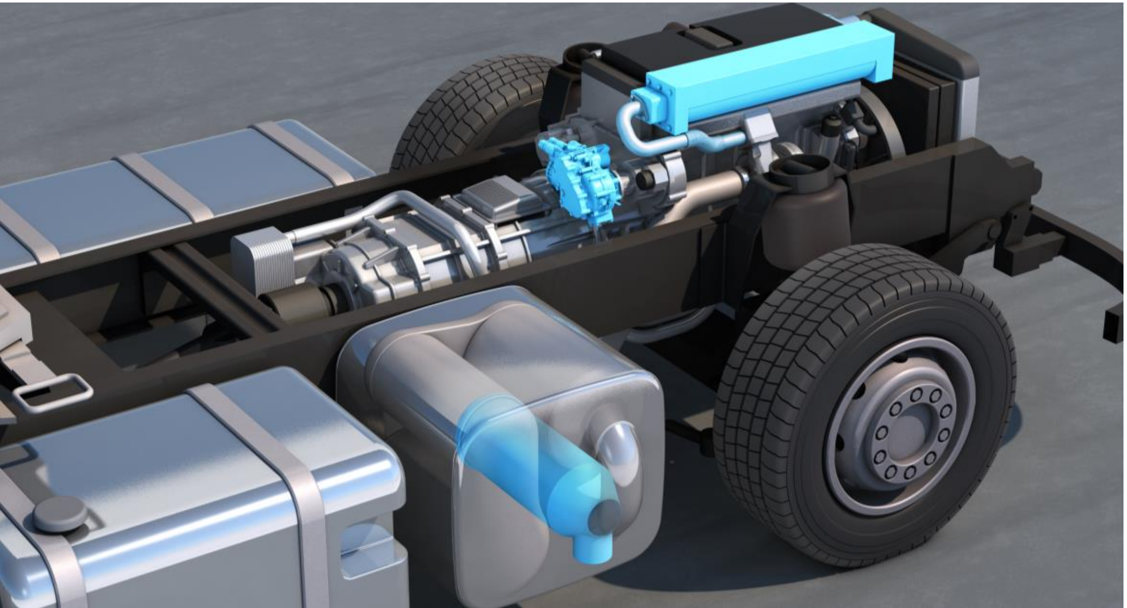
Combination of ORC System and Electrified Auxiliaries on a Long Haul Truck Equipped with 48-Volt Board Net

IV International Seminar on ORC Power Systems

Oliver Dingel, Tobias Töpfer, Jan Treutler, Milano, September 2017



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EPA and NHTSA Fuel Economy and CO_2-Emissions Standards

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Model Year	Tractor Engine Standards (SET-Cycle)			
	BSFC / (g/kWh)	BTE / (%)	CO2 / (g/kWh)	*Reduction compared to Phase 1*
2021-2023	189.5	44.4	599	*-1.8%*
2024-2026	184.8	45.5	584	*-4.2%*
2027-later	183.1	45.9	579	*-5.1%*

*due to new cycle no reference to phase 1 possible

Future *engine* fuel economy standards demand high thermal efficiency (i.e. ORC)

EPA and NHTSA Fuel Economy and CO_2-Emissions Standards

Model Year	Tractor Engine Standards (SET-Cycle)				Class 8 High Roof Sleeper Cab (GEM-Cycle)		
	BSFC / (g/kWh)	BTE / (%)	CO2 / (g/kWh)	*Reduction compared to Phase 1*	Diesel / (gallons / 1000 ton-miles)	CO2 / (g / ton-mile)	*Reduction compared to MY 2021**
2021-2023	189.5	44.4	599	*-1.8%*	7.436	75.7	
2024-2026	184.8	45.5	584	*-4.2%*	6.945	70.7	*-6.6%*
2027-later	183.1	45.9	579	*-5.1%*	6.316	64.3	*-15,1%*

*due to new cycle no reference to phase 1 possible

Future *engine* fuel economy standards demand high thermal efficiency (i.e. ORC)

