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BB and BOP actual achievements, issues to be solved and future perspectives (HCPB)

E. Bubelis, W. Hering, F. A. Hernandez, S. Perez-Martin (KIT)

Institute for Neutron Physics and Reactor Technology

Outline

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- **Future perspectives**

  Worldwide, in Europe and for Germany
- **Who will need fusion electricity?   ('Who' – means 'Renewable energy')**
- **Production costs of Power Plants**
- **Requirements for DEMO and FPP**
- **BOP – From Plasma to Grid for HCPB DEMO**
  - **Direct (DCP) & indirect (ICP) coupled power trains**
  - **Some critical issues**
  - **Present achievements while integrating industrial equipment**
  - **Issues to be solved in order to answer challenging questions**
- **Conclusions & Perspectives**

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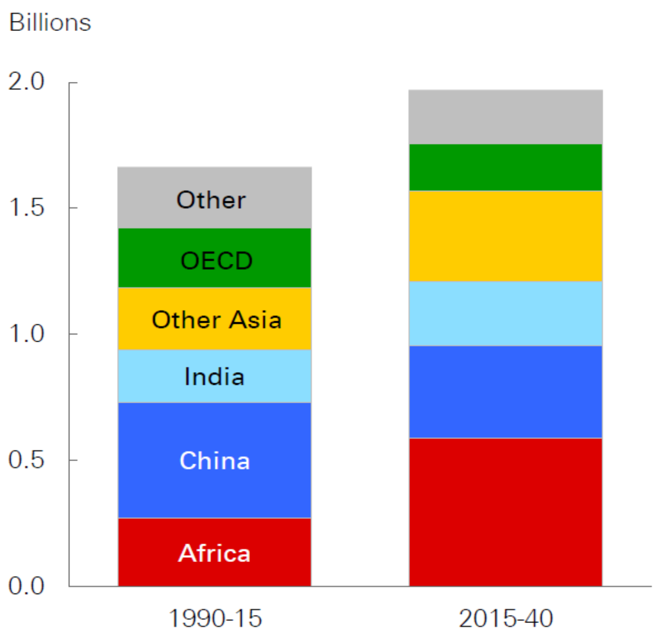
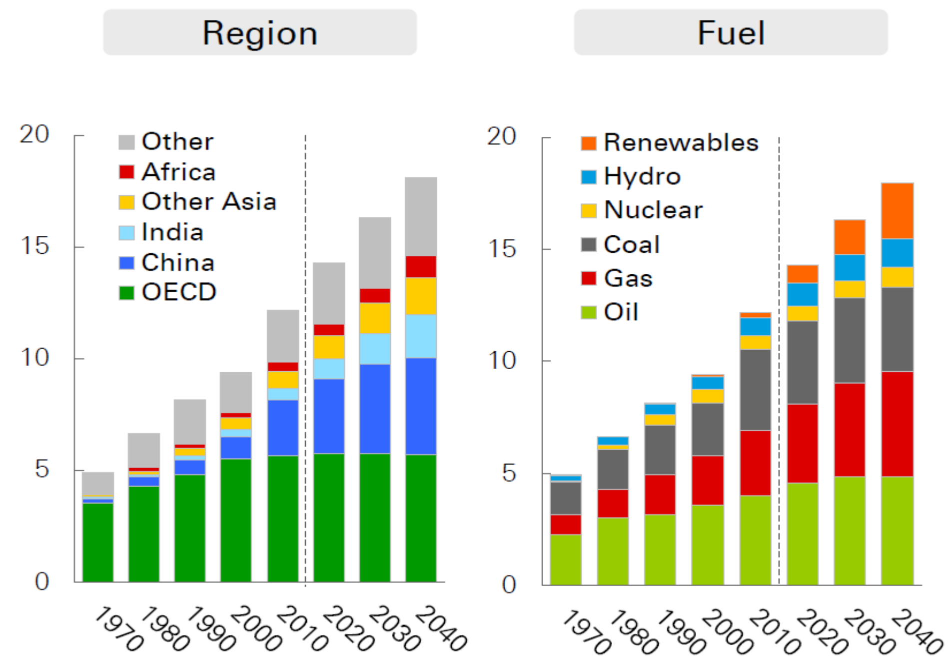
World: Challenge – growth rate and GDP increase

- World population will increase by ~1.7 billion to reach ~9.2 billion people in 2040,
- World Gross Domestic Product (GDP) will be more than double by 2040, driven by increasing prosperity in fast-growing emerging economies,
- Rising prosperity drives an increase in global energy demand,
- World continues to electrify, with ~70% of the increase in primary energy going to the power sector.

Growth in urban population by region



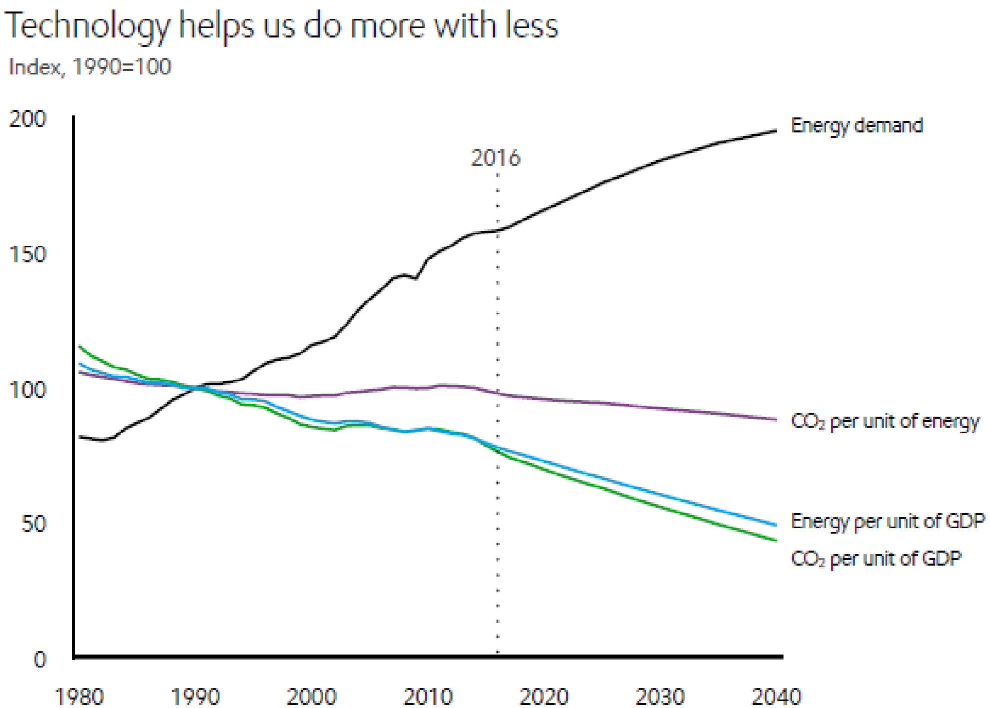
Primary energy demand

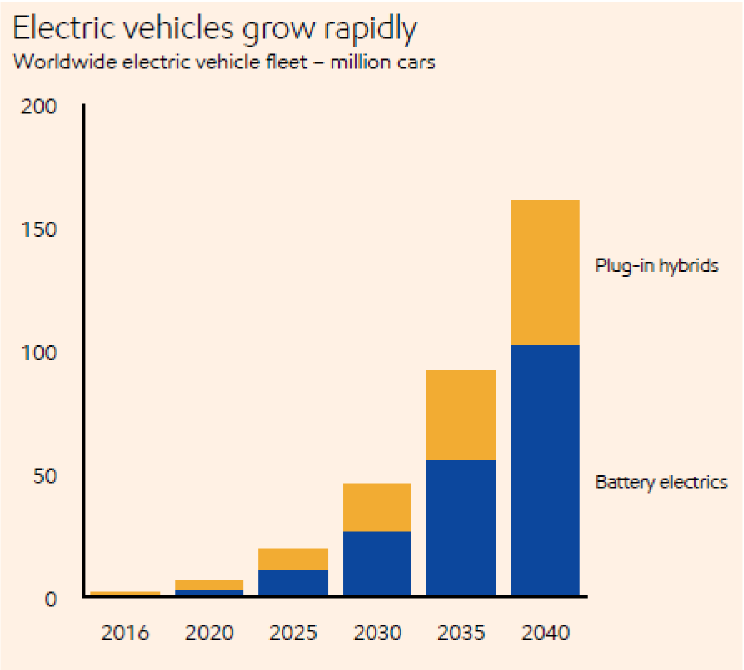


Ref: BP Energy Outlook. 2018 edition

World: Post fossil mobility

- Global CO_2 production should decrease, to keep the global warming < 2°C,
- The carbon intensity of energy (CO_2 content per unit of energy used) has been up to now fairly flat; the pace of improvement is likely to pick up until 2040,
- Recently, some car manufacturers and governments (i.e. Denmark) have announced plans to limit future vehicle sales to those with an electric motor, including hybrids, plug-in hybrids and battery electric vehicles.

