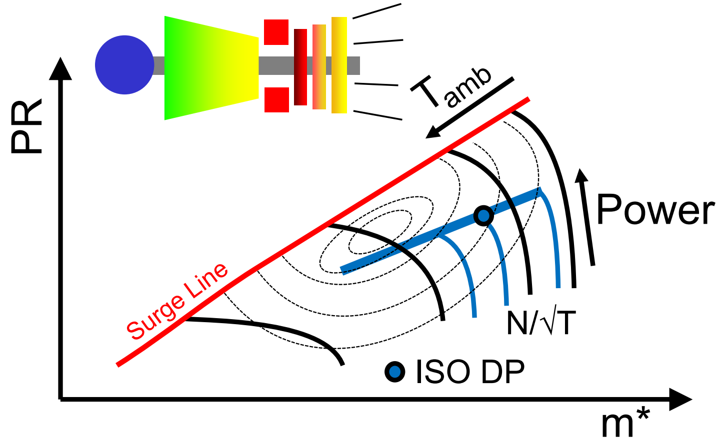
Single- vs. multi-shaft industrial II



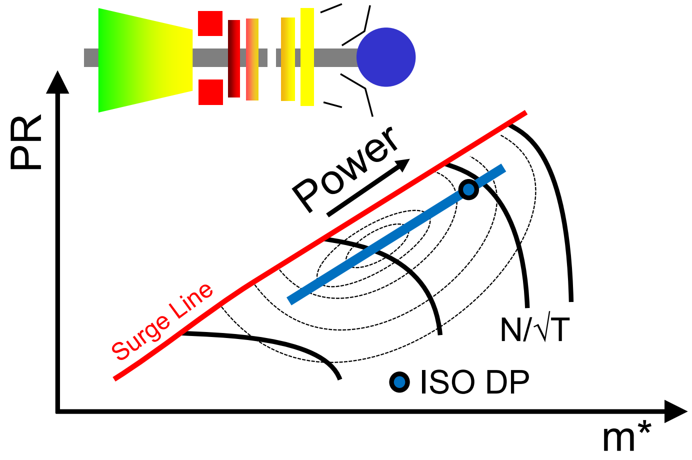
$$\underbrace{P_{Starter}}_{(A)} + \underbrace{P_{Turbine}}_{(B)} + \underbrace{\Delta P \cdot I}_{(C)} - \underbrace{\left|P_{Compressor}\right|}_{(D)} \geq 0$$

Where:
(a) Starter power
(b) Power delivered by the turbine
(c) Power required for the defined acceleration
(d) Power absorbed by the compressor