***Vehicles* need further measures (i.e. reduced parasitic losses)**

EPA GHG II Final Rule: Projected Engine Technologies and Reduction

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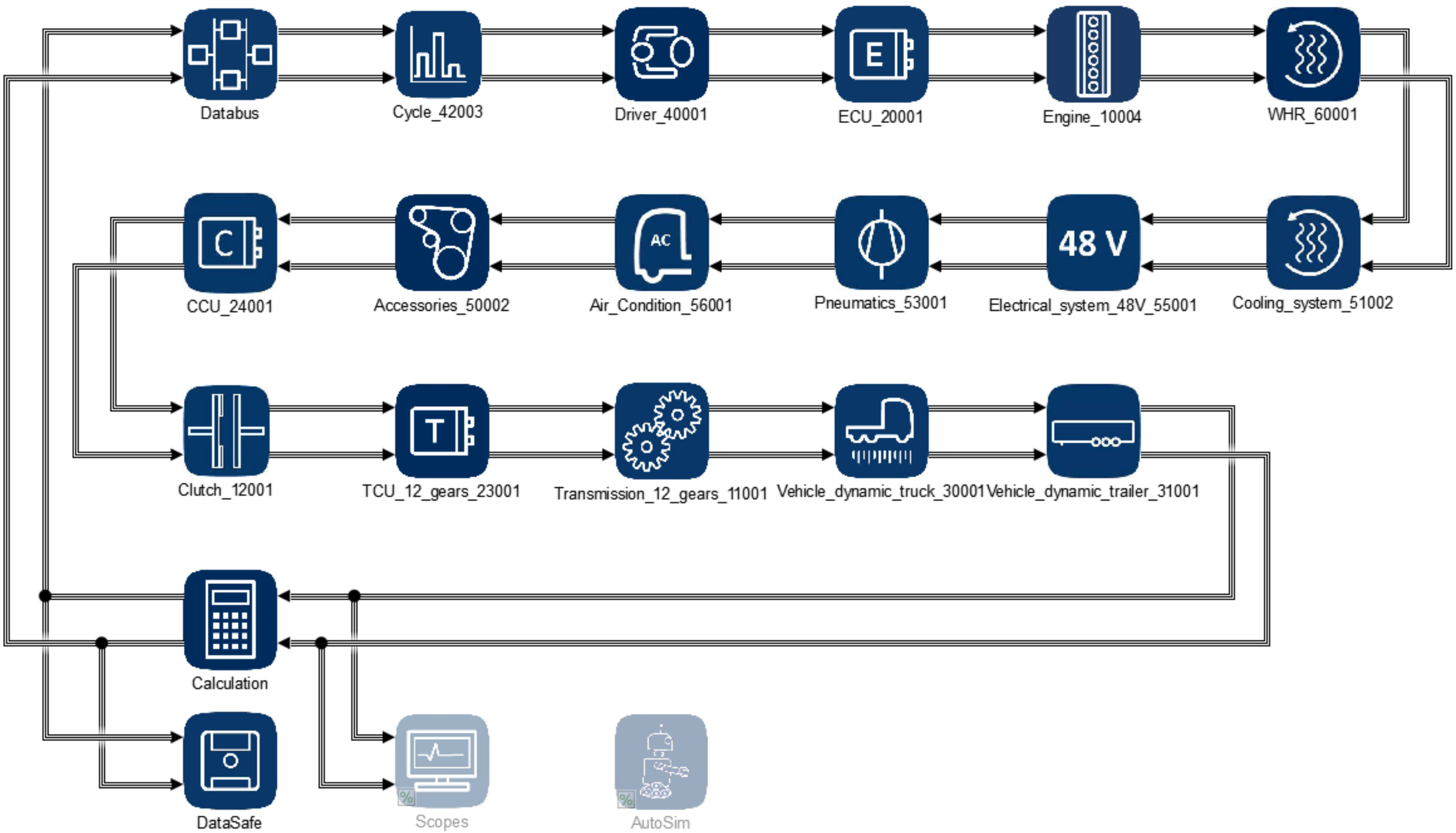
SET Mode	SET weighted reduction (%) 2020-2027	Market penetration (2021)	Market penetration (2024)	Market penetration (2027)
Turbo compound with clutch	1.9%	5%	10%	10%
WHR (Rankine cycle)	3.6%	1%	5%	25%
Parasitic/Friction (Cyl Kits, pumps, FIE), lubrication	1.5%	45%	95%	100%
After-treatment (lower dP)	0.6%	30%	95%	100%
EGR/Intake & exhaust manifolds/Turbo /VVT/Ports	1.1%	45%	95%	100%
Combustion/FI/Control	1.1%	45%	95%	100%
Downsizing	0.3%	10%	20%	30%