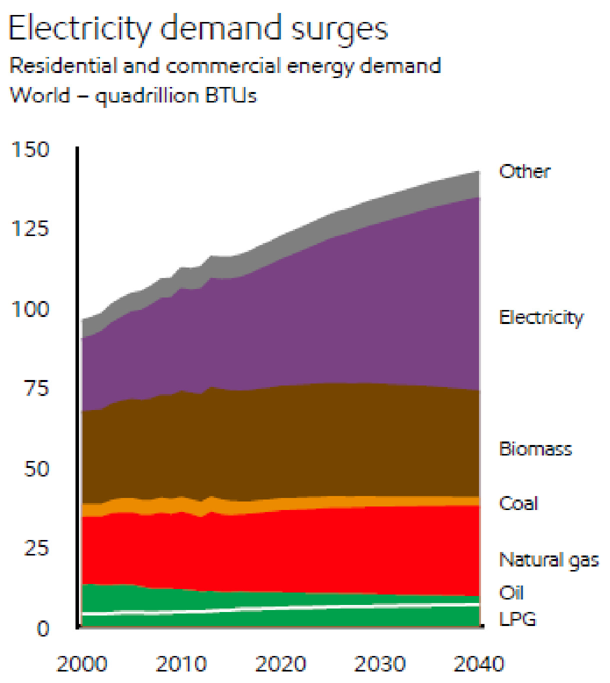


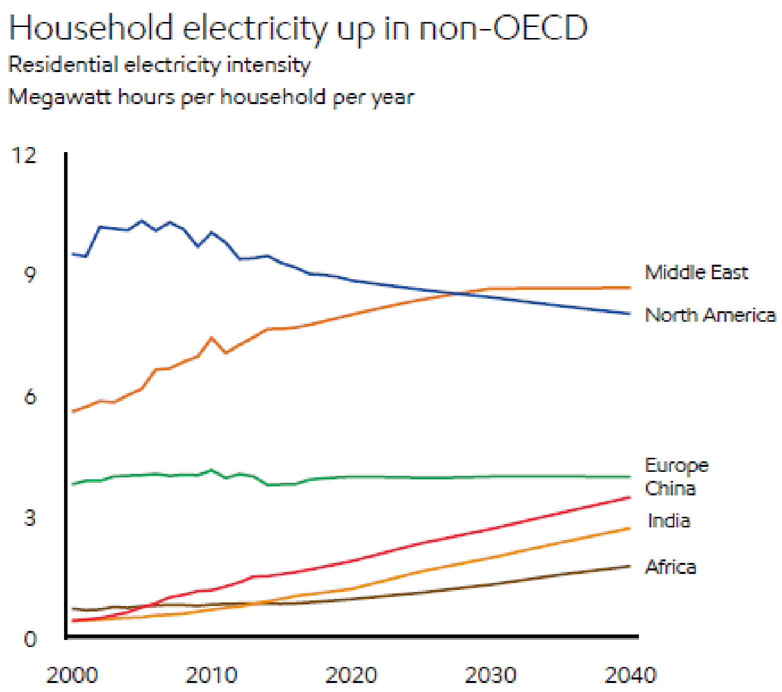


Ref: 2018 Outlook for Energy: A view to 2040. ExxonMobil

World: Energy shift and replacing of fossil heat

- Energy shifts reflect rising living standards and increasing urbanization through 2040,
- Residential electricity use will rise about 75 percent by 2040, driven by a nearly 150 percent increase in non-OECD nations,
- Electricity use per household in OECD nations will be flat-to-down as efficiencies will help limit electricity demand.





Ref: 2018 Outlook for Energy: A view to 2040. ExxonMobil

Europe and Germany: Efficiency vs. Consumption

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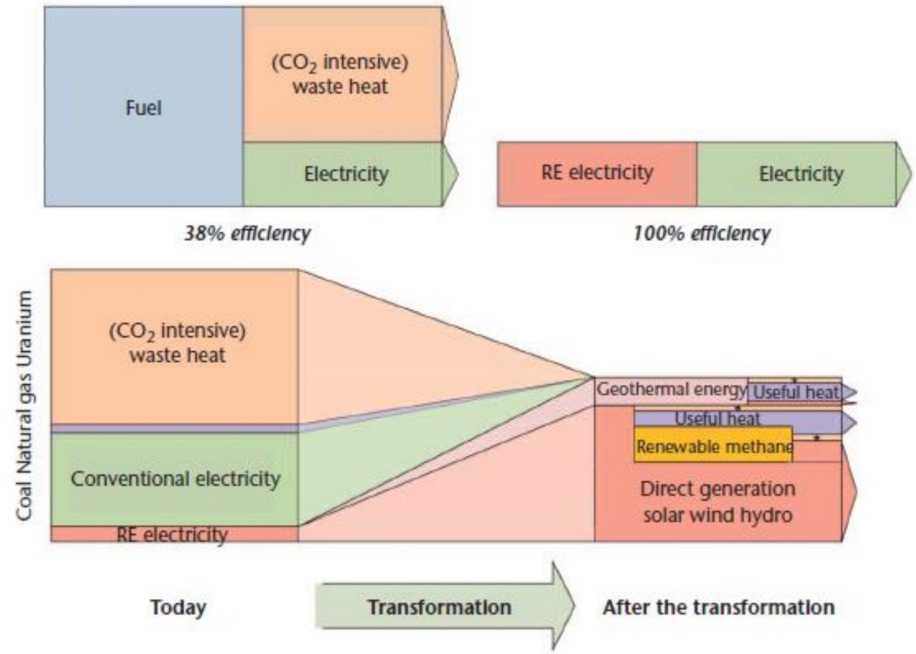
- Limiting the increase in global warming < 2°C, requires a reduction of at least 90% in energy-related carbon dioxide emissions in the European Union and Germany, and thus the complete reorganization of the entire energy system,
- This idea is based on significantly more efficient use of energy resources, and for all residual energy to be supplied by renewable energy,
- The wish is – moving from a centralized, load-optimized system to a decentralized, intelligent, load and supply-oriented energy supply structure,
- The construction and integration of (very) large storage capacity in the energy supply system is a basic requirement for a large share of fluctuating energy sources

Efficiency gains in the power sector through an increase in direct power generation from renewable energy and combined heat and power (CHP) – an example of such transformation.

Ref: Energy Concept 2050 for Germany with a European and Global Perspective



 2018.11.23. E. Bubelis, W. Hering, F. A. Hernandez, S. Perez-Martin

EFPW-2018, Bad Dürkheim, Germany

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T. Donné: Why do we need fusion electricity?

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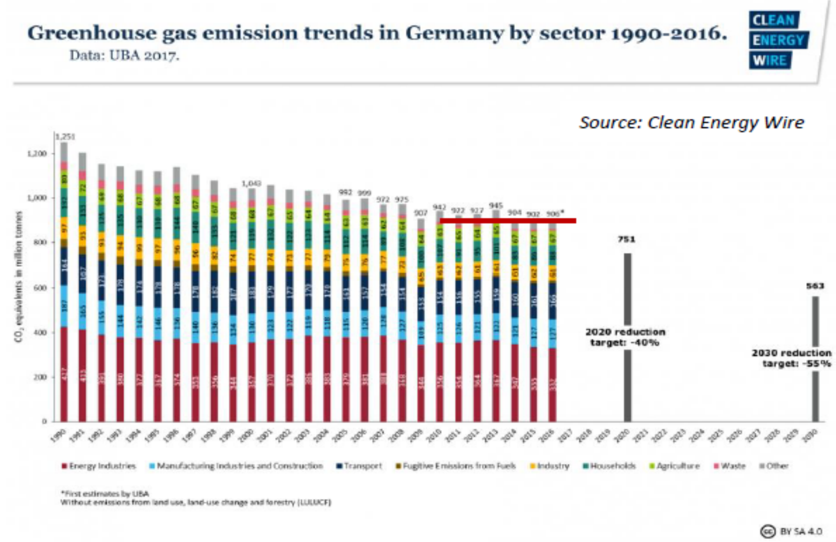
Some lessons from Germany:

- However, CO_2 emission due to electricity generation doesn't go down[1]
- Recent studies show that <u>even with storage and EU super grids</u>, intermittent sources as wind and solar can't contribute more than 50-60% to the electricity needs[2,3]



- Large scale back-up energy sources are needed!
- Nuclear being the only option to replace fossils and to reduce the CO_2 emission
- Fusion is one of the nuclear options, and its potential utilisation should be pursued with vigour

1 www.cleanenergywire.org/news/german-co2-emissions-rise-2015-despite-renewables-surge.

2 F. Wagner, *Eigenschaften einer Stromversorgung mit intermittierenden Quellen, Proc. Deutsche Physikalische Gemeinschaft*, Arbeitskreis Energie, Berlin, 138-155 (2015).

3 H.W. Sinn, Buffering volatility: a study on the limits of Germany's energy revolution, http://www.nber.org/papers/w22467

Note: Fusion is not in competition with other renewables. It is needed as back-up and as part of the energy mix

A.J.H. Donné | SOFT, Sicily, IT | 17 September 2018

Production costs of Power Plants

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Total Costs

Capital Costs
Construction Phase

(per capacity of the plant, €/kW)

- **Overnight costs:**
  - Site preparation
  - Construction
  - Manufacture
  - Commissioning
- **Financing the investment:**
  - Construction period
  - Debt interest charges

Operating Costs
Operation Phase

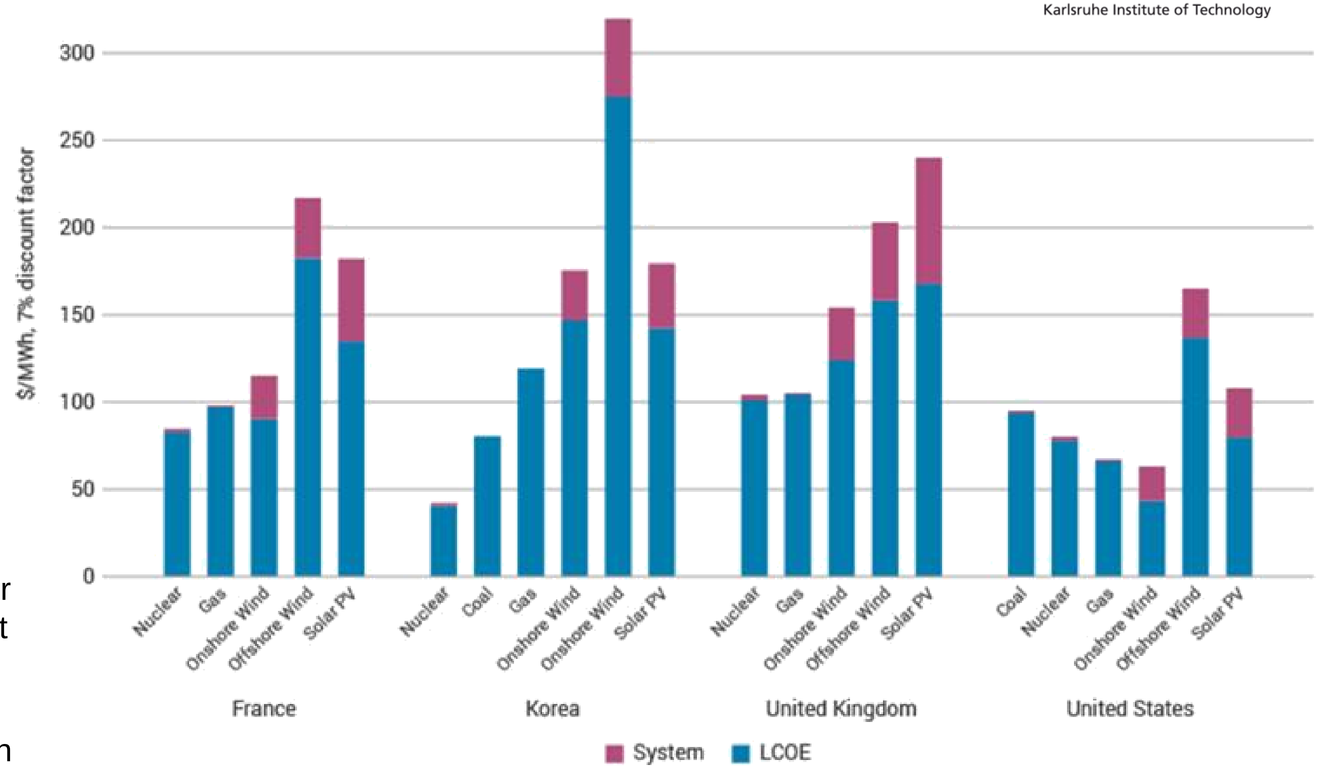
(fixed + variable, per unit of electricity, c€/kWh)

- Fuel
- Operation and maintenance (O&M)
- + for nuclear: provision for funding decommissioning of the plant and treating and disposing of used fuel and wastes

External Costs
- Health- and the environment-related costs
- Quantifiable but not built into the cost of the electricity

Other Costs
- **System costs:**
  - Backup
  - Transmission/distribution
- **Production-specific taxes**
- **…**

Comparative LCOEs and system costs in four countries



- The LCOE varied much more for nuclear than coal or CCGT plant with different discount rates, due to it being capital-intensive.
- The nuclear LCOE largely driven by capital costs
  - At 3% discount rate, nuclear was substantially cheaper than the alternatives in all countries
  - At 7% it was comparable with coal and still cheaper than CCGT plant, at 10% it was comparable with both.
  - At low discount rates it was much cheaper than wind and PV.

