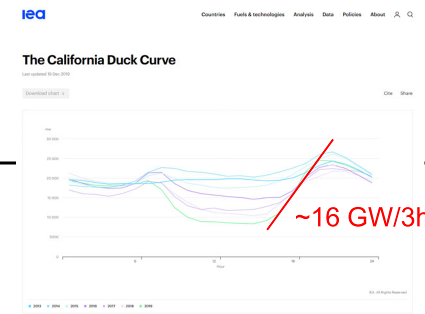
Annual workshop -21

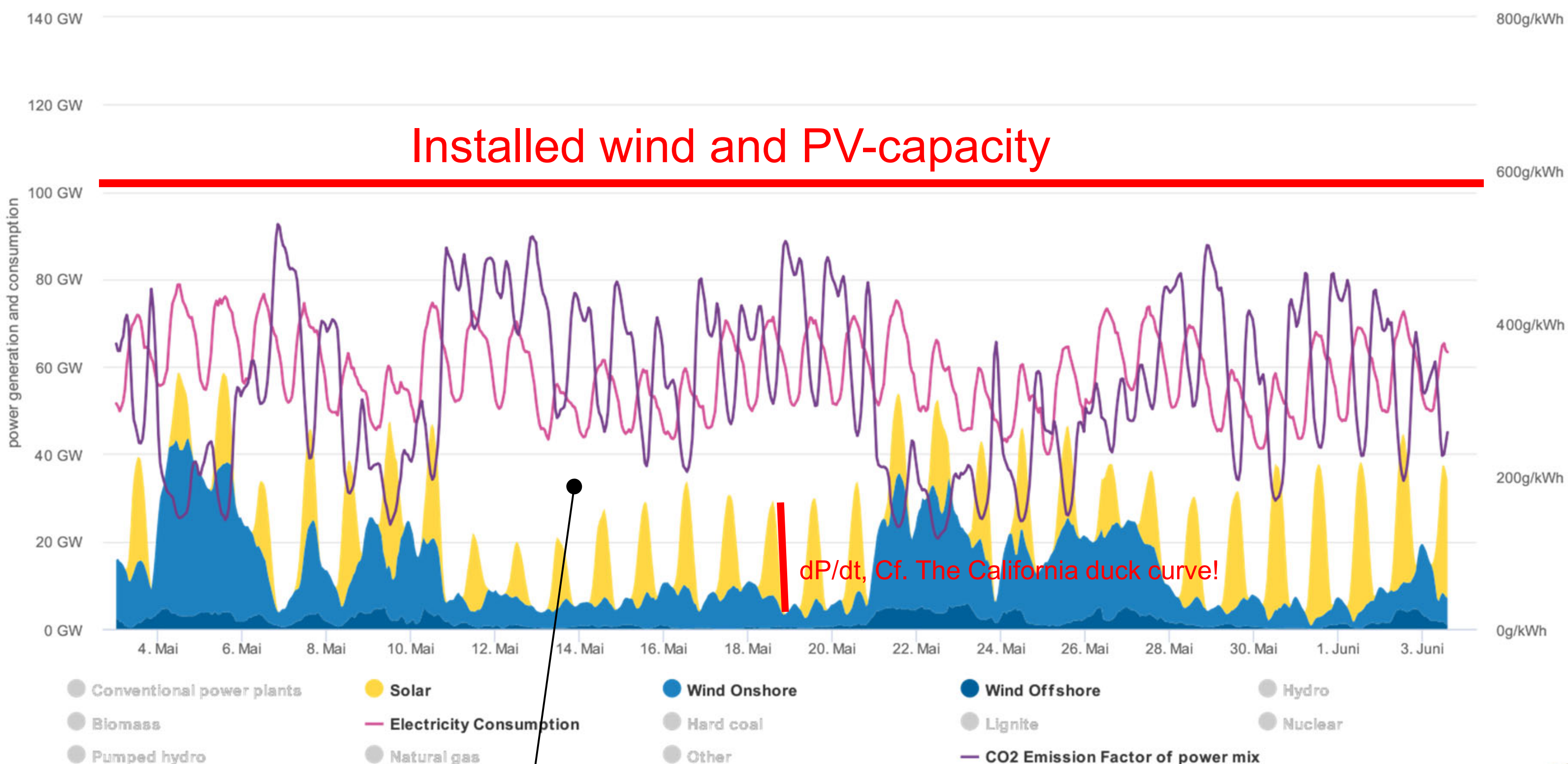
Lund University

Some highlights

- The transformation is gaining momentum!
  - Renewables
  - Nuclear
- Notable things
  - 30 new engines during last 6 years
  - ÖVT
- Emerging technologies
  - AM-components (incremental)
  - New cycles (leapfrogging)
- Fuels
  - Hydrogen
  - Ammonia
  - Liquid bio-fuels
- 9 large hydrogen transition projects
- Production costs
- Steam turbine life extension

Germany May -21

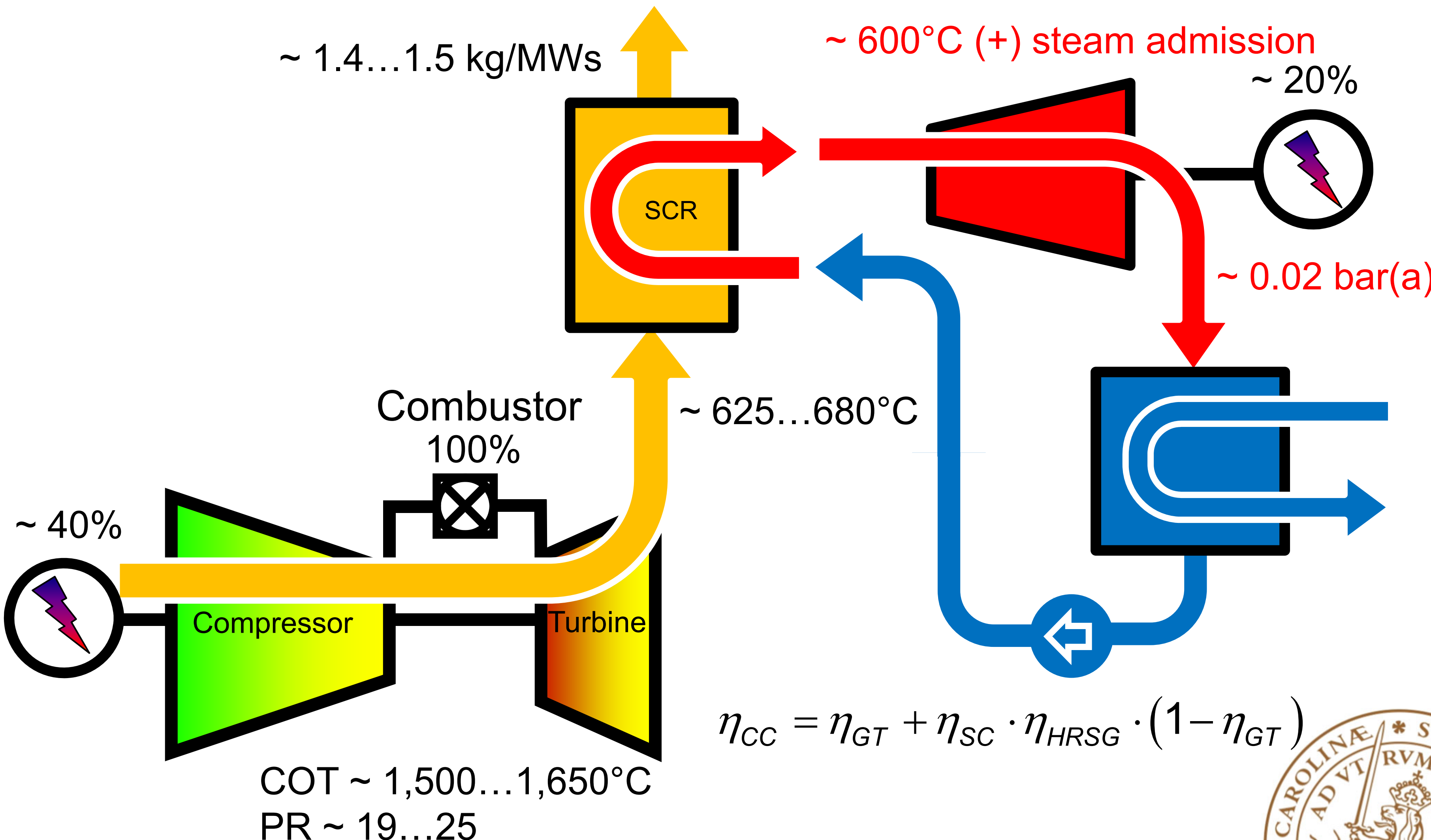




$$P\text{-}ratio = \frac{1}{LHV/HHV \prod_i (\eta_i)} \qquad E_{Wind} \approx 2.4...3.9 \int_0^{8760} P_{GT}\, dt$$

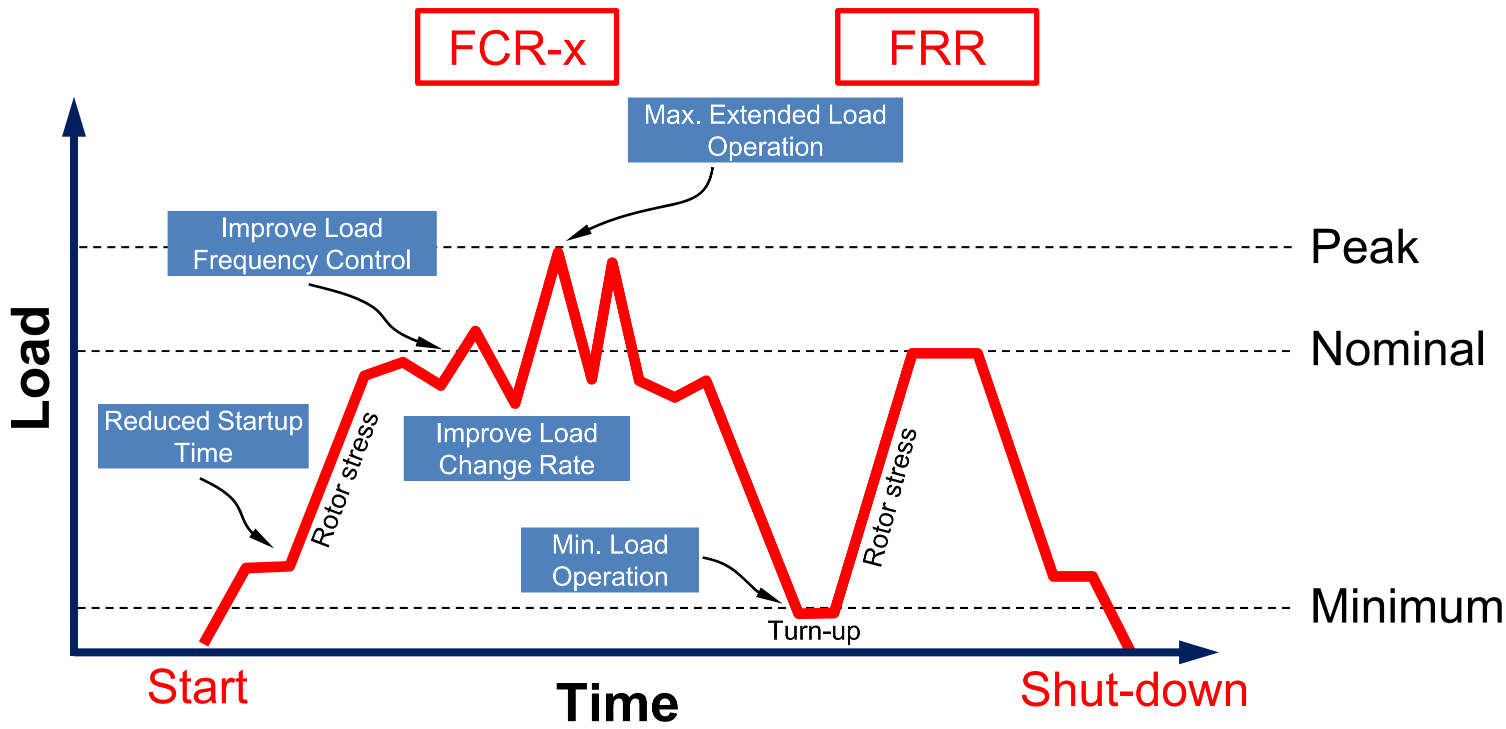
Agora Energiewende; Current to: 03.06.2021 15:45