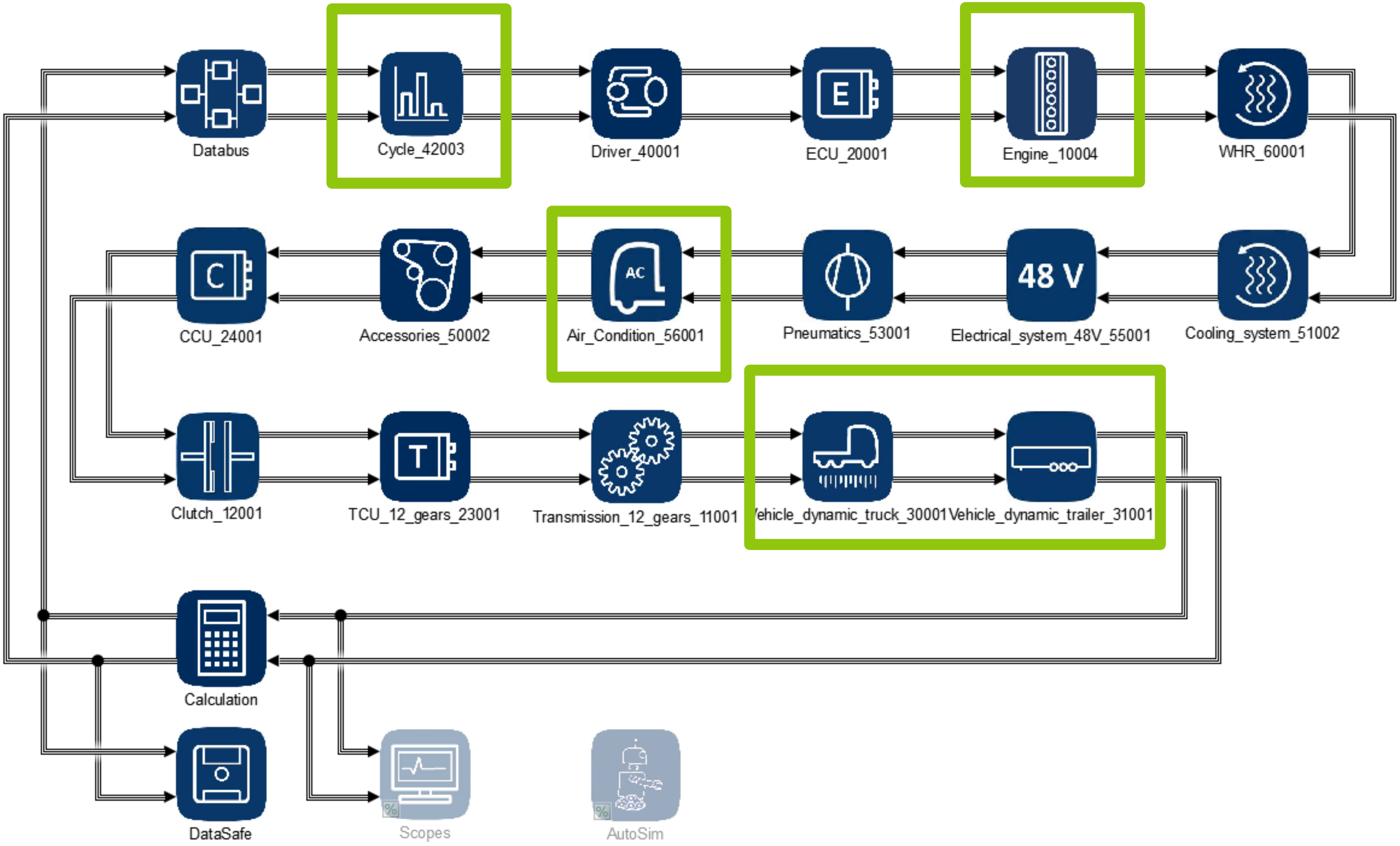
- **WHR (Rankine cycle) offers highest fuel consumption reduction potential**
- **Reduction of parasitic losses by variable auxiliaries will be mandatory**
- **Variable “power on demand” use of auxiliaries can be realized on mechanical way or by electrification**
- **ORC expander can also be coupled in mechanical or electrical way**