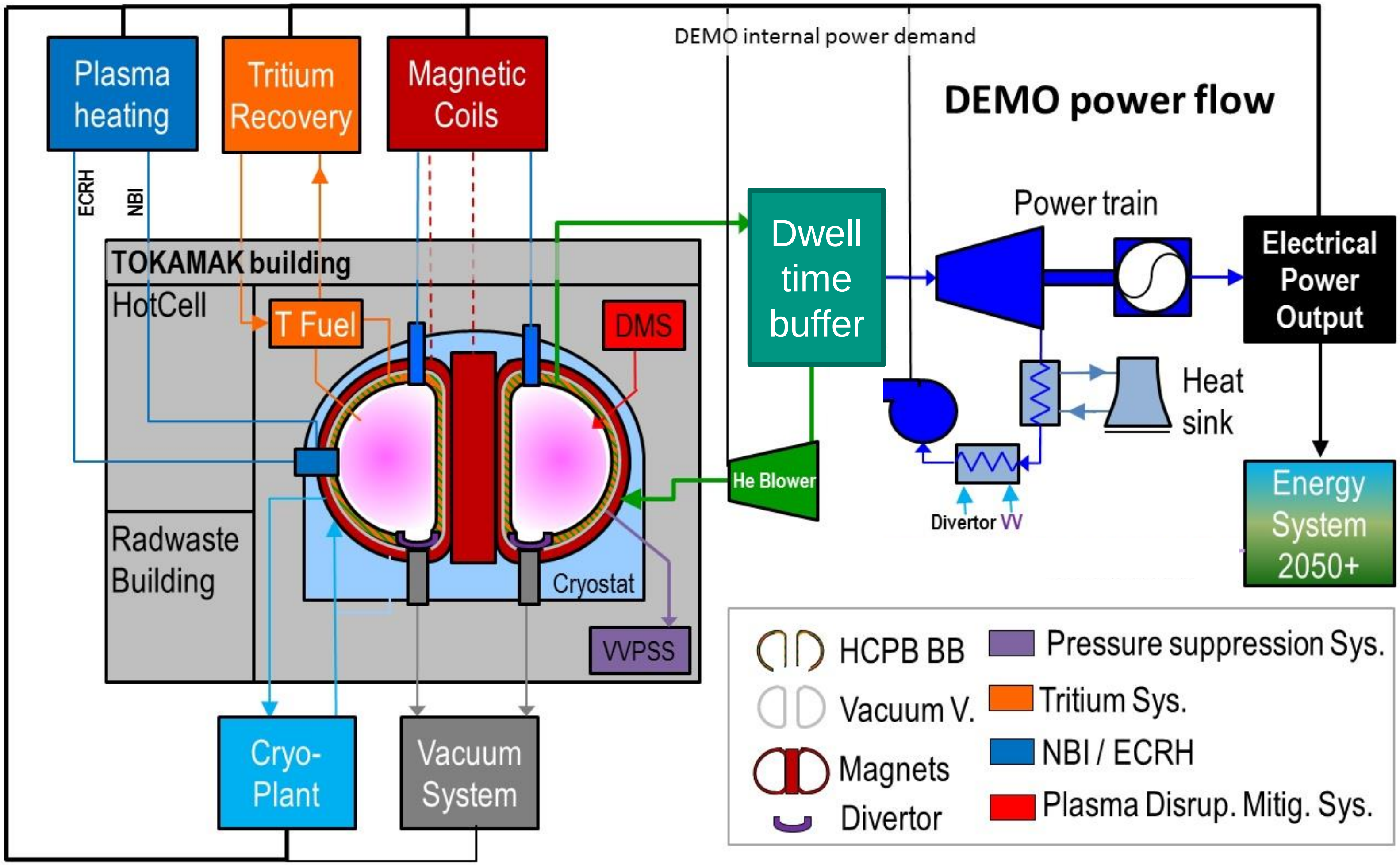
Levelized Cost of Energy (LCOE) plant costs from *Projected Costs of Generating Electricity* 2015 Edition (OECD).
System costs from *Nuclear Energy and Renewables* (NEA, 2012).
www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx
LCOE figures omit system costs. For all technologies, a $30 per tonne carbon price was included. A 30% generation penetration level for onshore & offshore wind and solar PV assumed in the NEA estimates of system costs (include back-up costs, balancing costs, grid connection, extension and reinforcement costs). A discount rate of 7% is used throughout, consistent with the plant level LCOE estimates given in the 2015 edition of *Projected Costs of Generating Electricity*. The 2015 study applies a $30/t CO_2 price on fossil fuel use and uses 2013 US$ values and exchange rates.

Requirements for DEMO and FPP

- All the design activities related to DEMO should be carried out in close cooperation with the designers of DEMO BoP,
- BB and BoP should be designed together for an optimized heat transfer and electricity production,
- DEMO and FPP should be able to provide electricity in a reliable and safe manner,
- The design of DEMO and FPP should respect all the main safety requirements for such type of nuclear facility, especially these of minimized radioactive material inventory and minimization of accidental releases in case of an accident, so that there would be no need for sheltering and evacuation of population living near such a plant,
- All the main risks identified in an early phase of the design should be eliminated either by the design measures, or prevented by the corresponding safety measures.

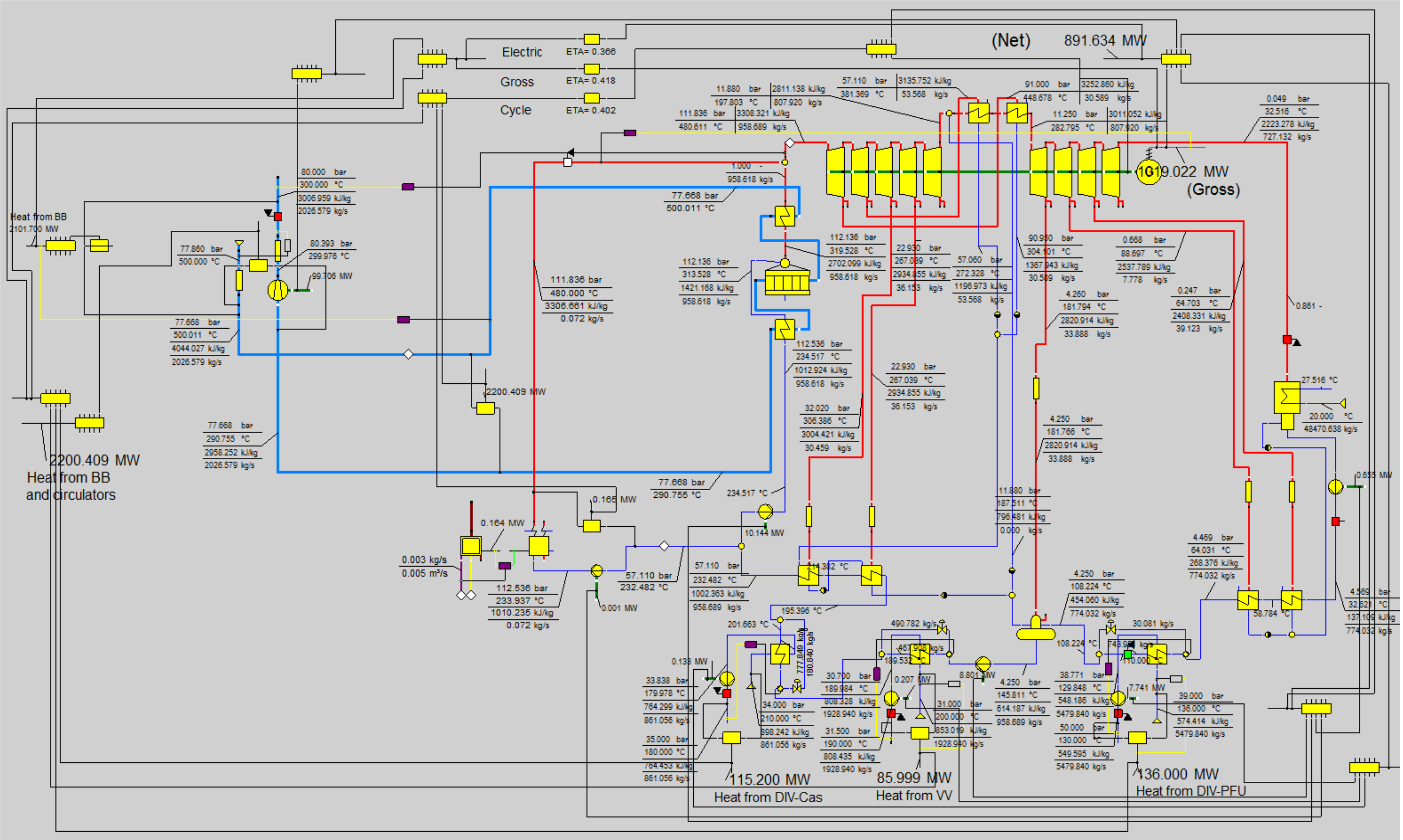
- The main role of a future FPP should be the supply of electrical energy when renewable energy sources are not available, thus direct participation in the stabilization of the electrical grid performance,
- FPP should act also as an energy storage facility in the environment, where the biggest part of electricity is being produced from renewable energy sources in a variable manner,
- FPP should act as a primary energy reserve, while prices for primary energy are normally ~10 times higher than for the base load energy.