State-of-the-art combined cycle – GTCC



$$\eta_{CC} = \eta_{GT} + \eta_{SC} \cdot \eta_{HRSG} \cdot (1 - \eta_{GT})$$

Flexibility – steam plants (schematic)



Wind – hydrogen transformation

- Sweden has to 6,835 MW installed nuclear capacity
  - True base-production (no FCR but inertia, voltage control, FRT,…)
  - Frequently argued that we can run without…
- Assume 5,000 MW installed hydrogen gas turbine capacity beyond the nuclear era
  - I.e. ~3.6 times the capacity of today
  - Do the numbers:

$$\text{Electrolyzer energy} = \frac{HHV}{\eta} \cong \frac{39.41}{0.75} = 52.55\left[\frac{kWh}{kg}\right] = 189.18\left[\frac{MW_{\text{Input}}}{(kg/s)_{H_2}}\right]$$

$$\text{Gas turbine hydrogen flow} = \frac{\overbrace{Power/\eta_{TH}}^{\text{Fired heat}}}{LHV} = \frac{5000/0.4}{120}\left[\frac{kg}{s}\right] \approx 104.16\left[\frac{kg}{s}\right]$$

$$\therefore 189.18 \cdot 104.16 \approx 19706.25\,[MW]$$

  - **This will call for some 4,900 4 MW wind turbines*!**
  - For “back of an envelope” type of calculation use: $P-ratio = \frac{P_{Wind}}{P_{GT}} \cong \frac{1.5598}{\eta_{TH}}$
  - A gas turbine with 40 percent efficiency will yield a P-ratio of 3.9, whilst a combined cycle with 64 percent will have 2.4!

$$P\text{-}ratio = \frac{1}{LHV/HHV \prod_i (\eta_i)} \qquad E_{Wind} \approx 2.4...3.9 \int_0^{8760} P_{GT}\,dt$$

Water per mass hydrogen = 9:1, hence 3,375 ton/h demineralized water
*Back-to-back

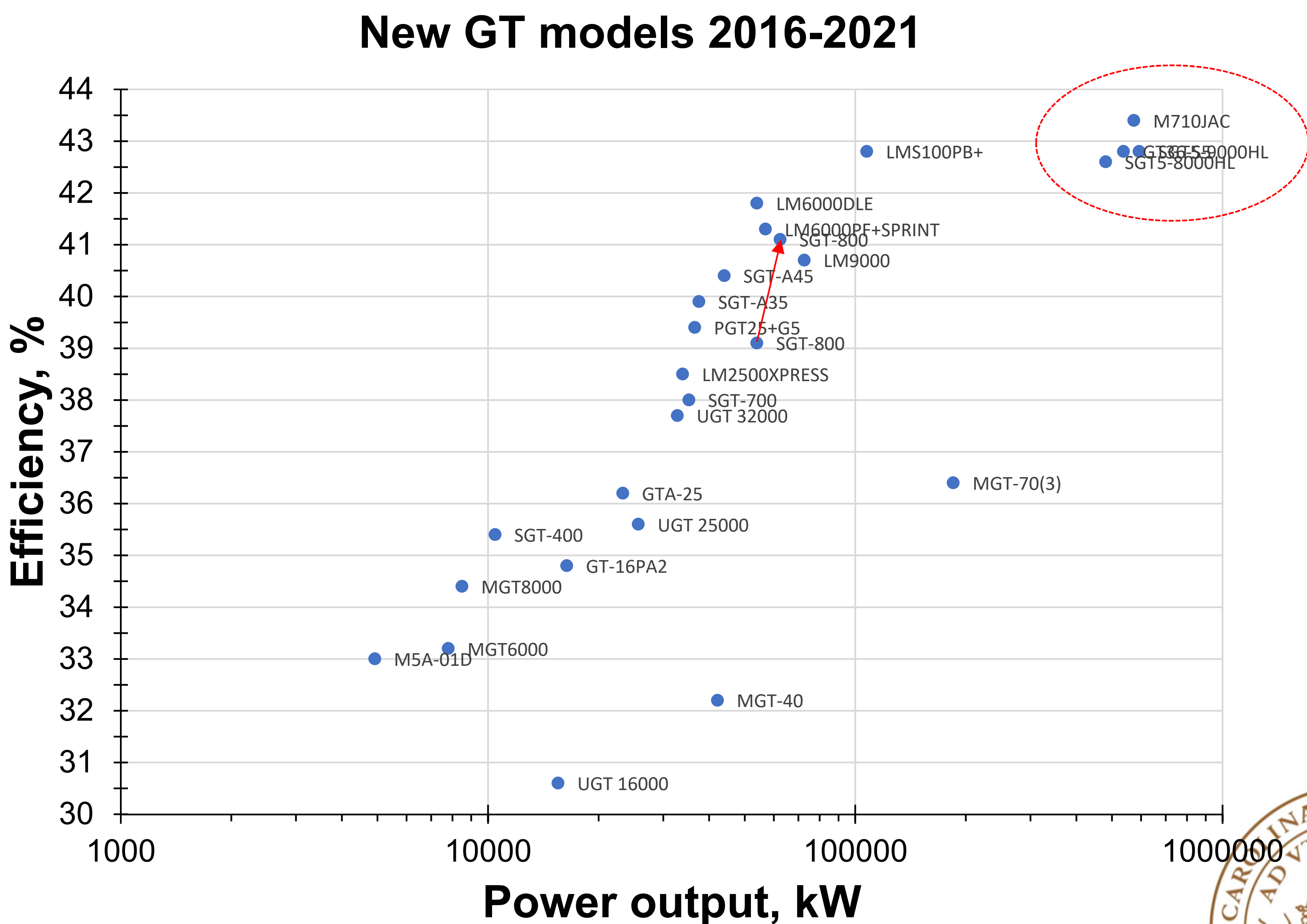
How do we fix this?

- Still no true omnivorous gas turbine
- Hydrogen is reactive, very…
  - Issues related to combustion and the fuel system
- Can we do it today?
  - Yes, we can!
  - Wet diffusion in aero-derivatives
  - DLE is the challenge above 40…60 percent
  - Do we have enough hydrogen?
- Other fuels?
  - Ammonia is still based on hydrogen
  - E-Methanol
  - Liquid biofuels such as HVO,…

Notable things…

- 30 new engines during since -17
  - 5…593 MW
- ÖVT sold

New gas turbines



GE LM2500XPRESS

	LM2500XPRESS +G4	LM2500XPRESS +G5
Power, MW	33.9/96.2	36.3/103.3
Efficiency, %	38.5/55.0	38.1/55.1
Start-up, min	5/30	
Nox, ppm	25	25
CO, ppm	25	25
Reliability, %	99.5	
Availability, %	98.7	
Start reliability, %	98.3	
MO/Hot section	50/25	50/25

Courtesy of General Electric

- 95 percent factory assembly
- 10 modules with 25 electrical interconnections
- 14 days installation with 20 people

Siemens SGT-800 vs. GE 6F.01

6,608 rpm
657 kg/s@3000 rpm
PR 1.23

7,266 rpm
787 kg/s@3000 rpm
PR 1.29

$$\dot{m}_{@3000\,rpm} = \dot{m}_n \left(\frac{n}{3000}\right)^2$$

15 stages

≥50% H_2

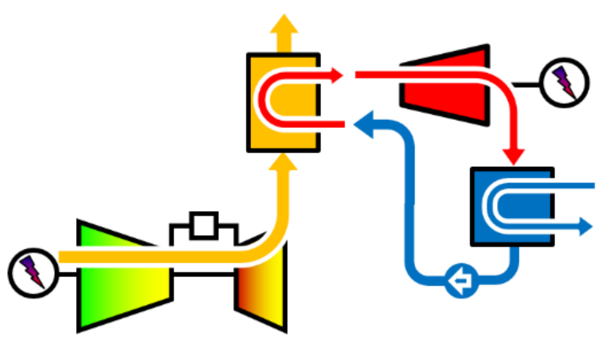
12 stages

≥65% H_2

		SGT-800 B-ratings				C	6F.01
Power	kW	47.5	50.5	54.0	57.0	62.5	57.0
Efficiency	%	37.7	38.3	39.1	40.1	41.1	38.0
PR	-	20.1	21.0	21.4	22.0	21.1	22.3
Flow	kg/s	132.8	134.2	135.5	136.6	135.5	134.2
Specific P.	kWs/kg	357	376	398	417	461	425
EGT	°C	541	553	563	565	596	613
NOx (gas)	ppmvd	<15	<15	<15-17	<20	15…20	25
NOx (oil)	ppmvd	<42…74					-

Siemens SGT-800 vs. GE 6F0.1

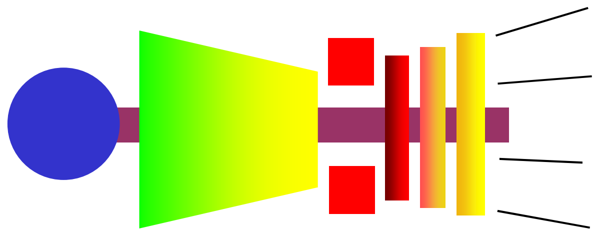
			SCC-800 B-ratings				C	6F.01
SCC-800 1+1	Power	MW	66.6	71.4	75.9	80.7	88.0	84.0
	Efficiency	%	53.8	55.1	56.0	58.0	59.0	57.1
	Heat Rate	kJ/kWh	6,693	6,530	6,427	6,207	6,100	6,309
	Cycle		2PNRH	2PNRH	2PNRH	3PNRH	3PNRH	3PNRH
SCC-800 2+1	Power	MW	135.4	143.6	153.7	163.1	180.0	170.0
	Efficiency	%	54.7	55.4	56.7	58.6	60.0	57.5
	Heat Rate	kJ/kWh	6,583	6,494	6,349	6,143	6,100	6,259
	Cycle		2PNRH	2PNRH	2PNRH	3PNRH	3PNRH	3PNRH



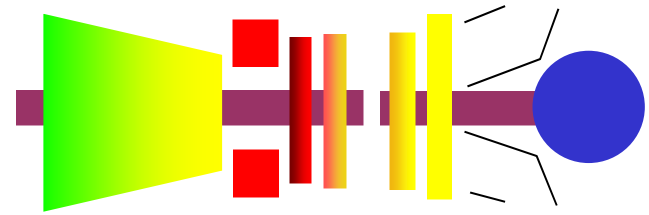
1+1: STF-A100 (geared), 120 bar_a, 566°C
2+1: STF-A200, 120 bar_a, 566°C

$$\frac{P_{ST,1+1}}{\dot{m}_{Exh}} = \begin{cases} 0.17 & \text{SGT-800} \\ 0.21 & \text{GE 6F.01} \end{cases}$$

Single- vs. multi-shaft industrial I

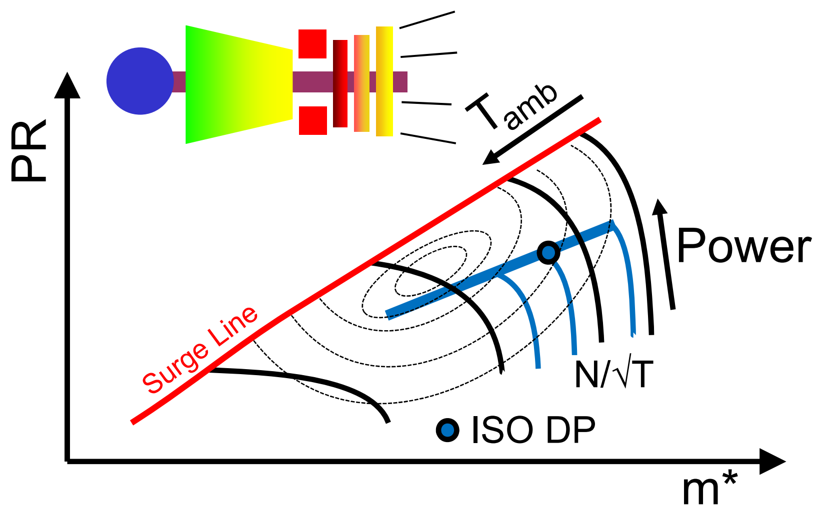


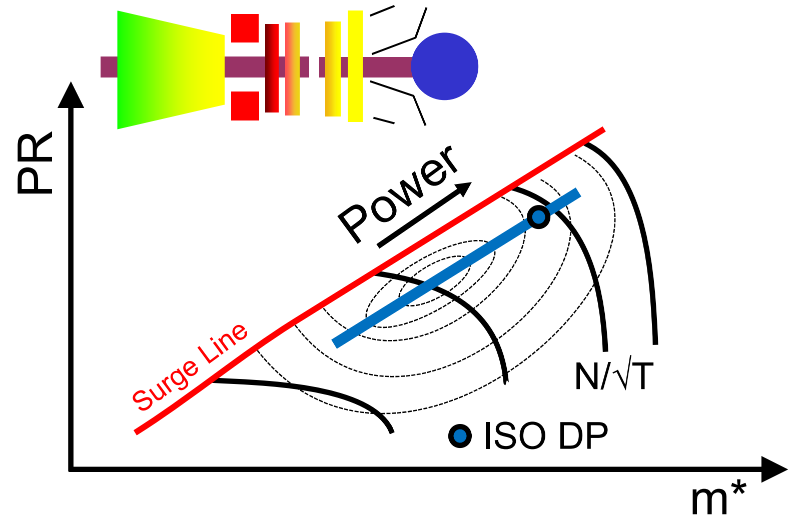
- Only power generation (torque issues)
- Part-load (pro's and con's) – effective way of controlling engine flow for high/constant exhaust temperature
- Exhaust size limitations (lower speed or high outlet velocity)
- Efficient exhaust
- 50/60 Hz direct drive for large units
- Beam rotor with two bearings