Single- vs. multi-shaft industrial III

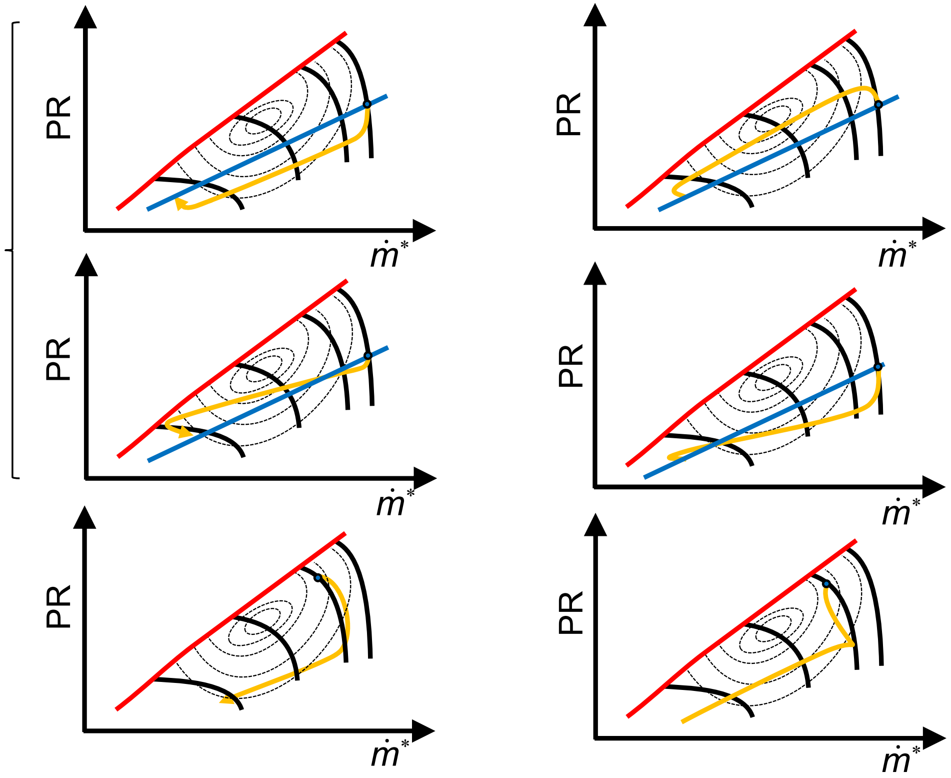


- Physical speed set by grid and gear ratio (<100 MW)
- Locus of operation at different ambient temp’s with nominal firing could be seen as a “running line”
- No rotor inertia lag (frequency response)
- Typically reduced surge margin at high ambient temperatures (COT/T_1)
- Grid code requirement of 6% under-speed at +50°C – may be problematic!



- Typical speed range 60…105 %
- Compressor speed is decoupled from the load
- The running line is, more or less, a function of firing – not ambient temp – for a certain engine
- No real grid code issues except for inertia requirements ☺