DEMO: DCP / ICP



DEMO internal power demand
DEMO power flow
Plasma heating
Tritium Recovery
Magnetic Coils
ECRH
NBI
TOKAMAK building
HotCell
T Fuel
DMS
Radwaste Building
Cryostat
VVPSS
Dwell time buffer
He Blower
Power train
Electrical Power Output
Heat sink
Divertor VV
Energy System 2050+
Cryo-Plant
Vacuum System
HCPB BB
Vacuum V.
Magnets
Divertor
Pressure suppression Sys.
Tritium Sys.
NBI / ECRH
Plasma Disrup. Mitig. Sys.

HCPB DEMO – Direct coupled power train



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HCPB DEMO – Direct coupled power train

Positive effects:

- No need for IHTS/ESS between PHTS and PCS.

Serious adverse effects:

- No stable generation of the electrical power supplied to the grid,
- Big thermal fluctuations within PCS due to pulse-dwell-pulse operation of DEMO,
- Due to thermal fatigue, lifetime of all DEMO components will be significantly reduced,
  → For compensation of the above, DEMO needs an external power source or additional ESS within PCS for dwell time compensation,
- External heat source would be using fossil energy source (i.e. natural gas), thus due to pulse-dwell-pulse operation of DEMO there is a need for natural gas storage facility at the plant site,
- Additional ESS within PCS itself could cost not less than normal IHTS/ESS and will require sufficiently large footprint within DEMO layout,
- Even with the existing selection of different storage concepts, the supply of additional steam to the steam turbine during dwell time operation might be problematic.

HCPB DEMO – Direct coupled power train

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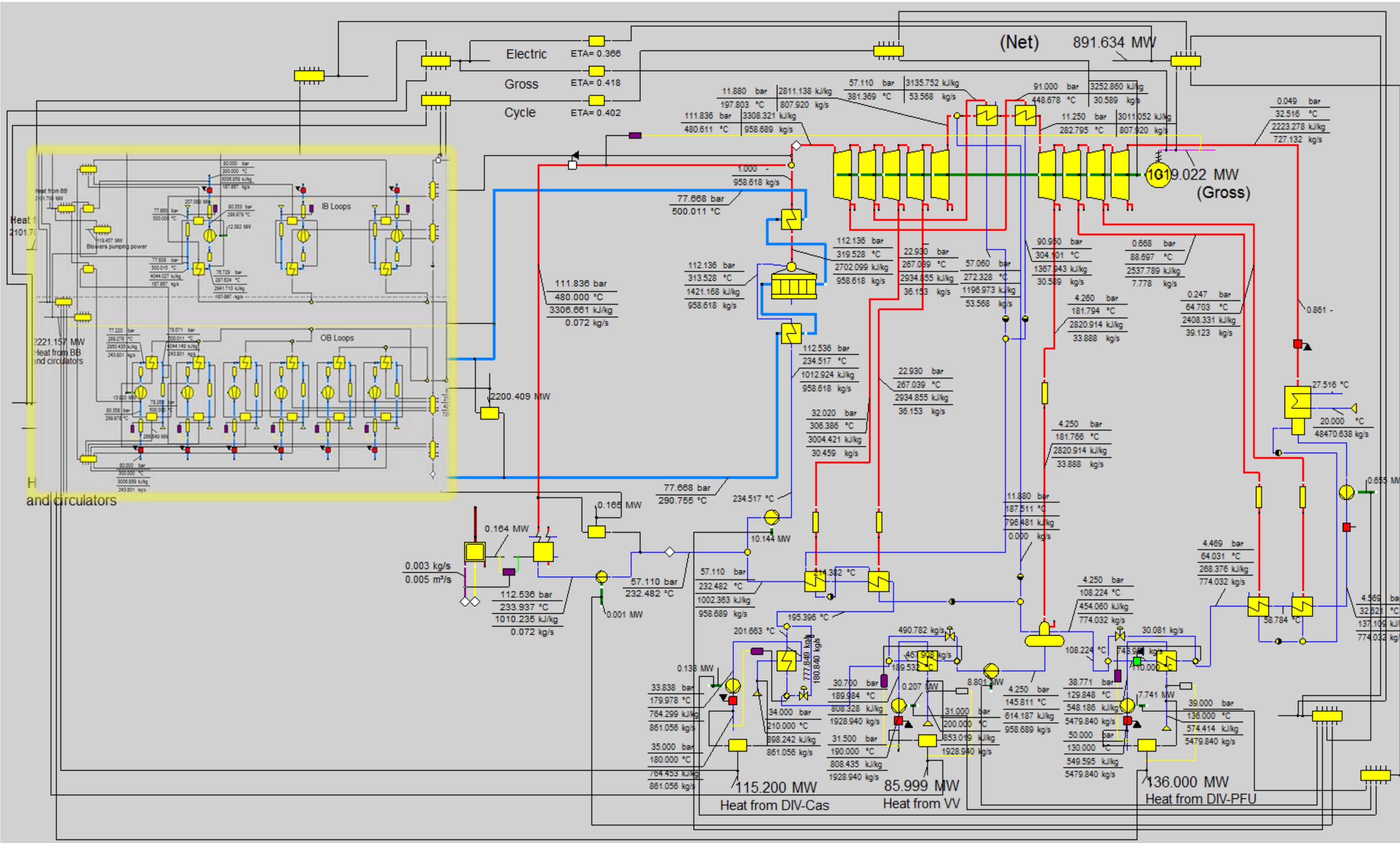

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HCPB DEMO – Indirect coupled power train (18 sectors)

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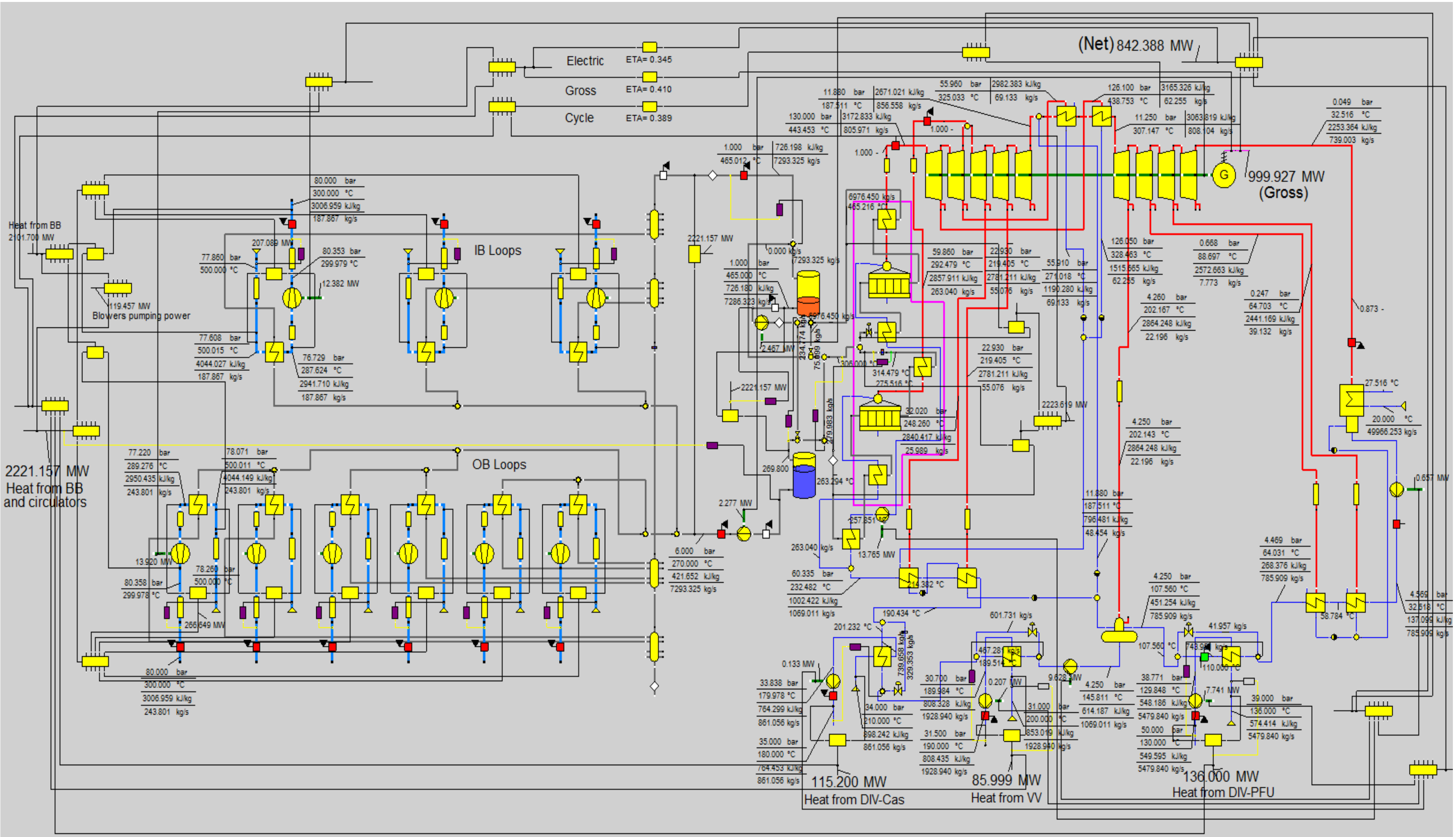

3 IB + 6 OB loops; He blowers power: ~120 MW

2018.11.23. E. Bubelis, W. Hering, F. A. Hernandez, S. Perez-Martin
EFPW-2018, Bad Dürkheim, Germany
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DEMO evolution (18 → 16): DCP / ICP – existing options

- Issues still under evaluation for **DEMO-18**:
  ICP ✓: solution with 3IB + 6OB loops (PHTS IHX design is being checked for feasibility – two passes design vs. once-through design),
  DCP ✓: solution with external boiler burning natural gas (not less than $0.5P_n$) is being checked for feasibility.

- Issues being solved for **DEMO-16**:
  ICP: checking consistency/feasibility; looking for Industrial availability
- Possible cases (draft result of KAH-KIT task):

PHTS configuration	Feasibility space / technology	Comments
4IB + 8OB loops	- / +	Too many incoming / outgoing pipes
2IB + 8OB loops	+ / +	1 loop more, but still ok
8 (IB+OB) loops	+ / ~	1 loop less, slightly bigger He compressors – ok; cost reduction due to standardization of loop equipment; IHX design should still be proved for feasibility

- DCP: possible solution(s) in work (challenging!)