- Both power and driver
- Part-load (pro's and con's)
- Lower starter power
- "Free" power turbine speed (lower outlet velocity level)
- Typically less efficient exhaust (lower recovery levels)
- Three-shaft aero-derivatives
- Low inertia!
- PT over-speed risk at load rejection

Single- vs. multi-shaft industrial II

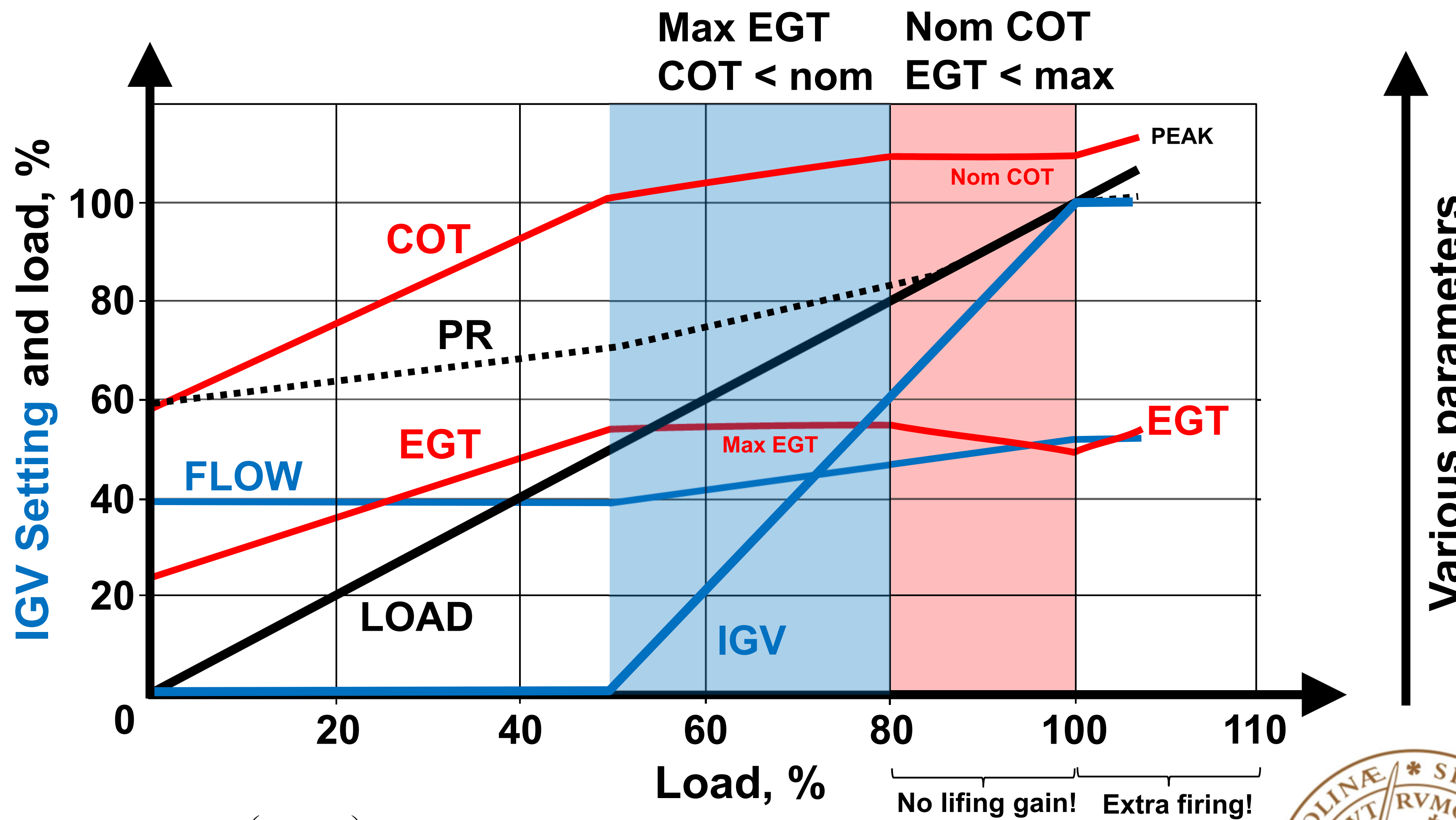




- Physical speed set by grid and gear ratio (<100 MW)
- Locus of operation at different ambient temp's with nominal firing could be seen as a "running line"
- No rotor inertia lag (frequency response)
- Typically reduced surge margin ay high ambient temperatures (COT/T_1)
- Grid code requirement of 6%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

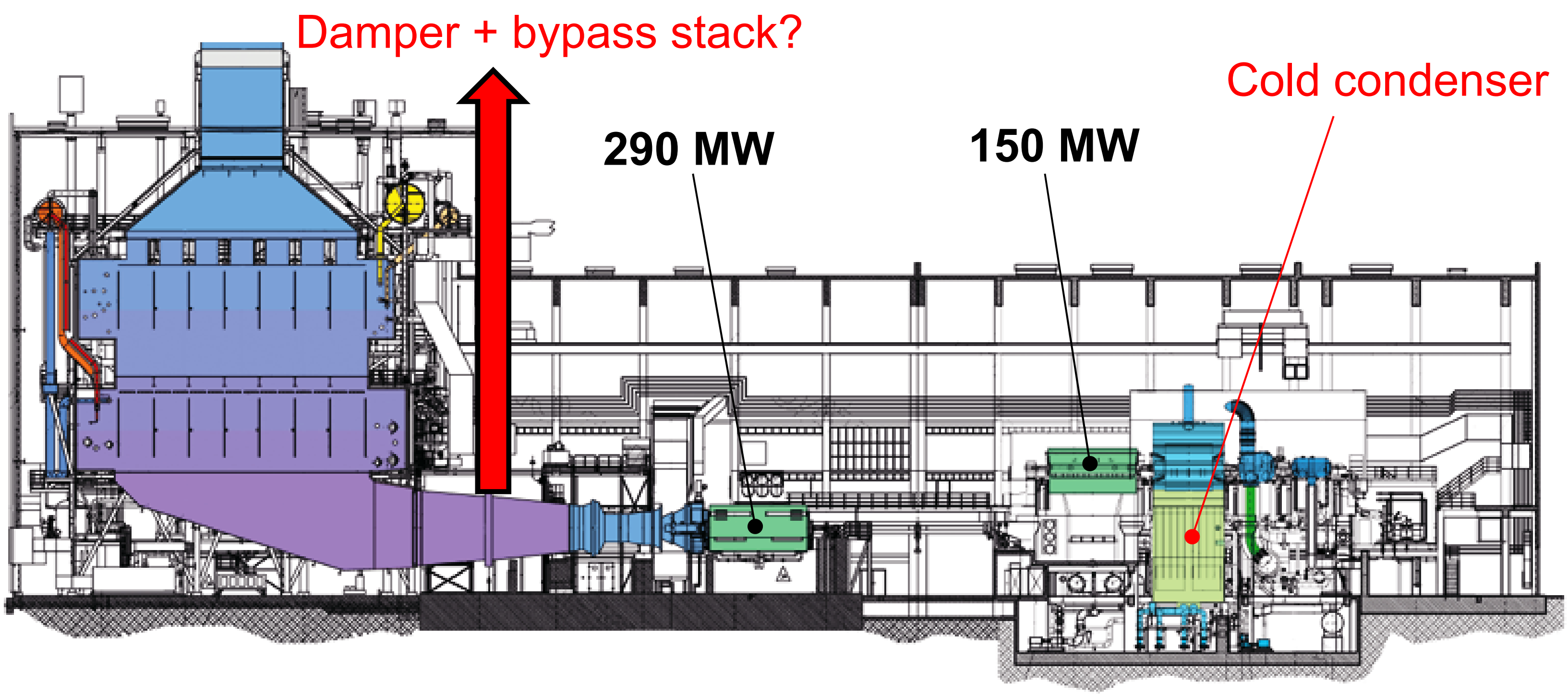
- Typical speed range 60…105 %
- Compressor speed is decoupled from load
- The running line is, more or less, a function of firing – not ambient temp – for a certain engine
- No real grid code issues except for inertia requirements ☺

Single-shaft EGT control – schematic



$$IGV\,(or\ VSV's) = \left(\frac{\chi_{\max}}{\chi} - 1\right)\cdot 100\,[\%] \Rightarrow \dot{m} = 45...100[\%]$$

E.ON Öresundsverket – 2008…2018

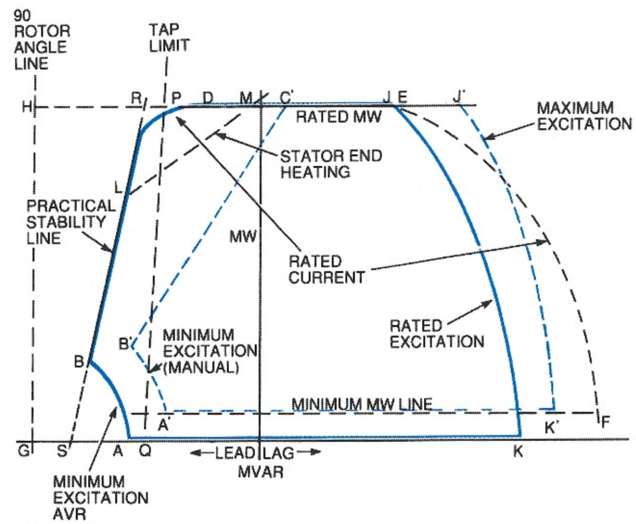


- Black-start capability
- Island-operation capability
- Synchronous condensation
- Could have been upgraded to 62… percent efficiency
- 12…15 min start and loading for the GT
- Todays standard is 28 minutes start-up for the entire plant