Single- vs. multi-shaft industrial IV



Deceleration

Acceleration

HP-compressor

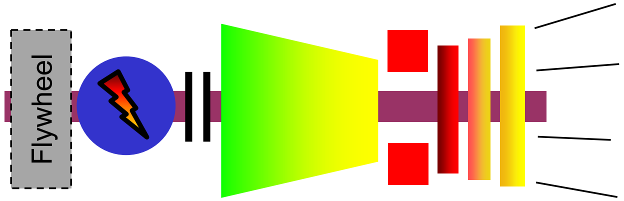
Multi-shaft

LP-compressor

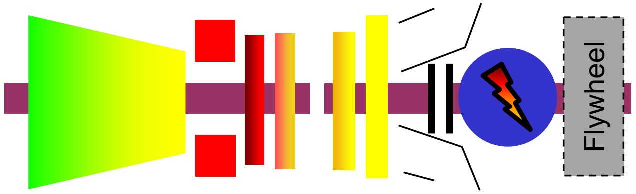
Single-shaft

Synchronous condensation

Single-shaft with SSS-clutch

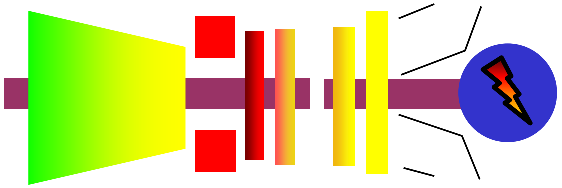


Twin-shaft with SSS-clutch



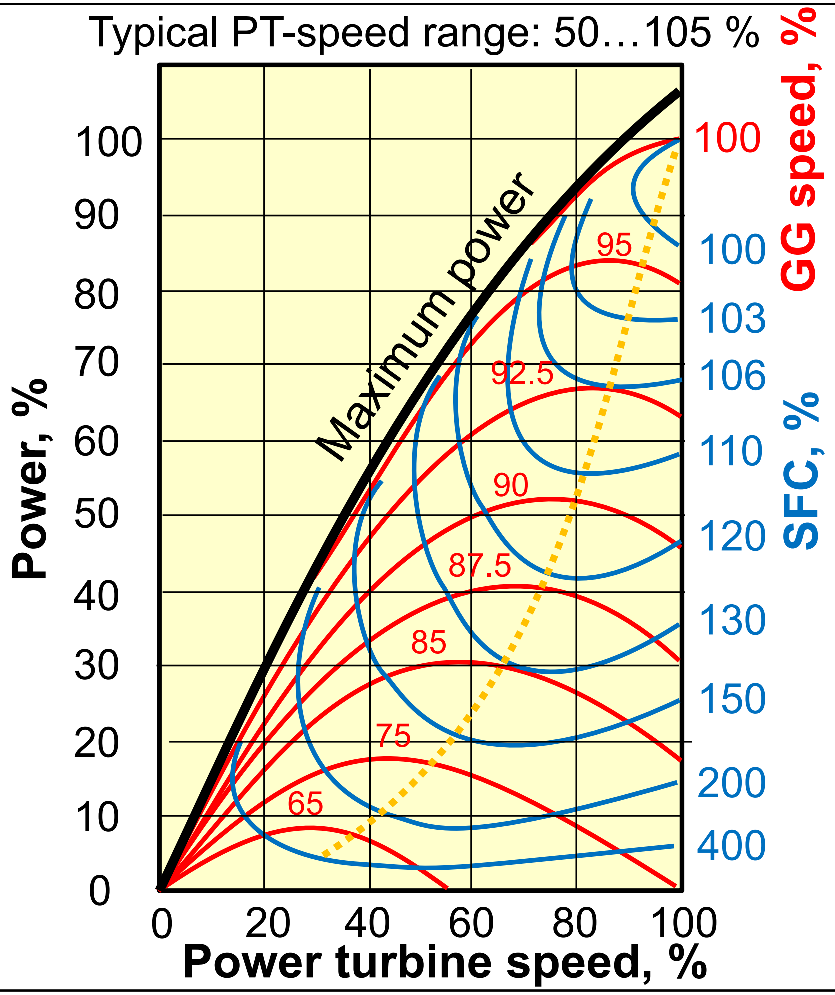
- Synchronous condensation without firing
  - ✓ Spinning PT?
  - ✓ SSS-clutch
  - ✓ Faster starts and less starter power
- Massive flywheel for increased inertia?
  - ✓ Inertia in a future grid with non-rotating turbines (< 4 m/s wind speed)?
- Power absorption
  - ✓ Single shaft compressor issues?
  - ✓ Gearbox (forcing)

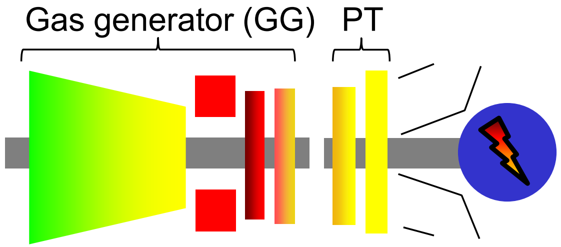
Twin-shaft with spinning PT



- Spinning PT – fast start
- 600…900 kW windage, **i.e. only non-geared PT's (heat ~ speed^3)**