HCPB DEMO – Indirect coupled power train (16 sectors)

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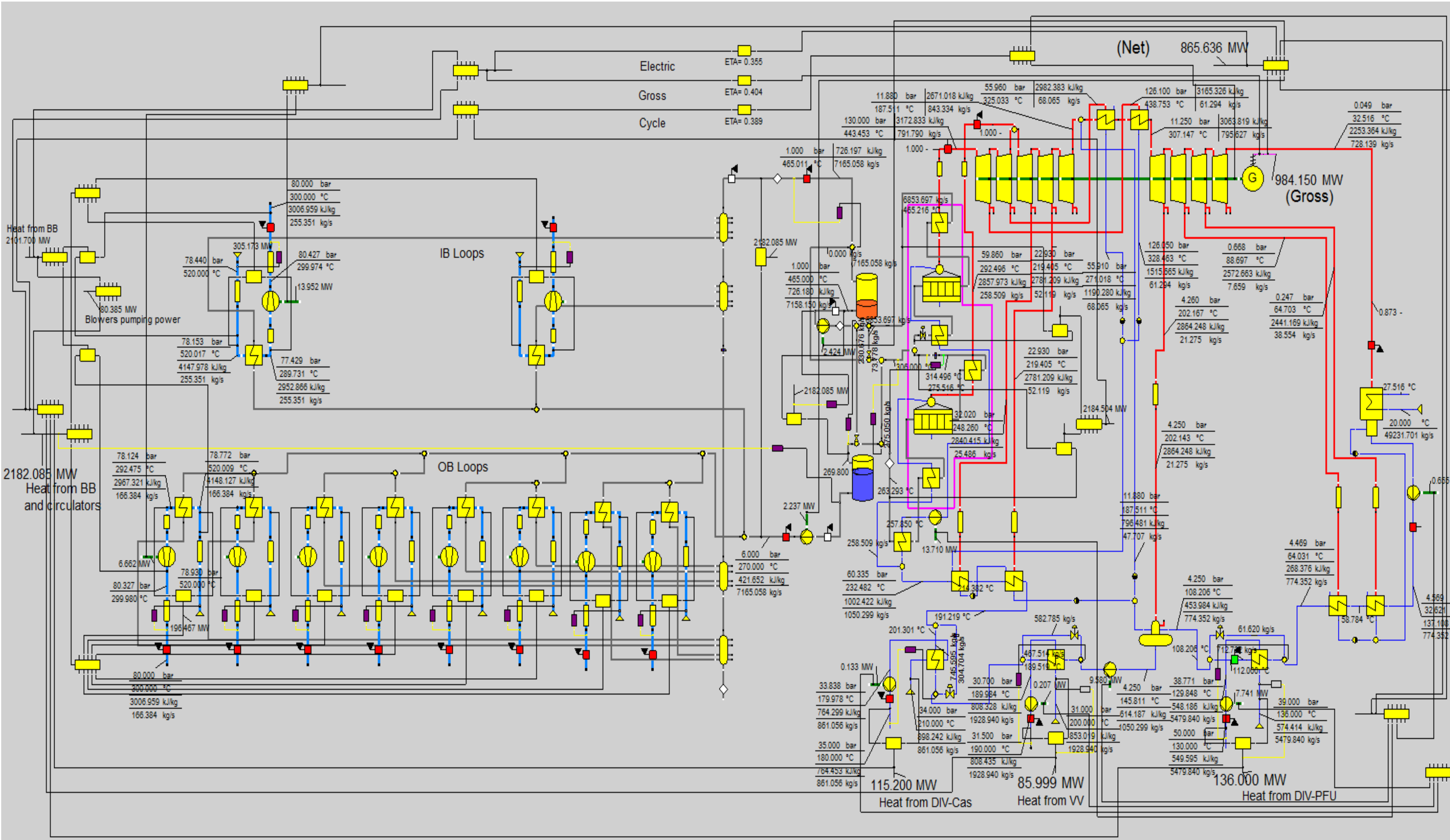
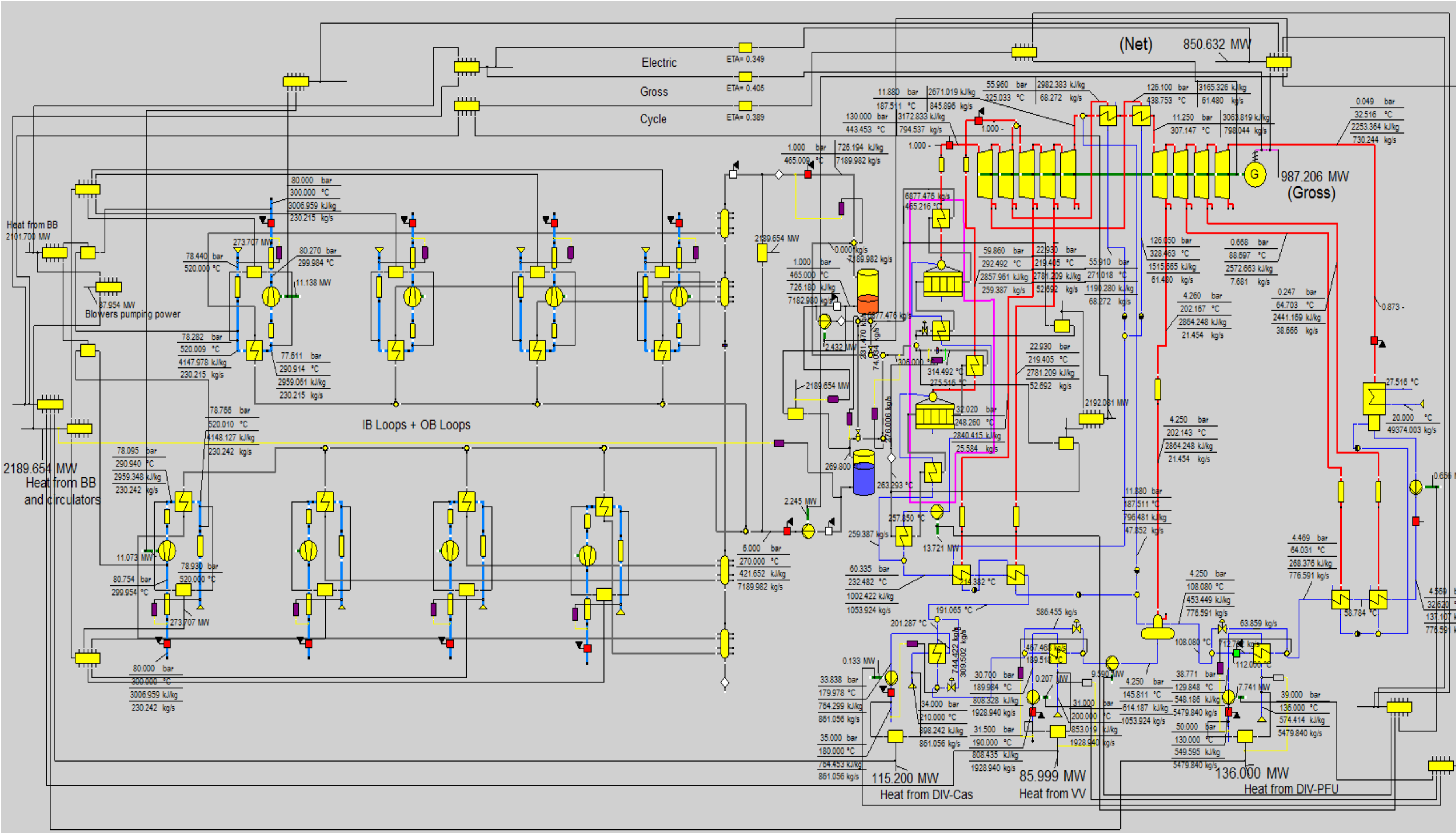


2 IB + 8 OB loops; He blowers power: ~80 MW

HCPB DEMO – Indirect coupled power train (16 sectors)



8 IB+OB loops; He blowers power: ~88 MW

HCPB DEMO – Indirect coupled power train

Positive effects:

- IHTS/ESS between PHTS and PCS gives us possibility to operate either in a stable electricity generation mode, or to act as heat storage facility (primary energy reserve) and thus participate in the stabilization of the electrical grid performance,
- Most of the PHTS-IHTS-PCS circuits components can be directly ordered from the industry or designed/adapted to our needs by our industrial partners within a short time period,
- Electrical output decoupled from pulse/dwell duration evolution,
- Power range variation can be adapted to stakeholder's grid needs,
- Tritium inventory in coolant in HCPB BoP is lower (1.6 g) than for WCLL BoP design (~(75÷100) g),
  → easier extraction, simplified maintenance.

Potential adverse effects:

- Significant permeation of T in HCPB BoP is promoted by i) different coolant (He) in comparison with WCLL (water): water captures T and keeps it there, while He does not capture T, thus T can easily permeate further and ii) rather big HX surface of IHXs (~87000 m^2).

HCPB DEMO BoP – Critical issues (solved/open)

Solved:

- HXs big size – means large number of HXs tubes → difficult component manufacturing and transport → modular design necessary → suitable component configuration/design,
- HCPB BoP design involves kilometers of connecting pipes and a lot of welds → increases probability of leaks → to be optimized (reason: safety and routing issues),
- Station power demand increased by helium compressors, but station gross output is larger,
- BB pressure loss reduction using HCPB advanced BB concept by ~50% (allows using He circulator size not needing significant development efforts),
- Investigation done to assess risk of molten salt freezing in tanks due to loss of electrical power or long shutdown (min 20-30 days until freezing with 200 mm thermal isolation layer).

Still open:

- Because of big DEMO fusion power (~2100MW), DEMO BoP components are of big size, however comparable to other DEMO components (magnets, cryostat, VV, etc.),
- Safety concerns increase with the increasing size of components → coolant inventory loss in case of a leak,
- EV required for HCPB design in case of in-vessel LB-LOCA (~50000 m^3) is much more than for WCLL design (~3600 m^3) → segmentation needed to reduce burden plant layout,
- There is a need of a large duct size leading from VV to expansion volume (EV) > 2 m^2,
- BoP component maintenance: replacement / cleaning / repair.