- GT inertia moment: 59,078 kg·m^2
- Tau ~ 21 seconds

Capability diagram – large Frame

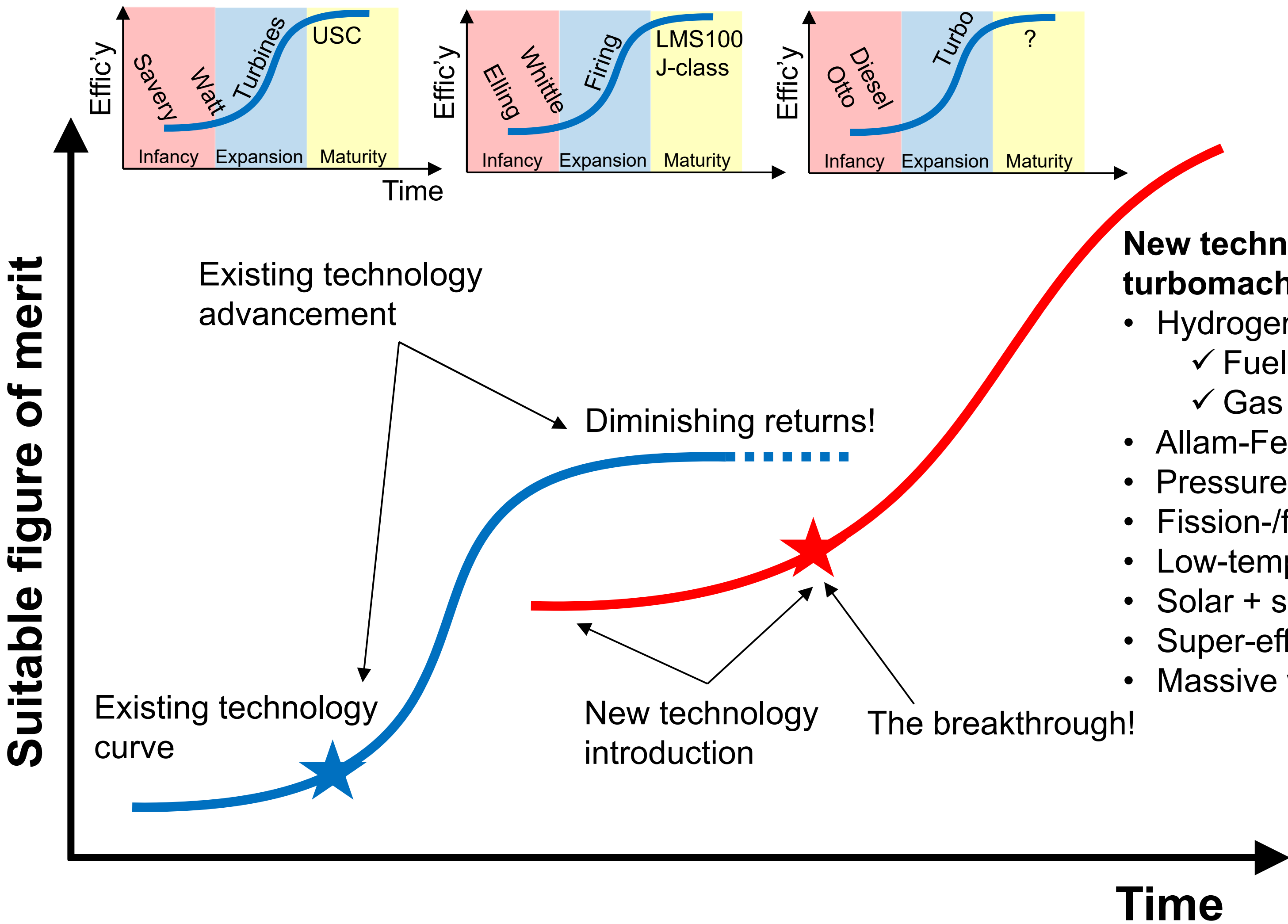
290 MW



- Most folks are having a hard time grasping the PI-equivalents and the need for this!
- In addition it, it only takes a rotor 20 ms to complete a turn, whereas most grid protection response time is ~150 ms…
- FRT capacity?

Technology

The technology S-curve – thermal



New technology curve with turbomachinery!

- Hydrogen/e-fuels
  - ✓ Fuel cell (w. GT)
  - ✓ Gas turbine
- Allam-Fetvedt
- Pressure-gain combustion
- Fission-/fusion energy?
- Low-temp geothermal
- Solar + storage
- Super-efficient bio
- Massive wind + storage

Based on Gülen in Goswami "Energy Conversion", 2nd ed.

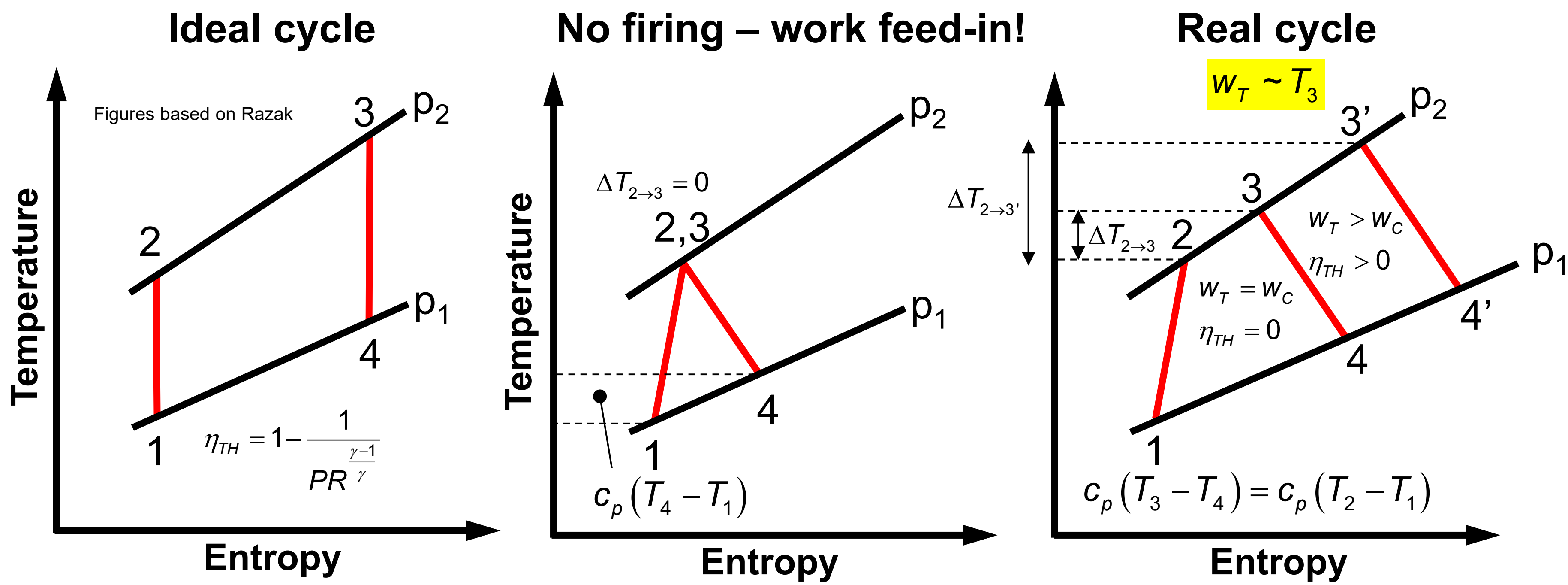
Fuel cell hybrids – optimum performance

Technology	Cycle PR, -	COT, °C	Effi'y, %	Sp. output
SOFC+GT	30.0	1,300	65.0	588
SOFC+REC	3.5	1,300	68.7	620
SOFC+ICR	4.0	1,300	67.8	614
MCFC	3.5	1,300	63.5	464
GTCC	23.0	1,600	64.0	650…700

SOFC flexibility issues?

Source: Bhargava, R.K., et al., J. Eng. Gas Turbines Power, 132, #022001, 2010.

Temperature influence on efficiency



- Combustor section temperature rise ($\Delta T_{2\text{-}3}$) is the best gauge of the cycle's ability to deliver power. When this is low, excess power is low and the losses due to component inefficiencies dominates, hence reducing both thermal efficiency and specific power.
- High thermal efficiency requires low exhaust temperature to minimize energy wastage. Maximum efficiency occurs at the minimum value of $\Delta T_{2\text{-}3}/T_4$ (combustor temp rise/exhaust temp).

$$T\,ds = c_p\,dT - v\,dp$$

$$\therefore \left.\frac{dT}{ds}\right|_p = \frac{T}{c_p}$$

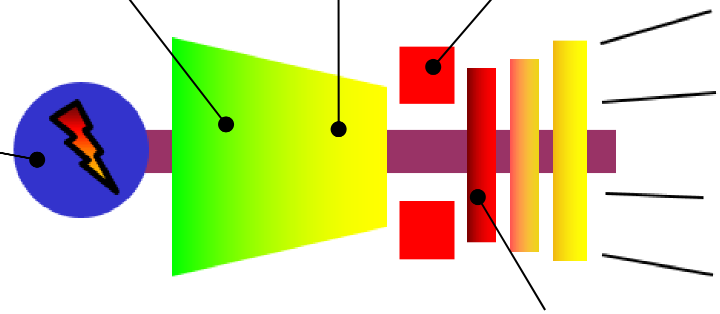
State-of-the-art-GT (Single-shaft)

- Welded rotor
- Bolted rotor
- Hirth-coupling
- Hydraulic ACC

- 3D Aero airfoils
- Multistage VSV
- "Super Finish"
- Field-replaceable blades

- DLE – Dual Fuel
- >1,600 °C
- Can-Annular
- Axial fuel staging
- Fuel flexibility
- Fuel saturation

- Hydrogen cooled
- 99 % Efficiency
- 600 MW



- >600 °C
- 1,000 kg/s
- <25 ppm NOx
- >10 ppm CO
- No toxic emissions

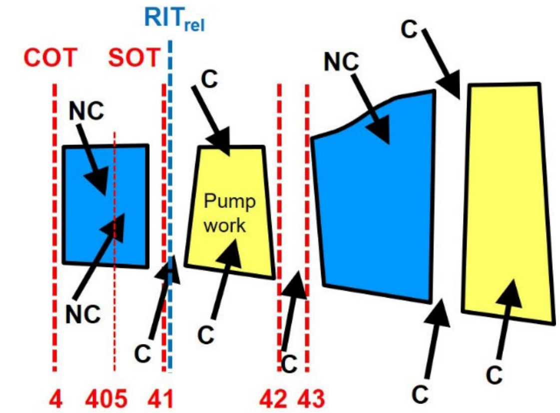
- Four-stage turbine
- Single-crystal Ni-based super-alloys
- TBC
- 3D Aero vanes and blades
- ACC
- Advanced film cooling
- Micro-channel cooling

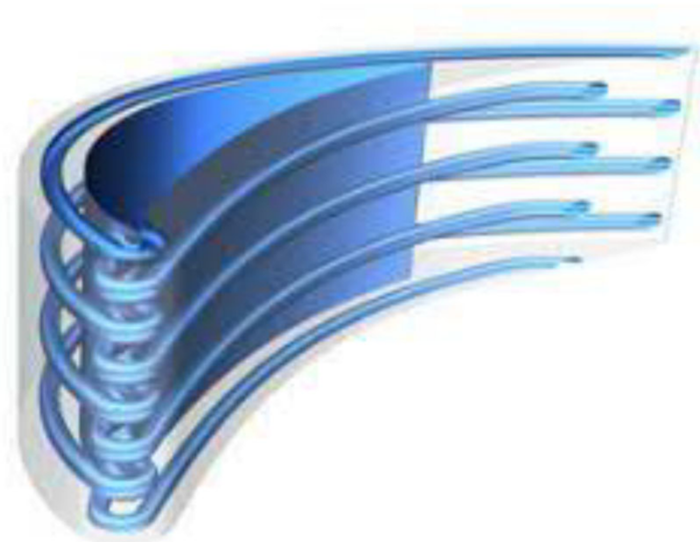
Future enablers (short term)

- 1,700 °C
- Ceramic matrix components
- **Additive manufacturing (AM)**
- Data analytics
- Controls and optimization
- No vane #1 Unlikely!!!

AM – vane 1

- Offers a way of bringing SOT closer to COT
  - ✓ More efficient – less cooling air
  - ✓ No film-cooling in the future?