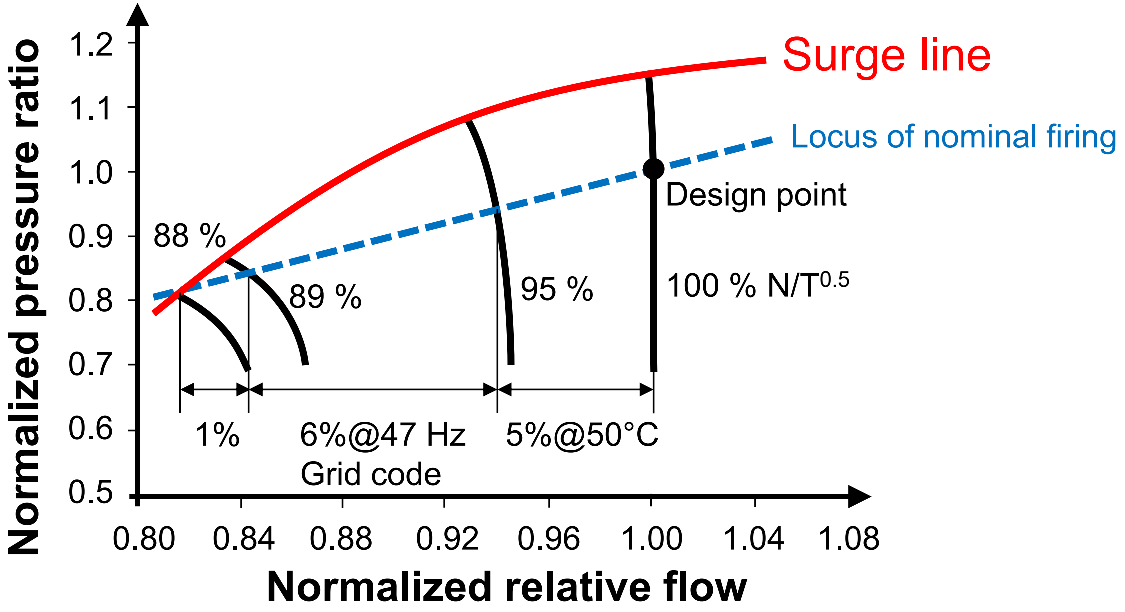
Power vs. PT- and GG speed





- No direct coupling between load speed and the compressor!
- Part-load (pros and cons)
- Lower starter power
- Slower than single-shaft units because of GG-lag
- Low inertia! (~1 s)
- PT over-speed risk at load rejection
- Break-away torque is typically twice the full load torque

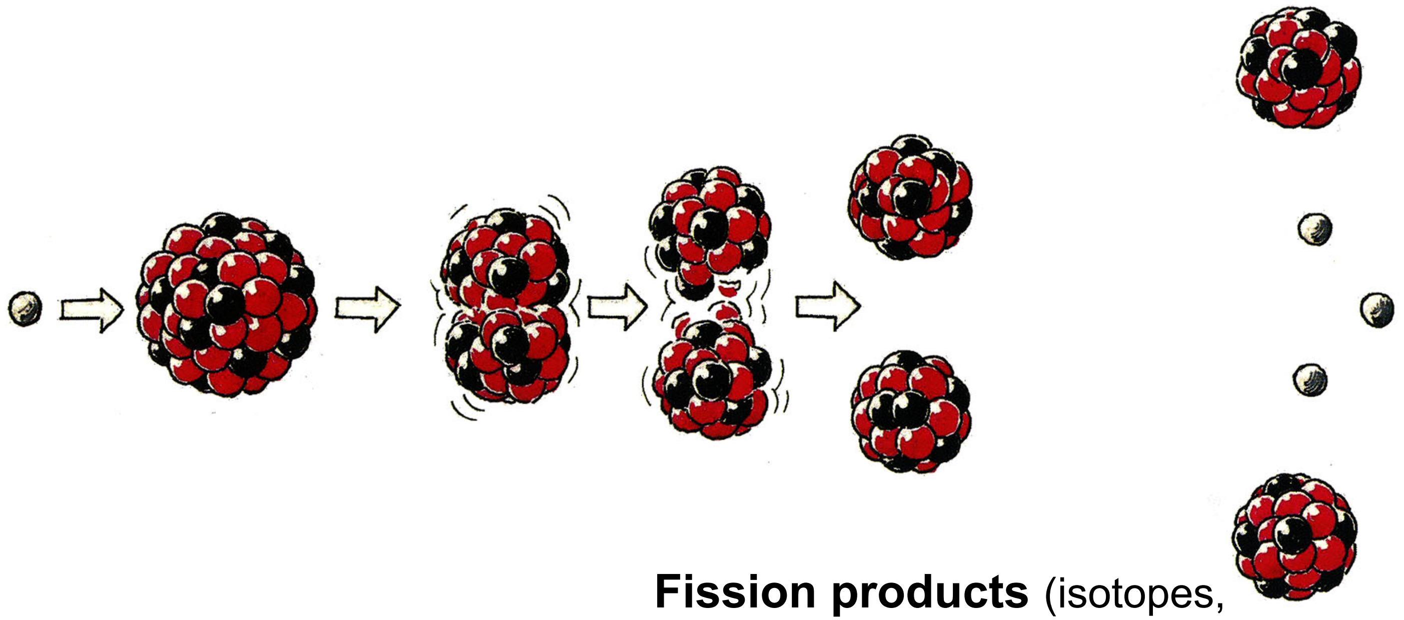
Compressor and grid code…



- Grid code requires only speed (47 Hz) and temperature variation
- Fouling has to be taken into consideration
- The load shall be nominal down to 49.5 Hz and then “pro rata” with frequency (hence over-firing or extra IGV) down to 47 Hz (UK)

Based on Wolfgang Kappis, ”Compressors in Gas Turbine Systems, in ”Modern Gas Turbine Systems”

NPP’s



Fission products (isotopes, e.g., Barium-141, Krypton-92)