HCPB DEMO – PHTS and BB design

- DEMO HCPB BoP = PHTS(He) + IHTS(MS) + PCS(Rankine)
- Goal: maximize TRL for He-cooled DEMO PHTS
  - PHTS TRL mostly driven by strict limit on He circulator power: currently, technology proven up to 6 MW/circ.
  - Design drivers HCPB PHTS: Δp_{PHTS} (Δp_{BB} & Δp_{IHX}) and $\dot{m}_{plant}$
  - $\Delta p_{BB} = \Delta p_{FW} + \Delta p_{BZ} + \Delta p_{BSS} \approx$ 1.6 bar(IB) / 1.1 bar(OB)

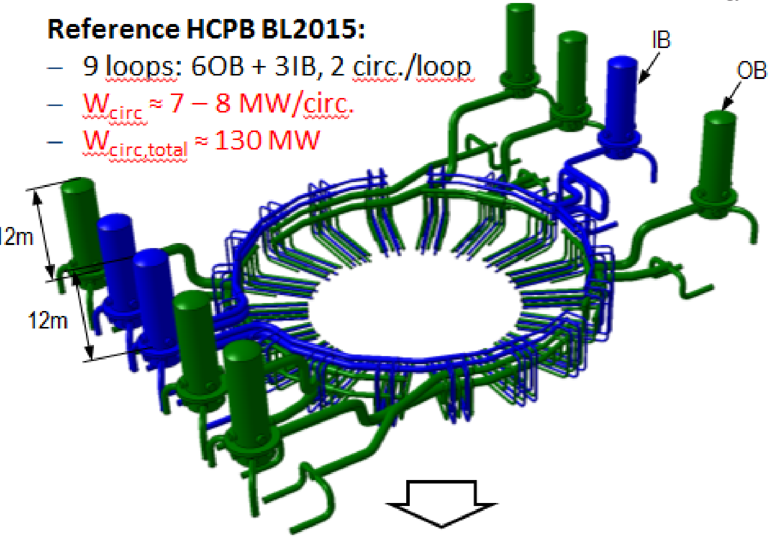
Base *PHTS BL2015*		
Reference HCPB $P_{BB,th} \approx 2100$ MW		
T_{in}/T_{out} He [°C]	**500**/292.5	
T_{in}/T_{out} MS [°C]	270/465	
Δp [bar]		
	IB	OB
In-VV	2.14**	1.74**
Piping	0.62	0.57
IHX *S&T U-tube* ***ΔT_{log} = 28°C***	0.88	0.85
Total	3.64	3.16
$P_{tot,circ}$ & $P_{tot,el}$ [MW]		
IB	OB	
36.5	80.9	
117.4	(η_{is}=0.85)	
130.4	(η_{el}=0.90)	

Base *PHTS BL2017*		
Enhanced HCPB $P_{BB,th} \approx 2100$ MW		
T_{in}/T_{out} He [°C]	**520**/291.1	
T_{in}/T_{out} MS [°C]	270/465	
Δp [bar]		
	IB	OB
In-VV	1.56	1.07
Piping	0.45	0.94
IHX *S&T 1-through* ***ΔT_{log} = 35°C***	0.63	
Total	2.68	
$P_{tot,circ}$ & $P_{tot,el}$ [MW]		
IB + OB		
86.1		
86.1	(η_{is}=0.85)	
94.2	(η_{el}=0.90)	

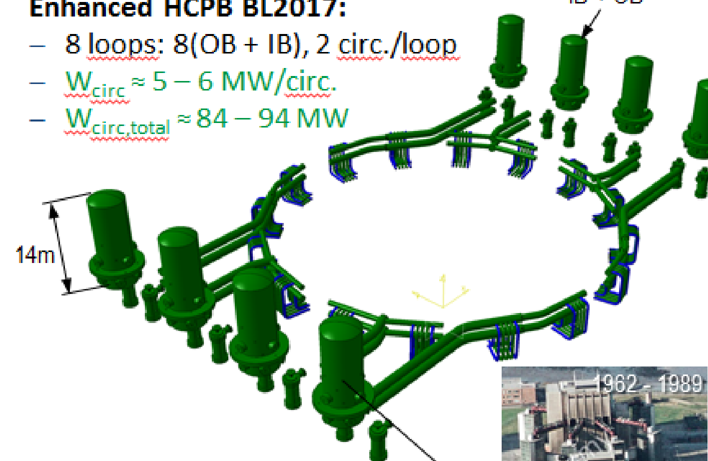
Advanced *PHTS BL2017*		
Enhanced HCPB $P_{BB,th} \approx 2100$ MW		
T_{in}/T_{out} He [°C]	**520**/292.3	
T_{in}/T_{out} MS [°C]	270/465	
Δp [bar]		
	IB	OB
In-VV	1.56	1.07
Piping	0.45	0.94
IHX *CWHE* ***ΔT_{log} = 36°C***	0.34	
Total	2.35	
$P_{tot,circ}$ & $P_{tot,el}$ [MW]		
IB	OB	
75.3		
75.3	(η_{is}=0.85)	
83.6	(η_{el}=0.90)	

***not conservative for BL2017: it does not take into account BB thickness reduction*

Reference HCPB BL2015:
- 9 loops: 6OB + 3IB, 2 circ./loop
- $W_{circ} \approx$ 7 – 8 MW/circ.
- $W_{circ,total} \approx$ 130 MW



Enhanced HCPB BL2017:
- 8 loops: 8(OB + IB), 2 circ./loop
- $W_{circ} \approx$ 5 – 6 MW/circ.
- $W_{circ,total} \approx$ 84 – 94 MW

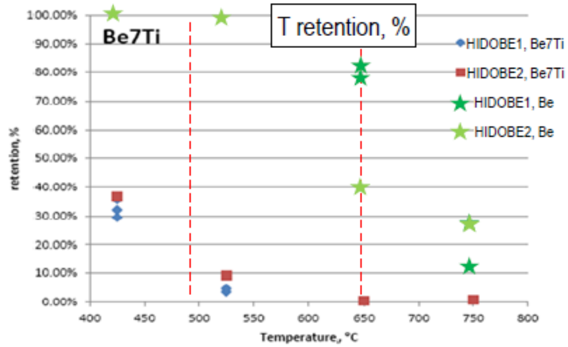


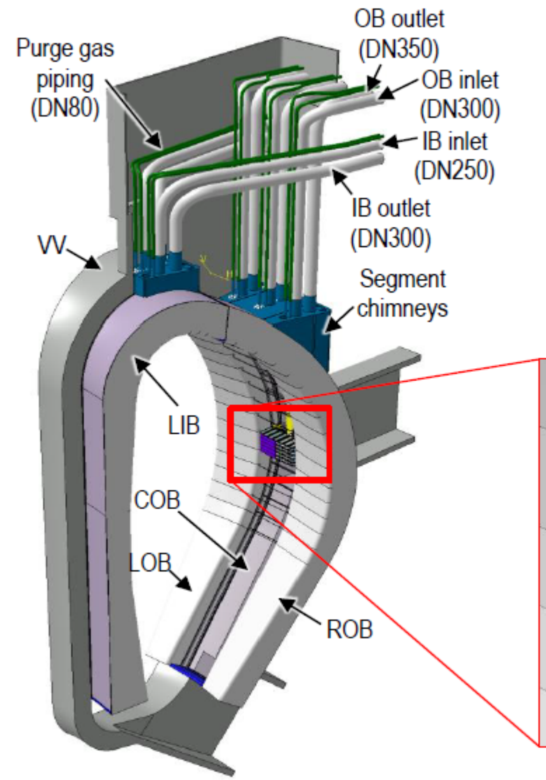
Berkley NPP, GCR (UK)

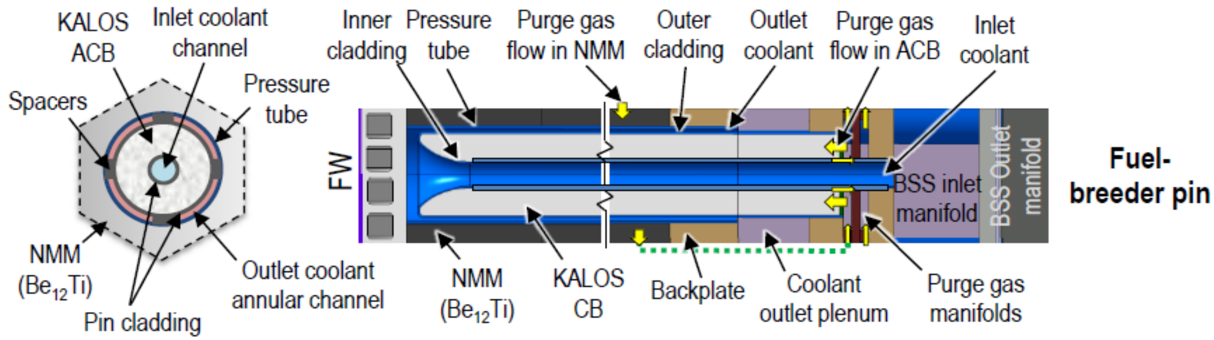
F. A. Hernández et al. | SOFT 2018 | Giardini Naxos | 18/09/2018 | Page 16

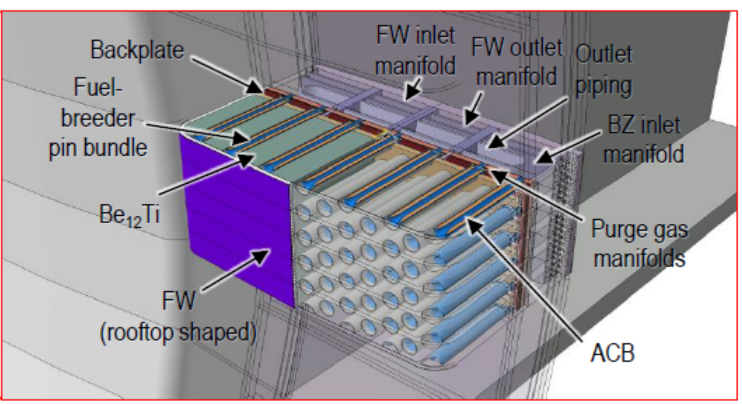
HCPB DEMO – PHTS and BB design – HCPB BB 2017 design

- Design highlights:
  - Introduction of SMS architecture and rooftop shaped FW
  - Elimination of coolant redundancy (too complex PHTS) => BZ flexibility
  - Simplest „core“: fission-like „fuel“-pin elements
  - Introduction of advanced functional materials:
    - Advanced Be NMM: $Be_{12}Ti$, lower retention, lower reactivity, lower swelling…
    - Advanced CB „KALOS“: Li_4SiO_4 + 25%mol Li_2TiO_3 (strength ≈2x, ΔTBR<-1% w.r.t. Li_4SiO_4)