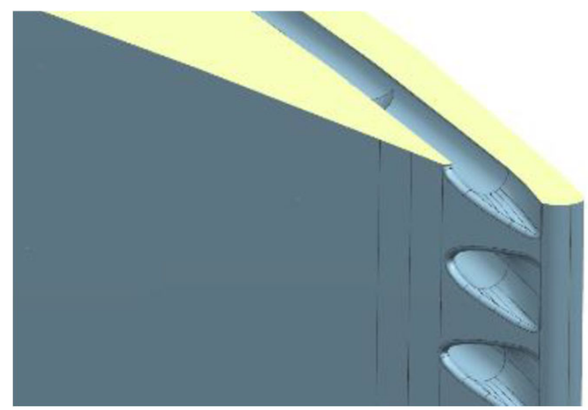
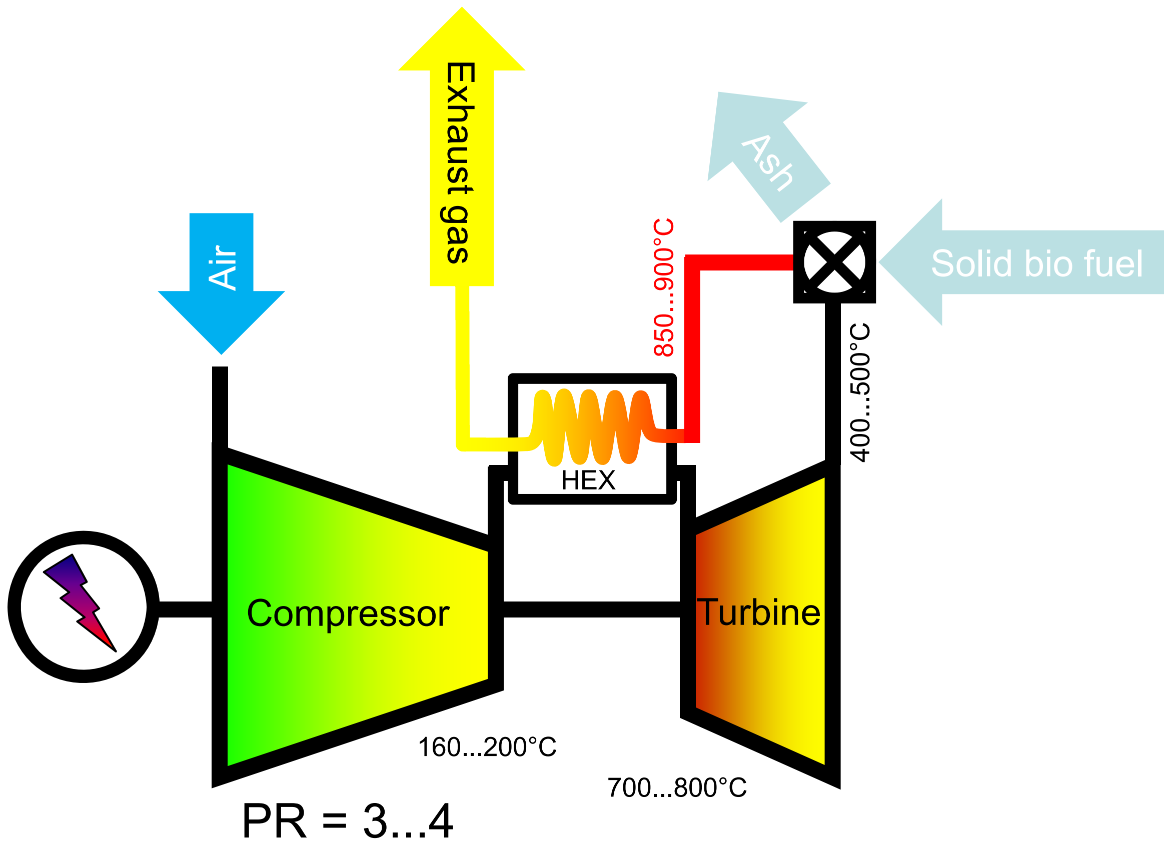
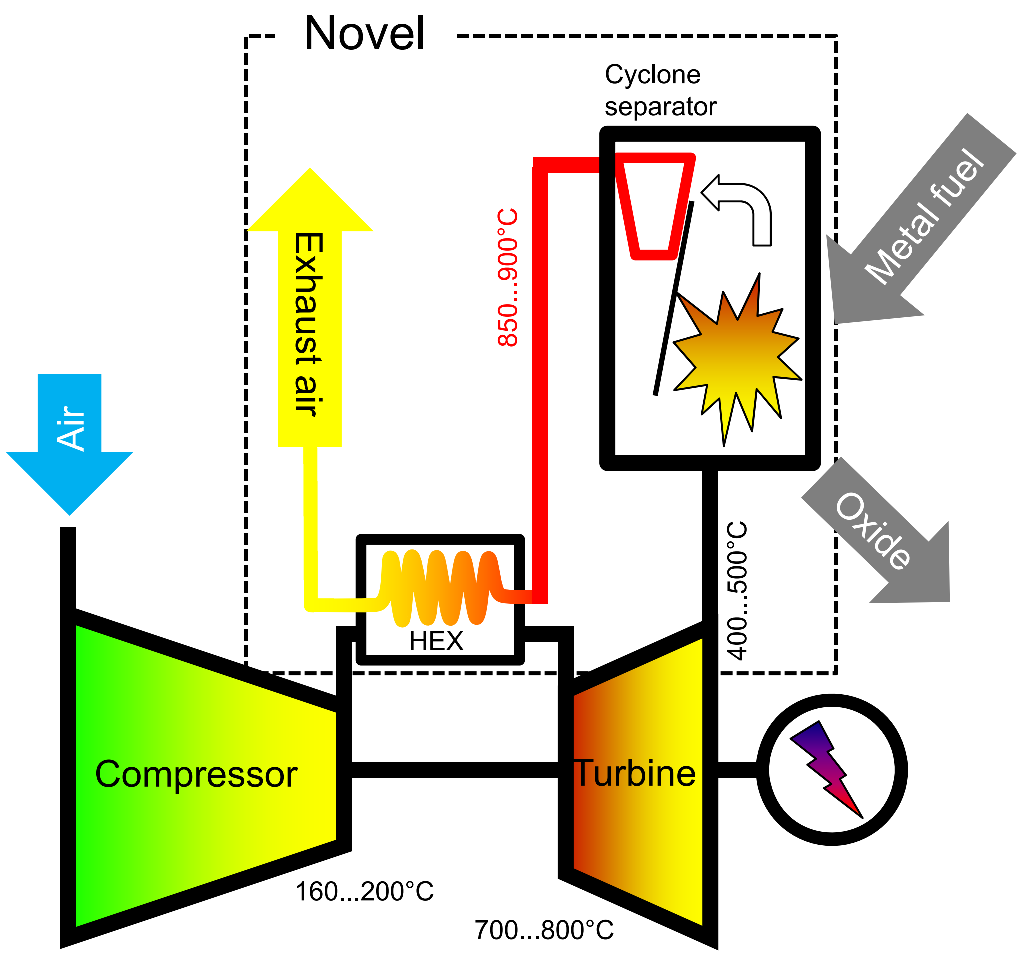


Figure courtesy of Siemens, GT2021-59523

Externally fired gas turbine cycle



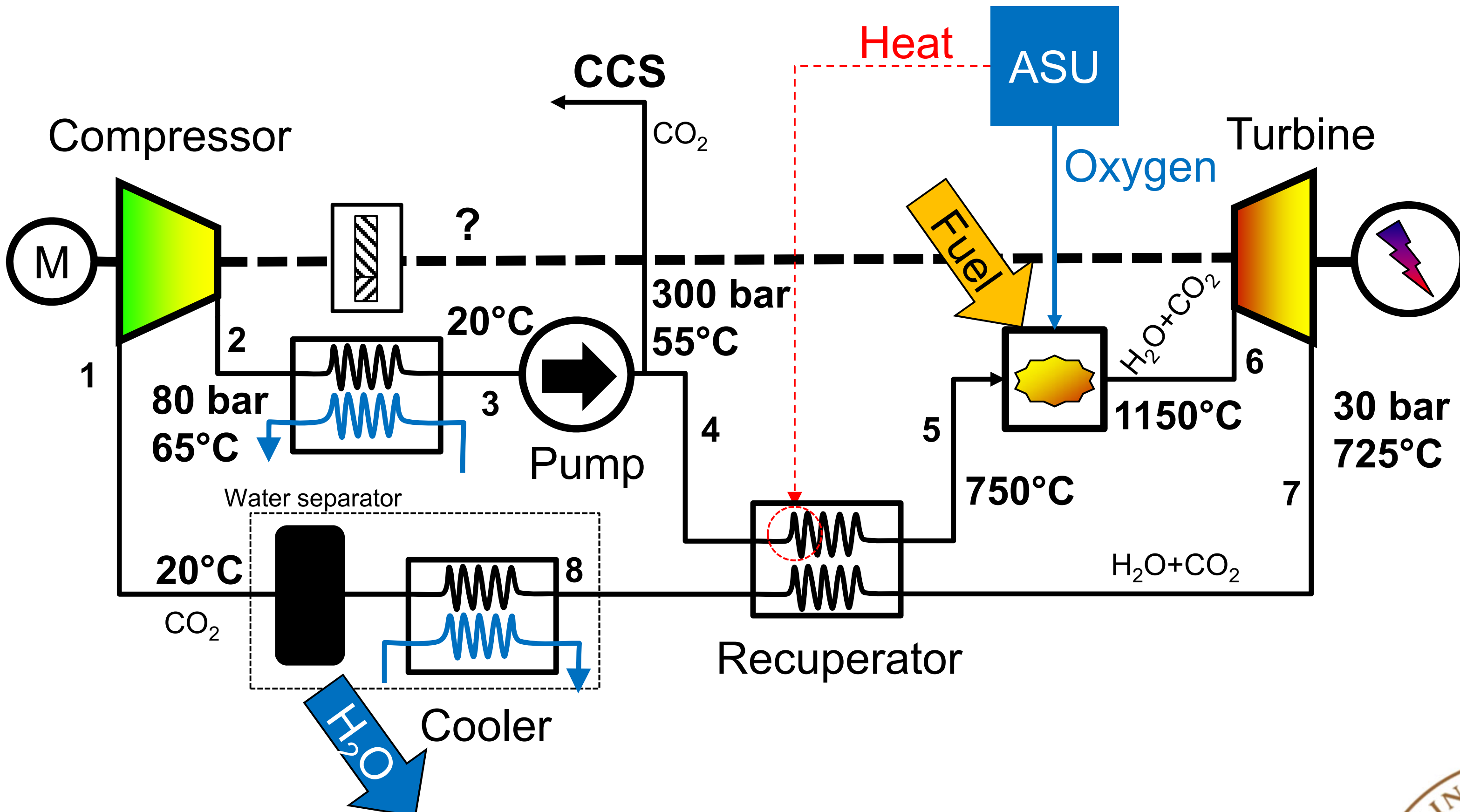
High-TRL metal combustion demonstrator



PR = 3...4

- **Metal combustion in a small scale GT**
  - ✓ Worlds first demonstrator!!!
  - ✓ Offers a fast track do demonstration
  - ✓ Low-cost
- **Bubbling or circulating bed type**
  - ✓ Inertial separator(s)
  - ✓ PFBC-competence for leverage
  - ✓ Heavier oxides are separated at the bottom and as "fly-ash"
  - ✓ No need for separate fan
  - ✓ Turbine exit velocity ~ 140 m/s offers significant head for fluidization
- **Heat exchanger**
  - ✓ No real oxide problems
  - ✓ Radial turbines cannot be operated with hard particles (a.k.a. the Ping-Pong effect)
- **Literally *any type* of fuel can be used**
  - ✓ Hydrogen
  - ✓ Ammonia
  - ✓ e-Methanol