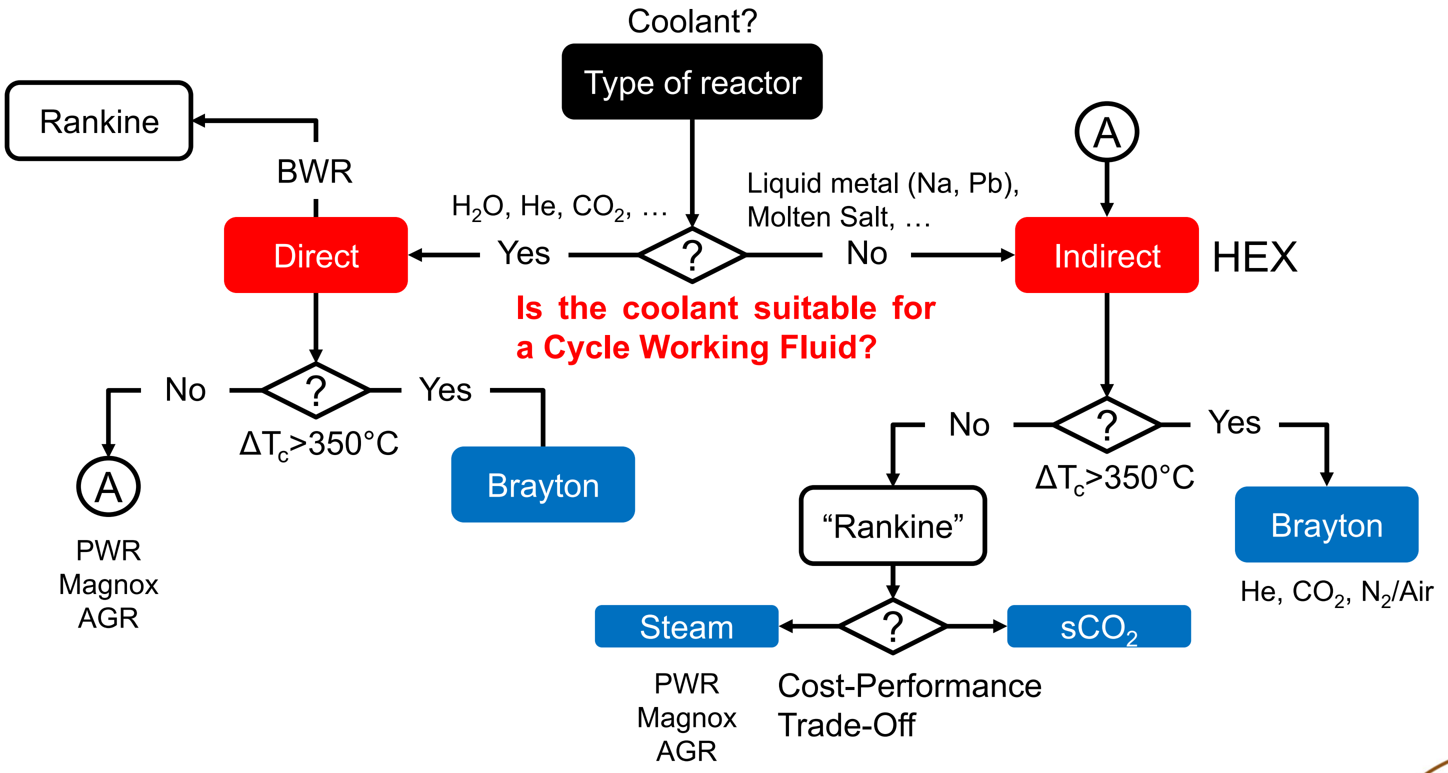
NPP Cycle selection – fundamentals

The material presented here is largely based on Dr Gülen

$$\eta_{th} \sim 1 - \frac{\bar{T}_{out}}{\bar{T}_{in}}$$

$$\bar{T}_{in} = \frac{\dot{Q}_{in}}{\int \frac{d\dot{Q}_{in}}{T}} = \frac{h_3 - h_2}{s_3 - s_2} = \left. \frac{T_3 - T_2}{\ln\left(T_3/T_2\right)} \right|_{c_p,p}$$

$$\bar{T}_{out} = \left. \frac{T_4 - T_1}{\ln\left(T_4/T_1\right)} \right|_{c_p,p}$$