- Coolant: He, 8 MPa, T_{in} = 300°C,

T_{out} = 520°C => key advantage for PHTS

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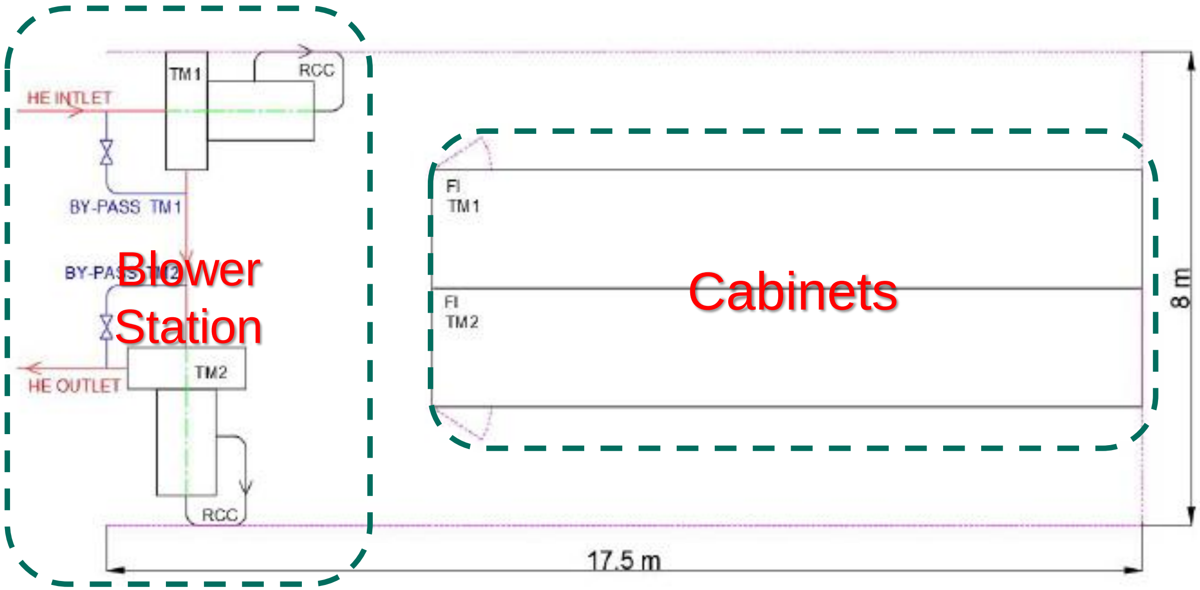
HCPB DEMO BoP – Examples of existing industrial equipment

In the below slides presented are examples of the existing industrial equipment that can be selected for HCPB DEMO BoP design:

HCPB DEMO BoP – Examples of existing industrial equipment – PHTS components

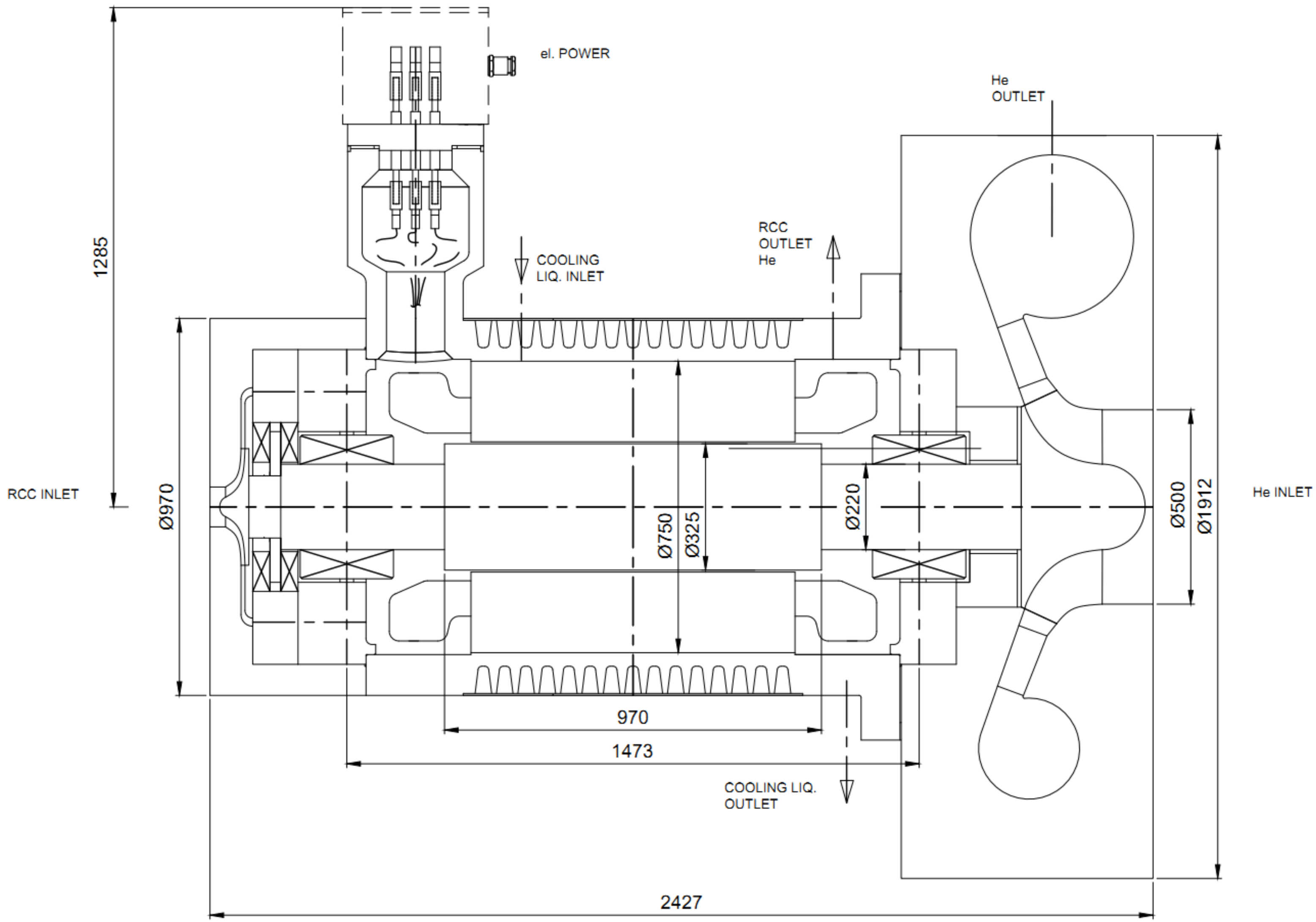
Design proposed by ATEKO – each He blower (circulator) shown in the DEMO BoP conceptual design for HCPB BB option (18 sectors), in reality will be represented by two He compressors of 8MW power each, connected serially with each other.



ATEKO: world leader of gas compressors

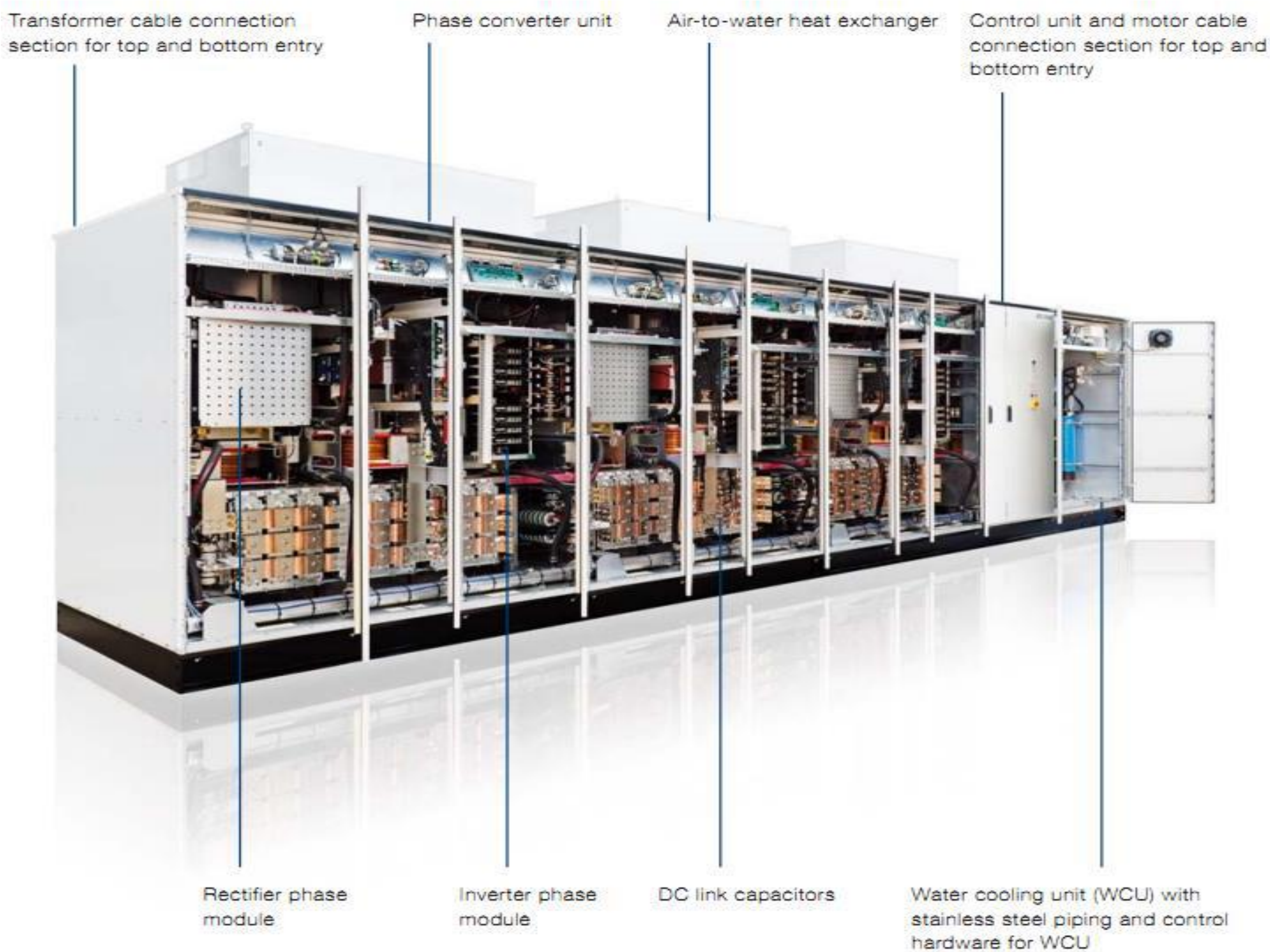
The reserved place for 2 He blowers with frequency inverters plus maintenance area is (~18x8x3 m³). However, frequency inverters can be placed also below or above TMs. Each TM weights 14 tons (~16M€); each FI (ACS 5000) weights ~9 tons (1M€).