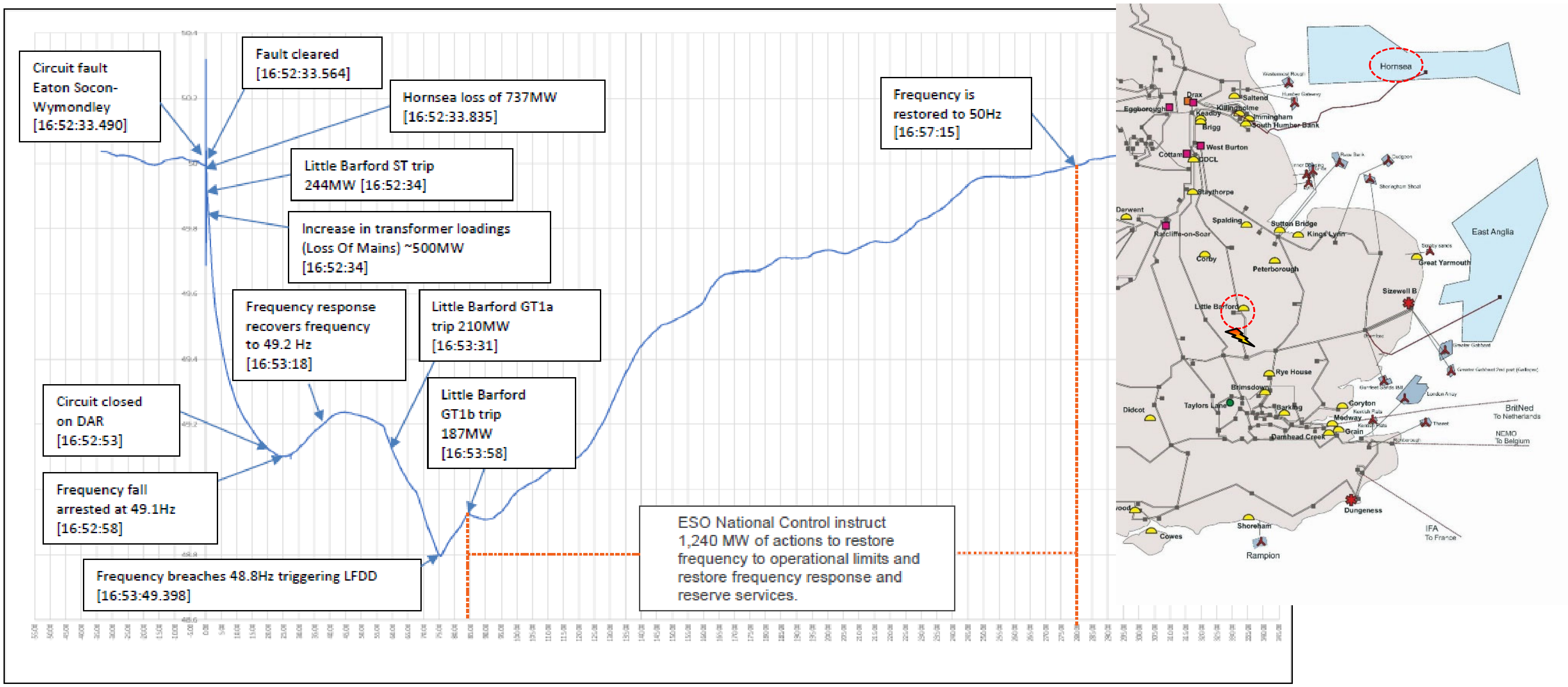
Schematic Allam-Fetvedt cycle



Efficiency ~ 55…60 percent

Based on Gülen, Gas Turbines for Electric Power Generation, Fig 22.3

Hornsea and Little Barford trip 190809



$$\frac{df}{dt} = \frac{\overbrace{\Delta P}^{+/-} - \overbrace{\left\{ \frac{a}{100} \cdot P_{init} \cdot \left(f_{nom} - f \right) \right\}}^{\text{Self regulating}}}{P_{nom}} \cdot f_{nom}^2 \cdot \frac{1}{2 \cdot f \cdot \tau_I}$$

GE LM6000 Hybrid EGT

FFR, FCRx, FRR

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

250 ms

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

5…10 min

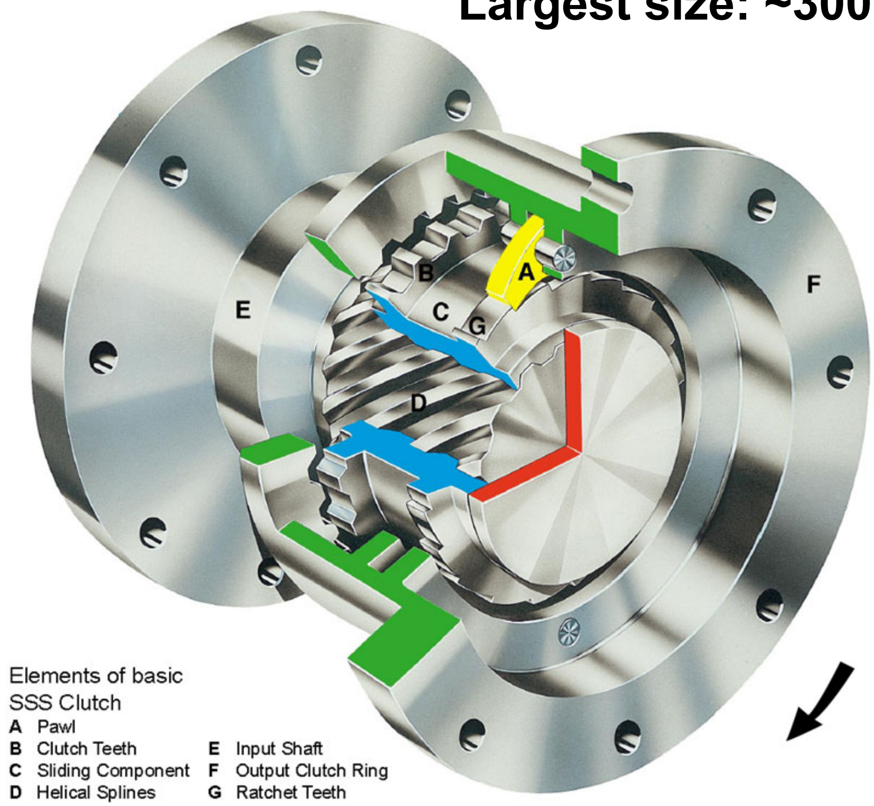
Siemens, MHI, … can offer the same capability!

Courtesy to General Electric

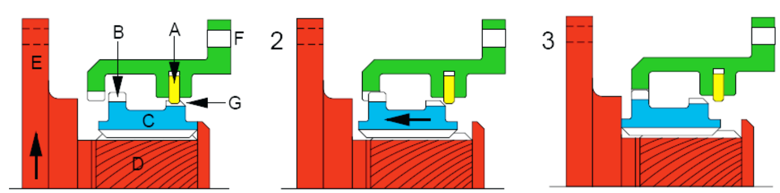
SSS clutch – a fantastic enabler!

Largest size: ~300 MW@3000 rpm

Turbine end

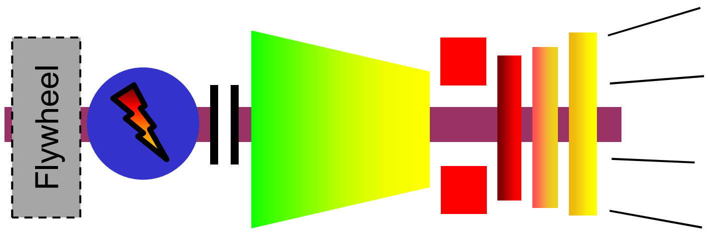


Alternator end

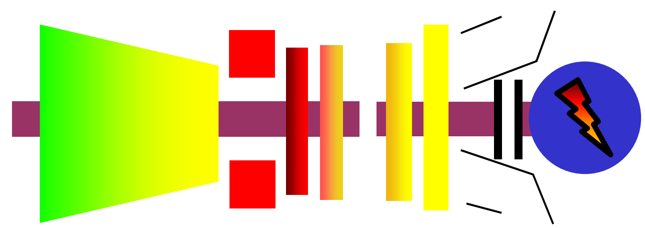


Synchronous condensation etc.

Single-shaft with SSS-clutch

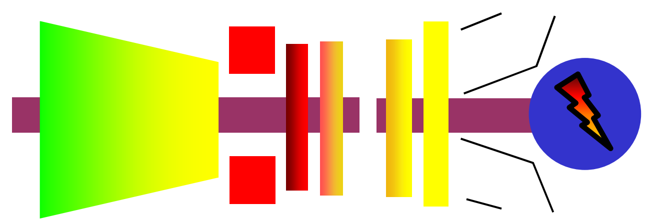


Twin-shaft with SSS-clutch



- 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)

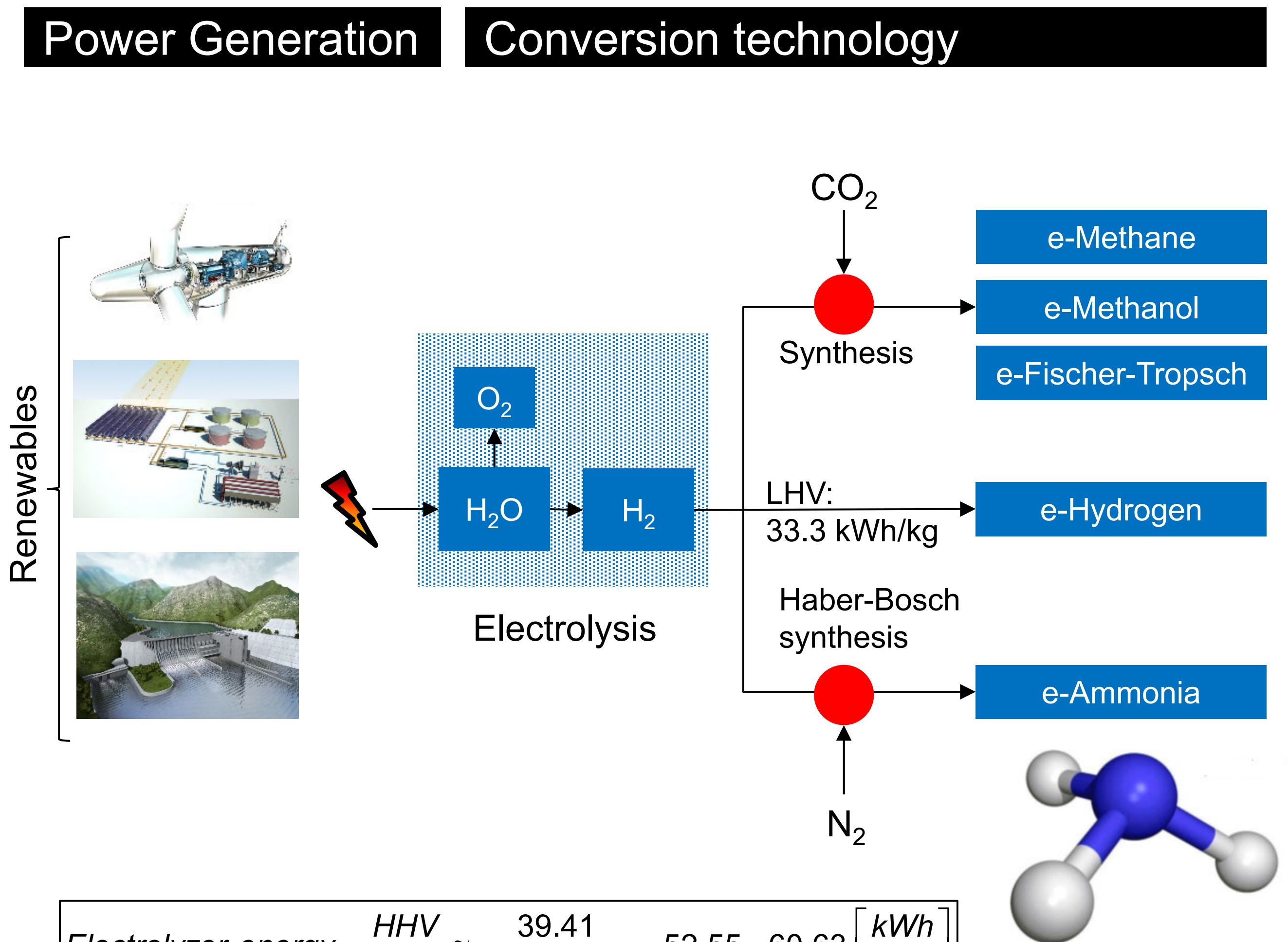
Twin-shaft with spinning PT



- Spinning PT – fast start
- 600…900 kW windage, **i.e. only non-geared PT's (heat ~ speed^3)**
- P&W FT8, P&W FT4000, GE LMS100,…

New fuels

Power-to-Hydrogen and e-fuels



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

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

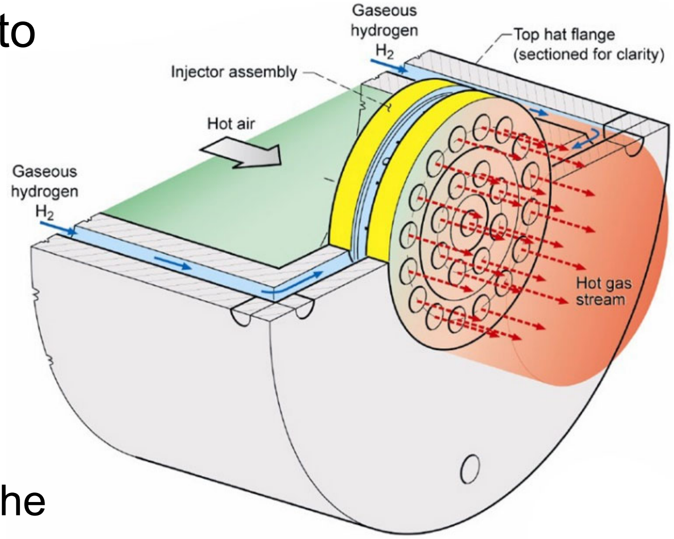
- Chemical feedstock
- Fertilizer
- H_2-carrier

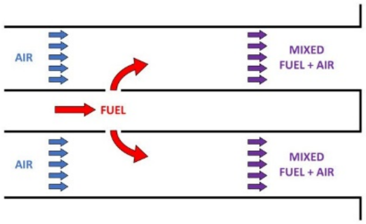
Carbon-free!