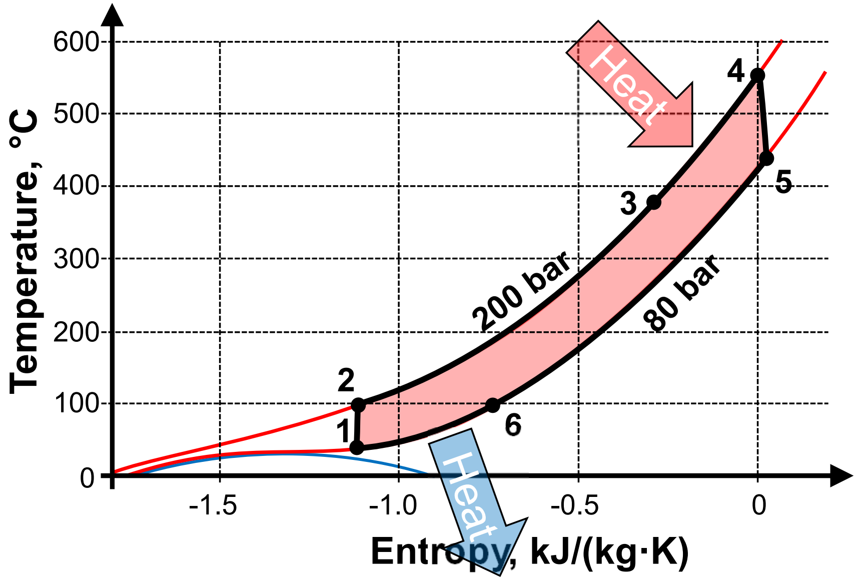


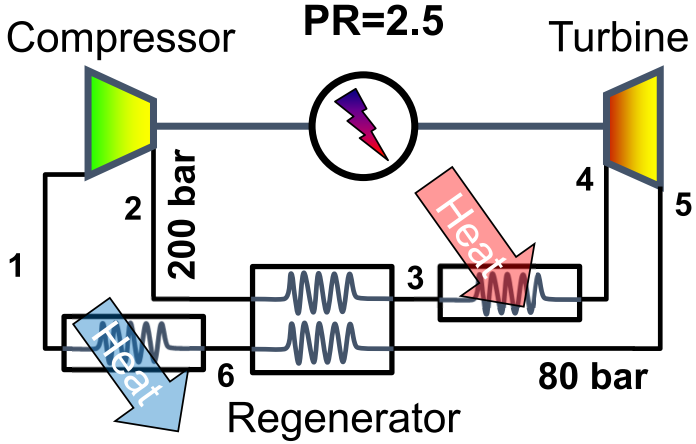
Is the coolant suitable for a Cycle Working Fluid?

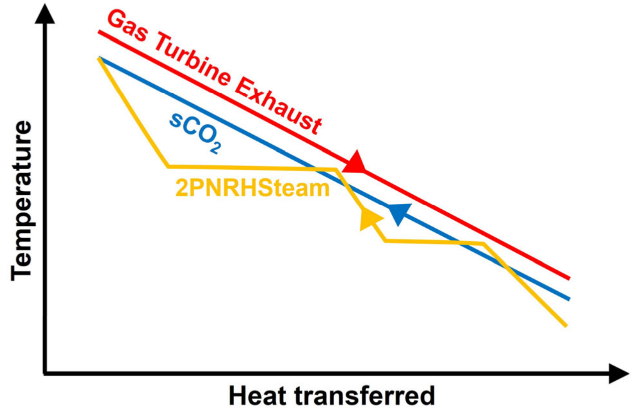
Super-critical CO_2-cycle (sCO_2)

$$\dot{Q} = \dot{m}\cdot\left(h_3 - h_2\right) = \dot{m}\cdot\left(h_5 - h_6\right)$$