HCPB DEMO BoP – Examples of existing industrial equipment – PHTS components



Helium TM

HCPB DEMO BoP – Examples of existing industrial equipment – PHTS components



FI (circulator invertor)

ABB ACS 5000

Improvements up to DEMO/FPP:

Power invertors based on HT-superconductors (Breakers already in operation)

HCPB DEMO BoP – Examples of existing industrial equipment – IHTS/ESS components

Two-tank thermal storage system was proposed by Kraftanlagen Heidelberg (KAH) from the available information of Concentrated Solar Power (CSP) plants as follows:

Thermal Storage System	
Heat transfer fluid	Molten Hitec salt
Total mass of Hitec XL salt per tank	5040000 kg
Tank nominal volume per tank	3000 m^3
Tank heat storage capacity	426 MWh_t
Size per tank	Diameter: 23.8 m; Height: 6.8 m
Footprint of thermal storage system	Approx. 2550 m^2

Commercial offer for a thermal storage system is expected in the coming months.

Costs for such a Thermal Storage system were estimated to be ~12.66M Euro, plus the costs for the HITEC salt, which are in the order of ~3.92M Euro.

HCPB DEMO BoP – Examples of existing industrial equipment – PCS components

Turbogenerator specification was provided by Siemens Power and Gas Division.

Turbogenerator (PCS ST)	
Live steam pressure	130 bar(abs)
Live steam flow rate	842 kg/s
Live steam temperature	447 °C
Max. PCS Output	≈ 1009 *MW*
Turbogenerator weight	Approx. 1285000 kg
Turbine manufacturer	Siemens
Turbine type	SST5-6000: I50 / 6x12.5m²
No. of turbine stages	1 IP turbine stage; 3 LP turbine stages
Turbine rated speed	3000 rpm
Electrical generator manufacturer	Siemens
Electrical generator type	SGen5-3000W
Electrical generator rating	965 MVA
Condenser cooling water quantity	35184 kg/s
Condenser cooling water inlet temperature	20 °C
Condenser cooling water outlet temperature	29.5 °C
Turbogenerator space reservation	L=52m;H=24m;W=19m

The DEMO BoP turbogenerator consists of the steam turbine (PCS ST) together with a condenser, including condensate drain, two steam re-heaters and the electrical generator.

HCPB DEMO BoP – Examples of existing industrial equipment – PCS components

Deaerator specification was provided by our industrial partner KAH.

Spray Type Deaerator	
Operation pressure	4.25 bar(abs)
Feed water outlet mass flow	1069 kg/s
Max. PCS Output	$\approx 1009\ MW$
Deaerator gross volume	415 m^3
Deaerator size	Diameter: 4 m; Length: 35 m
Total weight	Approx. 152000 kg
Performance	Approx. 7 ppb (oxygen)
Space reservation	L=40m;H=6m;W=5m

Reference deaerator design, Company Stork B.V.

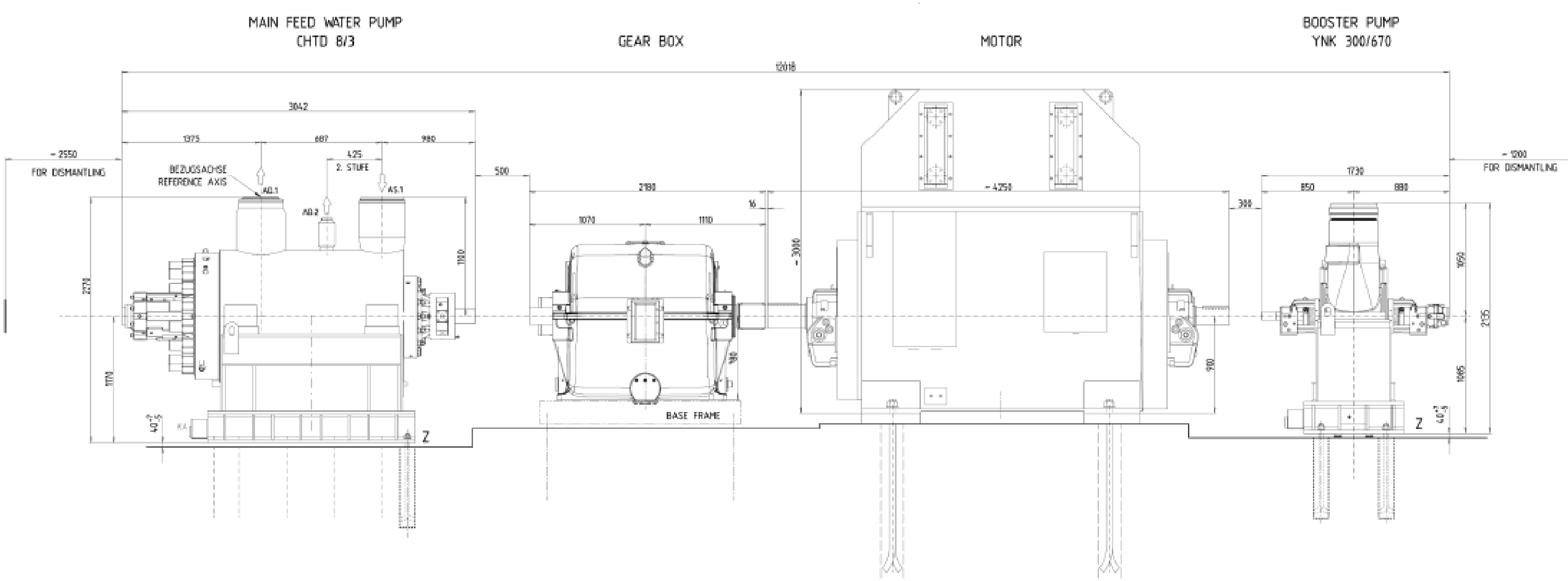
HCPB DEMO BoP – Examples of existing industrial equipment – PCS components

PCS Pump (Main FW pump) specification was provided by our industrial partner KAH.

Feed Water Pump Aggregate (PCS pump 1)	
Pump manufacturer	KSB
Pump drive type	Electrical drive
Main pump type	CHTD 8/3
Booster pump type	YNK 350-620
Gear box power rating	13 MW
Motor rating	14 MW
Space reservation	L=16m;H=3m;W=3.4m

Each feedwater pump aggregate consists of one booster pump, gearbox, electrical motor and main pump connected in series.

HCPB DEMO BoP – Examples of existing industrial equipment – PCS components



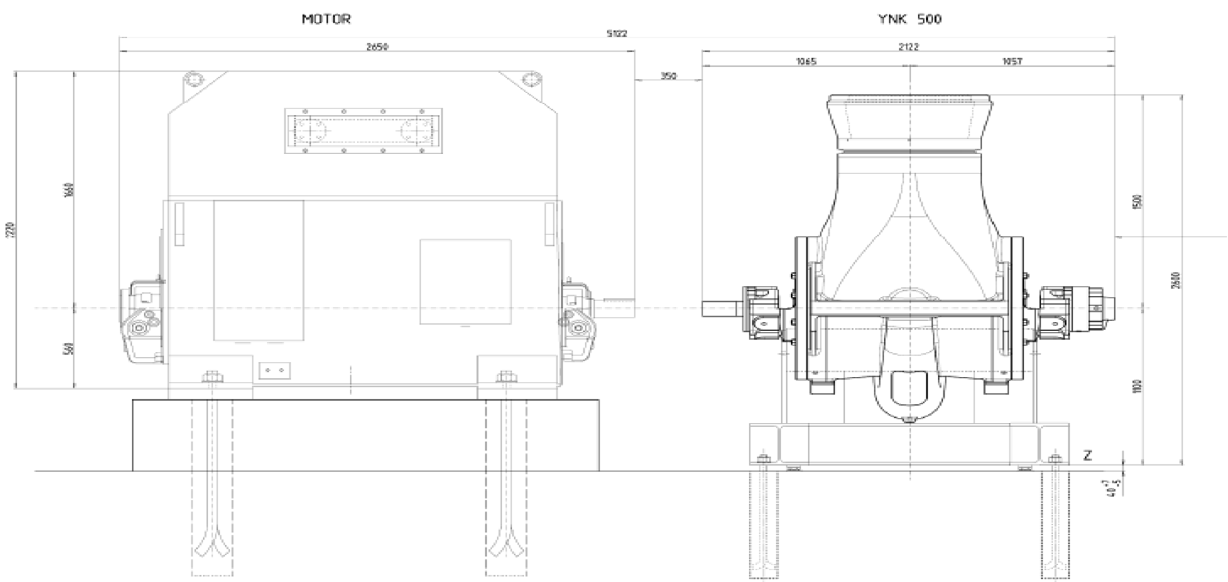
Main feedwater pump aggregate (KSB, Germany).

2018.11.23. E. Bubelis, W. Hering, F. A. Hernandez, S. Perez-Martin
EFPW-2018, Bad Dürkheim, Germany
Institute for Neutron Physics and Reactor Technology (INR)

HCPB DEMO BoP – Examples of existing industrial equipment – PCS components

PCS FW Pump (condensate extraction pump) specification was provided by our industrial partner KAH.

PCS circulation Pump (PCS FW pump)	
Pump manufacturer	KSB
Pump drive type	Electrical drive
Pump type	YNK 500/800
Motor rating	2 MW
Space reservation	L=7m;H=3m;W=2.9m



HCPB DEMO BoP – Issues to be solved

- Electricity supply lines and connections,
- Electricity supply needs during dwell time, especially for the start of the pulse.

HCPB DEMO BoP – Questions to be answered

- Is DCP possible without severe damaging of the main equipment because of thermal fatigue and thermal shocks in a short time period?
- Is DEMO BoP DCP layout much smaller than indirect coupling layout?
- Will DEMO BoP DCP show cost advantages compared to ICP?
- Will base load DEMO/FPP without ESS and no flexibility be attractive in energy systems beyond 2050?
- Do energy systems need inflexible power plants despite of >60% of variable renewable energy sources?

HCPB DEMO BoP – Perspectives

- HCPB DEMO ICP presents no major issues:
  Need for limited development for He circulators is expected. Potential feasibility issue of IHX design could be solved by optimization of PCS operational conditions,
- HCPB DEMO DCP is very challenging:
  it is not sure that it will be able to ensure lower costs in comparison to ICP option, plus to solve all complicated system integration issues,
- Scale-up of DEMO to FPP should be possible,
- Pairing of DEMO/FPP is necessary from safety and economics point of view,
- FPP should be designed to act as an energy storage facility (serving as a primary energy reserve) in the environment, where the biggest part of electricity around 2050 will be produced from renewable energy sources in a variable manner.

Acknowledgments

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