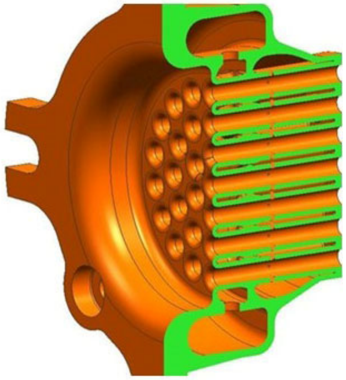
$$\textit{Electrolyzer energy} = \frac{HHV}{\eta} \cong \frac{39.41}{0.65...0.75} = 52.55...60.63 \left[\frac{kWh}{kg}\right]$$

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



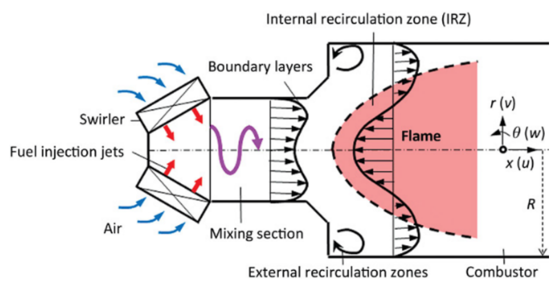




Hydrogen – key fuel characteristics

	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**	**Flash-back!**
Autoignition delay time[2] [ms]	**124**	112	107	104	103	**76**	**DLE!**
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**	

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



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

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

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

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

Hydrogen, 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

Pecuniary dimensions

Cost of Electricity – COE

COE = CAPEX + OPEX

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

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

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

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

$$\frac{CAPEX}{P} \approx (1.6 \ldots \mathbf{1.8} \ldots 2.0) \cdot \begin{cases} \geq 100\ MW : 2.339 \cdot 10^4 \cdot P^{-0.0064} - 2.145 \cdot 10^4 \\ < 100\ MW : 1.08 \cdot 10^5 \cdot P^{-0.53} + 49 \quad [USD/kW] \\ GTCC : 322 + 6.98 \cdot 10^4 \cdot P^{-0.4} \end{cases}$$

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

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

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!

Cost of Electricity – COE

COE = CAPEX + OPEX

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

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

Where:

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

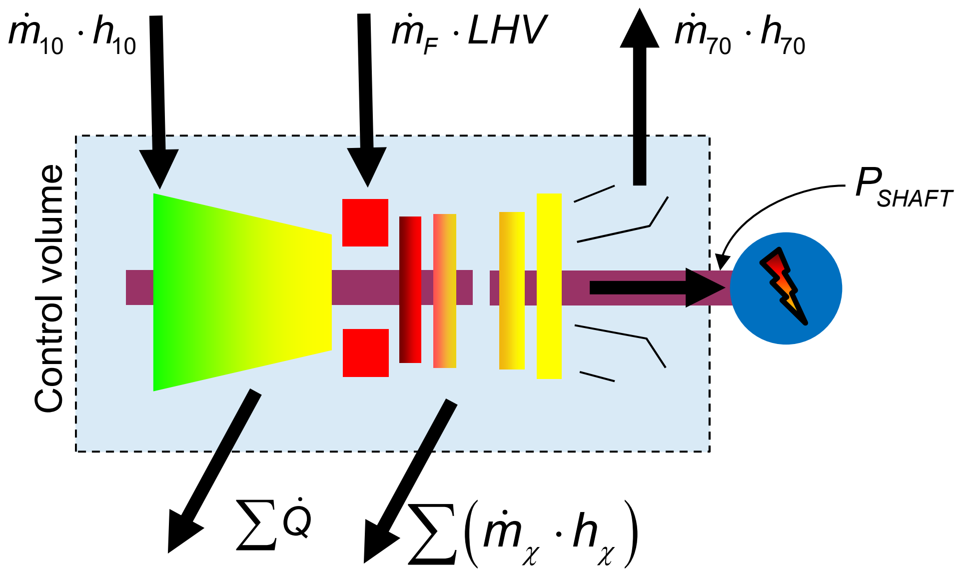
$$OM = \underbrace{10 \ldots 15 \quad [USD/kW_{installed}]}_{\text{per annum}} + (0.50 \ldots 1.50) \cdot 10^{3} \quad [USD/kWh]$$

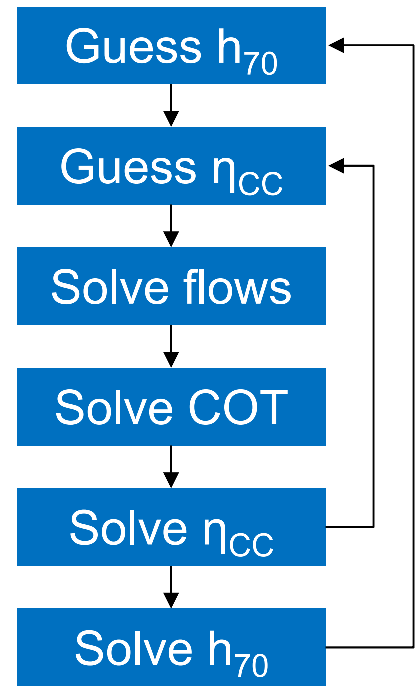
CAPEX	Capital Expenditure
β	Annuity factor
P	Power
H	Annual operating hours
f	Fuel cost [USD/kWh]
i	Interest rate
N	Number of years
OM_{fix}	Fixed OM-spending [USD]
OM_{var}	Variable OM-spending [USD/kWh]

	Cold starts	**Warm starts**	**Hot starts**	**H**	**μ**
Downtime	≥72	≤48	≤2		
Start time	~3 hours	≤2 hours	≤1 hour		
Peaking	40	100	10	600	10×
Cyclic load	5	45	225	4,800	2.5×
Base load	9	10	2	7,500	Datum
Continuous	3	5	10	8,200	1.1×

Engine performance testing

Engine heat balance mass flow calculation





$$\dot m_{10} = \frac{\dot m_F\left(LHV\cdot\eta_{CC} + c_{p,F}\left(T_F - T_{REF}\right) - h_{070}\right) - P_{SHAFT} - \sum\dot Q}{\sum\left(\chi\cdot h_\chi\right) + \left(1-\sum\chi\right)\cdot h_{070} - h_{100}}$$

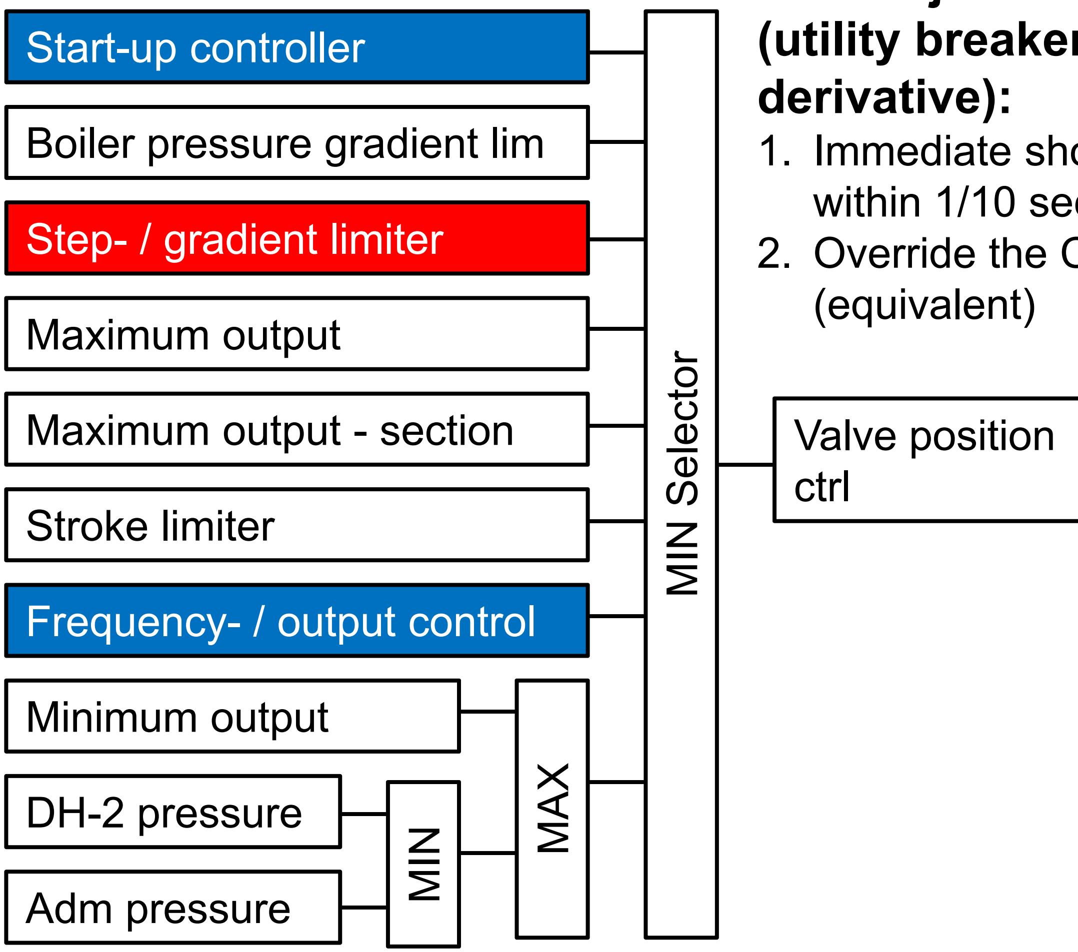
$$h_{70} = f\left(T_{070}, \dot m_{10}, \dot m_F, \ldots\right) \quad \eta_{CC} = f\left(COT\right) \quad COT = f(\dot m_{10}, \dot m_F, T_{030}, \chi, \ldots)$$

$$\eta_{gen}\left(P_{GEN}, PF, S_{RATED}\right) = K_{PF}\cdot\eta_{RATED}$$

$$K_{PF} = 1 + 0.0186\cdot\sqrt{\frac{P_{GEN}}{PF\cdot S_{RATED}}}\cdot\ln\left(\frac{PF_{RATED}}{PF}\right)$$

Steam turbines

Turbine governor – Example



Load rejection detection response (utility breaker trip or frequency (speed) derivative):

1. Immediate short drain pulse to the CVs, within 1/10 second* (100 ms)
2. Override the CV position controller until 51 Hz (equivalent)

Speed droop – load and frequency relation

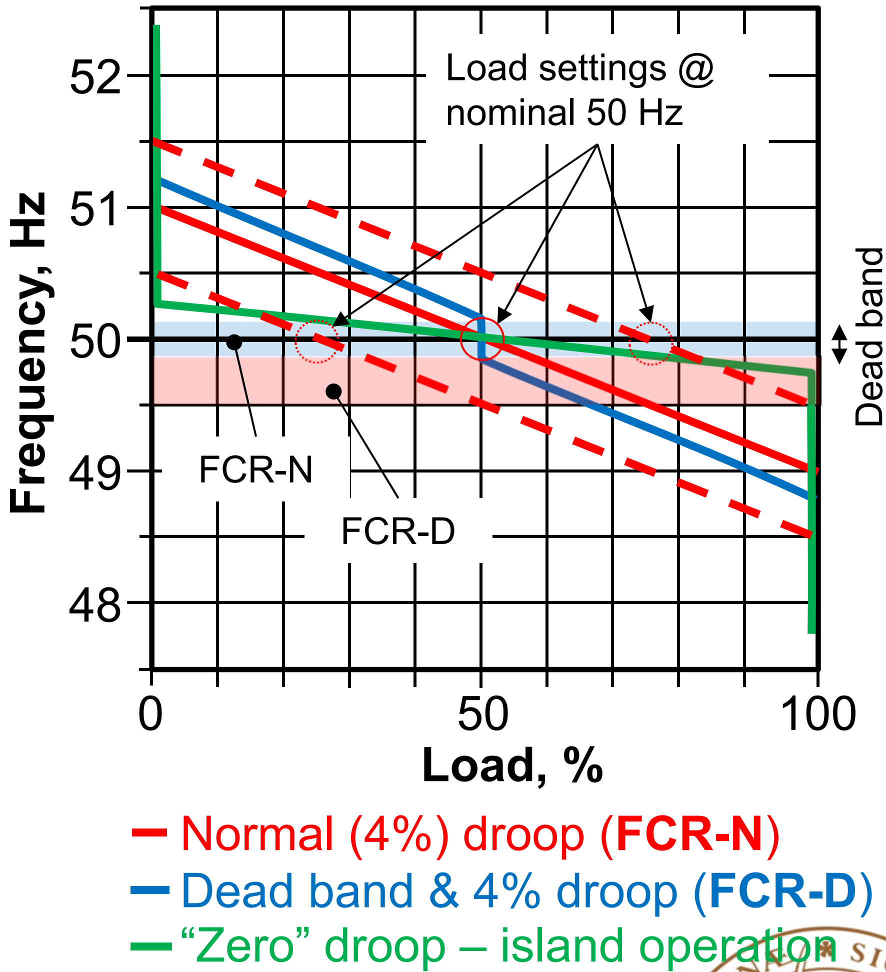
Speed drop is defined as:

$$Droop = d = \frac{\frac{\Delta f}{f_0}}{\frac{\Delta P}{P_{nom}}} \cdot 100\,[\%]$$