$$\varepsilon_{HX} \cong \frac{T_3 - T_2}{T_5 - T_2}$$

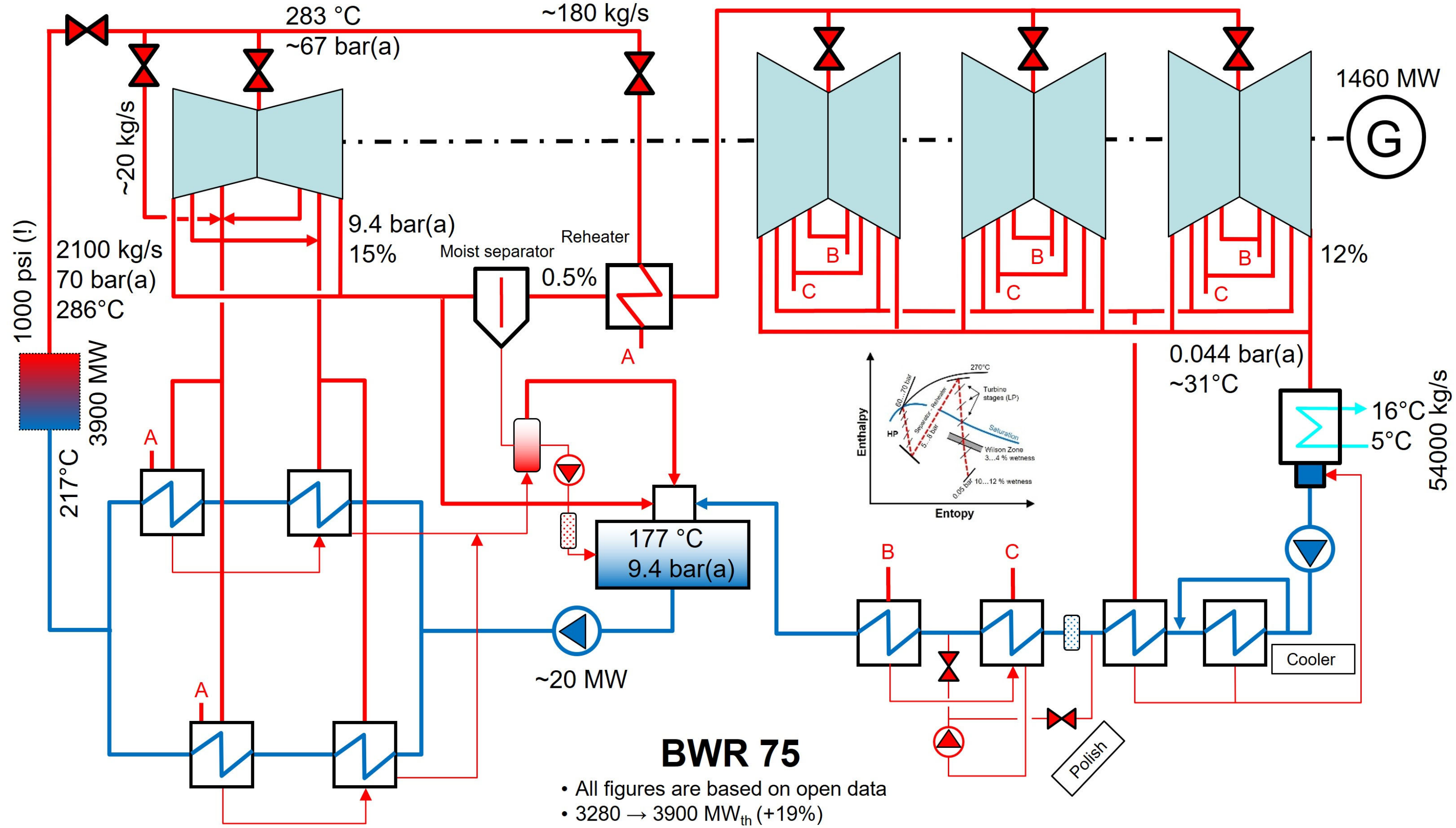






- **Critical pressure = 73.773 bar(a)**
- **Recompression cycle for optimum performance (e.g. 42 → 50 percent efficiency @ 700°C/37°C)**

Typical late 2nd generation BWR cycle



BWR 75

- All figures are based on open data
- 3280 → 3900 MW_{th} (+19%)

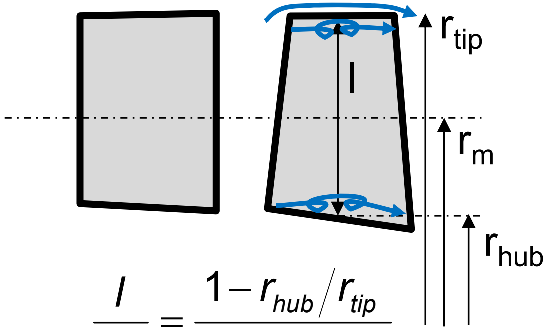
Stage efficiency level – Traupel 1977

$$A = \pi \cdot \left(r_{tip}^2 - r_{hub}^2\right) = \pi \cdot \frac{2 \cdot \left(r_{tip} + r_{hub}\right)}{2} \cdot \underbrace{\left(r_{tip} - r_{hub}\right)}_{l} \quad \dot{Q} = \pi \cdot d_m \cdot l \cdot \bar{c}_a = \pi \cdot l/d_m \cdot d_m^2 \cdot \bar{c}_a$$

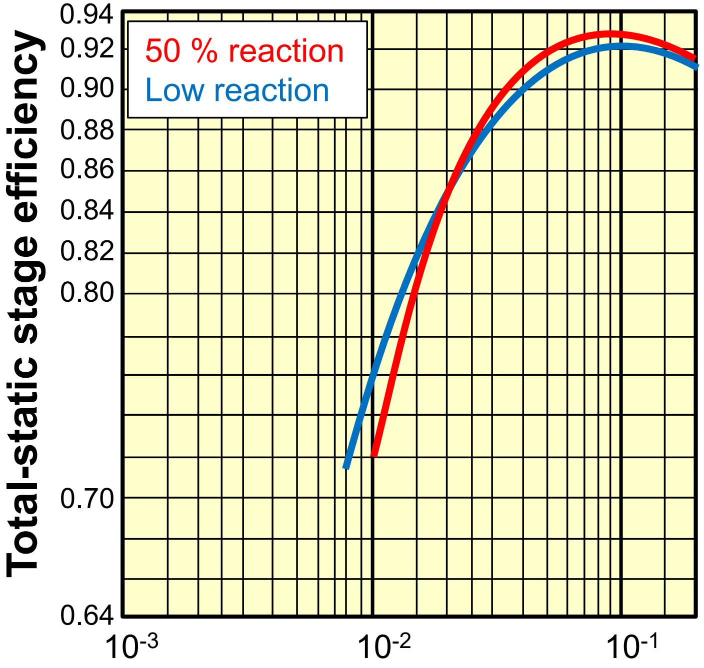
$$\left.\begin{aligned} & l/d_m \cdot \frac{\bar{c}_a}{u} = \frac{1}{\pi} \cdot \frac{\dot{Q}}{d_m^2 \cdot u} \\ & u = \omega \cdot r_m \end{aligned}\right\} \therefore l/d_m \cdot \frac{\bar{c}_a}{u} = \frac{4}{\pi} \cdot \frac{\dot{Q} \cdot \omega^2}{u^3}$$

$$\left.\begin{aligned} & l/d_m \cdot \frac{\bar{c}_a}{u} = \frac{4}{\pi} \cdot \frac{\dot{Q} \cdot \omega^2}{u^3} \\ & u = \sqrt{\Delta h_s / k} \end{aligned}\right\} \therefore l/d_m \cdot \frac{\bar{c}_a}{u} = \frac{4 \cdot k^{3/2}}{\pi} \cdot \frac{\dot{Q} \cdot \omega^2}{\Delta h_s^{3/2}} = \frac{k^{3/2}}{\pi} \cdot q$$

$$\left.\begin{aligned} & q = \frac{\dot{Q} \cdot \omega^2}{\Delta h_s^{3/2}} \\ & n_s = \frac{\omega \cdot \dot{Q}^{1/2}}{\Delta h_s^{3/4}} \end{aligned}\right\} \because q = n_s^2$$



$$\frac{l}{d_m} = \frac{1 - r_{hub}/r_{tip}}{1 + r_{hub}/r_{hub}}$$



Based on: Traupel – Thermische Turbomaschinen, Band I, 1977, Fig. 9.5.4

$$\varepsilon \cdot \frac{c_a}{u} \cdot \frac{l}{d_m} = const \cdot \frac{\dot{Q} \cdot \omega^2}{\Delta h_s^{3/2}} = const \cdot n_s^2$$

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