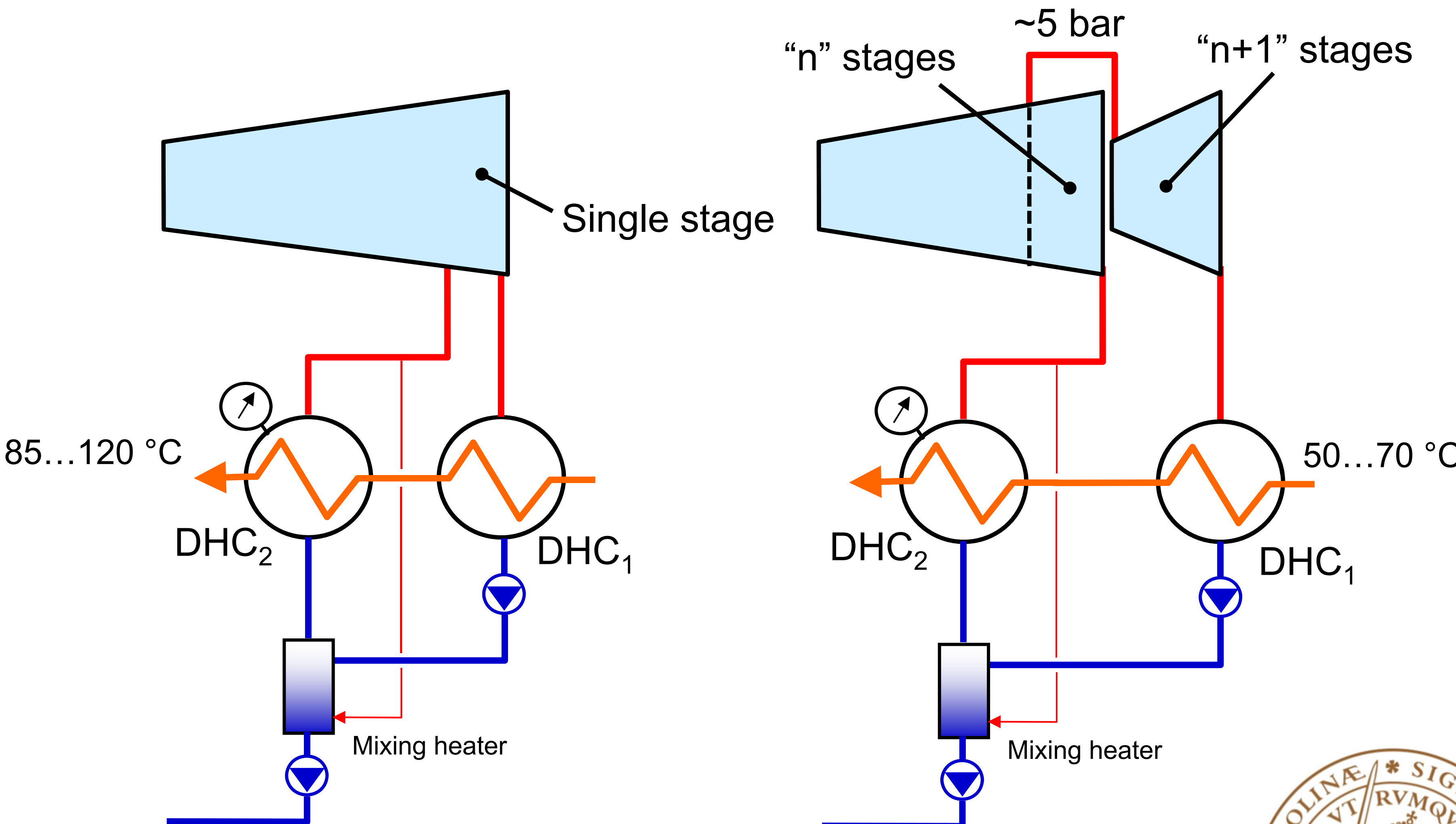
Recast to yield the convenient form:

$$\Delta P_{gen} = -\underbrace{\frac{P_{nom}}{d \cdot f_0}}_{P_{regulating}} \cdot \Delta f$$

"Regulating power"



CHP-plant – condenser couplings



Steam turbine life extension

Strength analysis

Stress analysis: ϑ_i, σ_i — $\sigma_i \le \sigma_{allowable}(\vartheta_i)$

Cyclic loading:

Strains:

$$\varepsilon_i = f(\Delta\sigma_i, \vartheta_i)$$

Number of cycles to crack initiation:

$$N_{S,i} = f(\varepsilon_i, \vartheta_i)$$

Creep loading:

Time to creep rupture or creep strain:

$$t_{S,i} = f(\sigma_i, \vartheta_i)$$

Cumulative damage:

$$E_n = \frac{\sum N_i}{N_{S,i}}$$

$$E_t = \frac{\sum t_i}{t_S}$$

Linear damage accumulation:

$$E_n + E_t \le E_{max}$$

As a rule, a safety factor of S = 1.5 is applied!

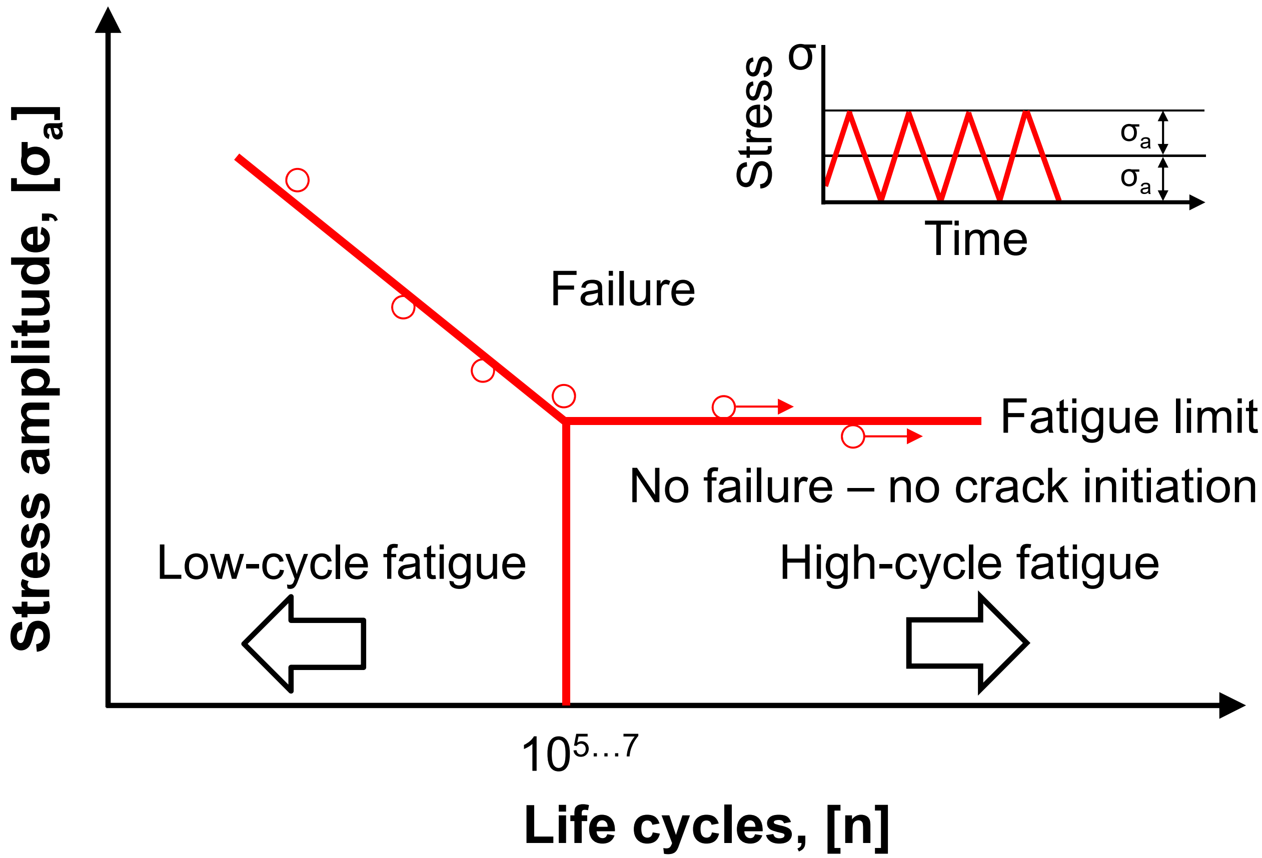
How to assess in practical terms?

✓Hours and events

✓Equivalent hours

Fatigue – low or high?

Wöhler- or σ,N curve



Status assessment

- Non-destructive testing
  - Location, orientation, shape and distribution of imperfections
  - Ultrasonic examination (DGS)
  - Surface crack examination
  - Radiography for casings
  - Visual inspections including replica technique

Cracks!

- Mechanical testing of specimens
  - Composition
  - 0.2% proof stress, tensile strength, elongation at fracture, area reduction,…
  - Hardness
  - Nil-ductility transition temperature (if applicable)
  - Structure
  - Creep-rupture strength
  - Ductility
  - Cyclic crack growth behavior
  - Strain cycle fatigue
  - Fatigue strength

Ultrasonic (US) testing I

Ultrasonic (US) testing III

Low-reaction turbine
- ✓ Massive rotor
- ✓ Siemens, …

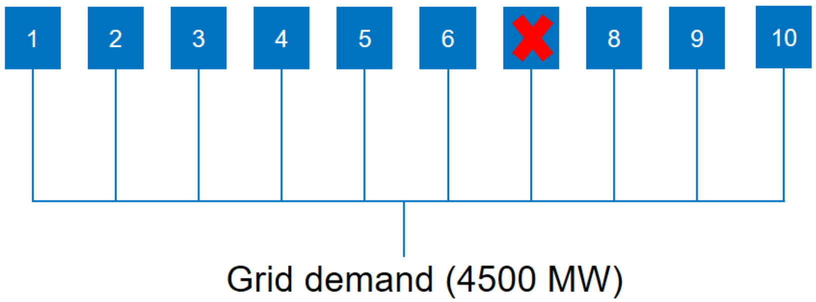
Replica and samples

Contents – course 2021/2022

- Historical perspective
- Basic cycle thermodynamics
- Introduction to turbines
  - Mollier diagram
  - Work and velocity triangles
  - Reaction
- Combined cycles
- Industrial turbines
  - Geared vs. non-geared
- Utility turbines
- Boilers
- Cycle thermodynamics
  - Components
- Glands
  - System
- District heating
  - Condensing tails
- Aerodynamics
- Exhausts
- Moisture
- Control- and safety system
  - Hydraulics
- Off-design (part-load)
  - Valves
  - Control stages
- Some chemistry
- Damage mechanisms
- Swedish turbine tradition
- Miscellaneous

Grid stability – impact from inertia…

10 units á 500 MW running at 90 % load – 4500 MW



$$\left(\frac{df}{dt}\right)_{t=0} = \frac{\Delta P}{2 \cdot \tau_l \cdot P_{nom}} \cdot f_{nom}$$

$$f(t) = \sqrt{f_{nom}^2 + \frac{\Delta P}{P_{nom}} \cdot \frac{f_{nom}^2}{\tau_l} \cdot t}$$

$$\frac{df}{dt} = \frac{\overbrace{\Delta P}^{+/-} - \overbrace{\left\{\frac{a}{100} \cdot P_{init} \cdot \left(f_{nom} - f\right)\right\}}^{\text{Self regulating}}}{P_{nom}} \cdot f_{nom}^2 \cdot \frac{1}{2 \cdot f \cdot \tau_l} \sim \frac{\Delta P}{\tau_l}$$

Rotor stability (loss of power):

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

N.B. The load angle “δ” must also be taken into consideration (≤90°). Cf. the literature on generators!

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