→ ***What is the most promising combination for a long haul truck?***

Model Structure in Velodyn4ComApps® Simulation Environment



Simulation Submodels: Vehicle, Engine, Air Conditioning and Drive Cycles



Data for Vehicle, Engine, Air Conditioning and Drive Cycle

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Vehicle

- 40 tons Long Haul Truck

Engine

- 12,4 liter, 6-cylinder engine
- Rated torque: 2300 Nm / 1000 – 1400 rpm
- Rated power: 377 kW / 1800 rpm

Boundaries for Air Conditioning

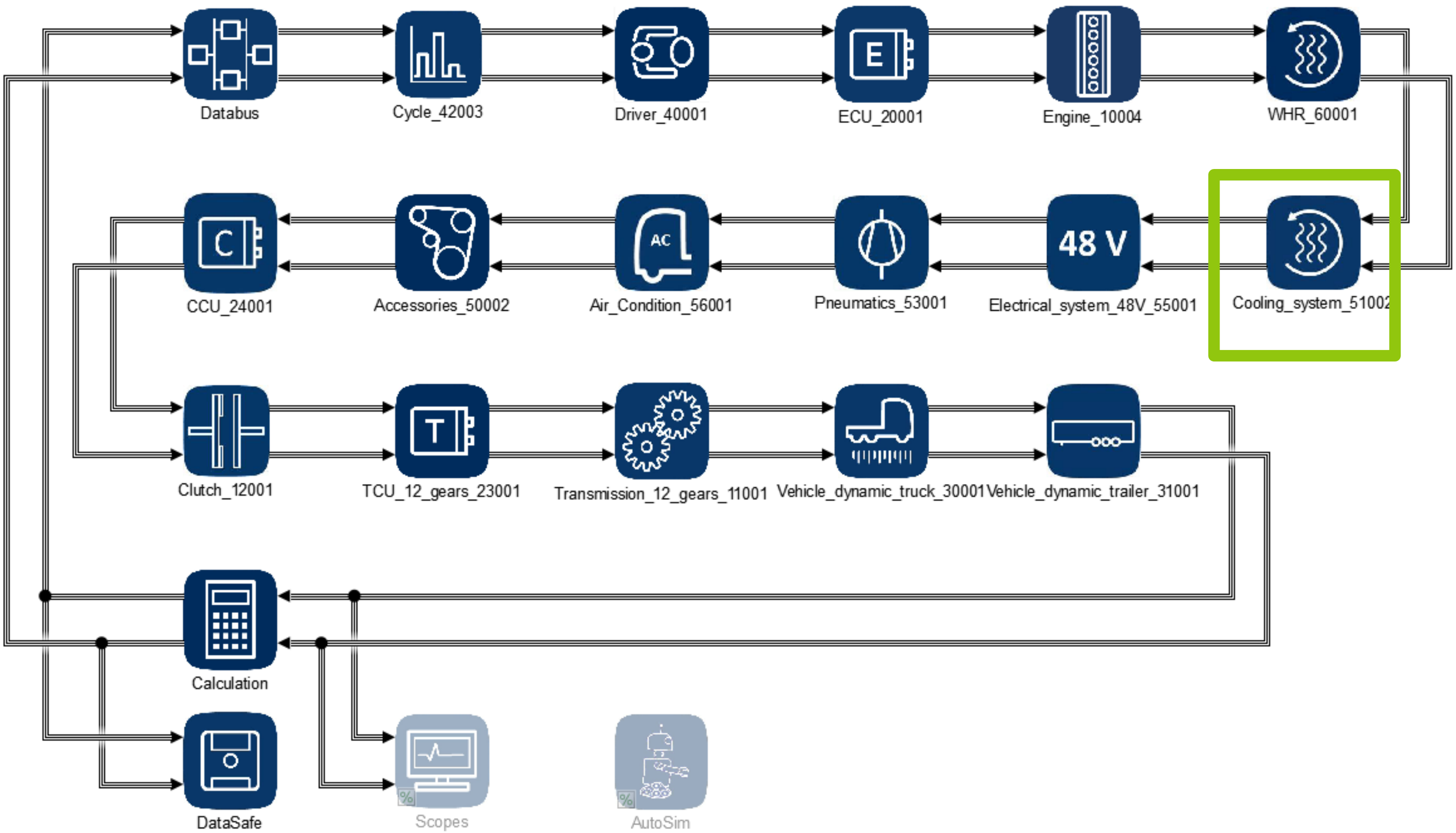
- Average spring/autumn day in Berlin
- Start time 07:00 am

Cycle

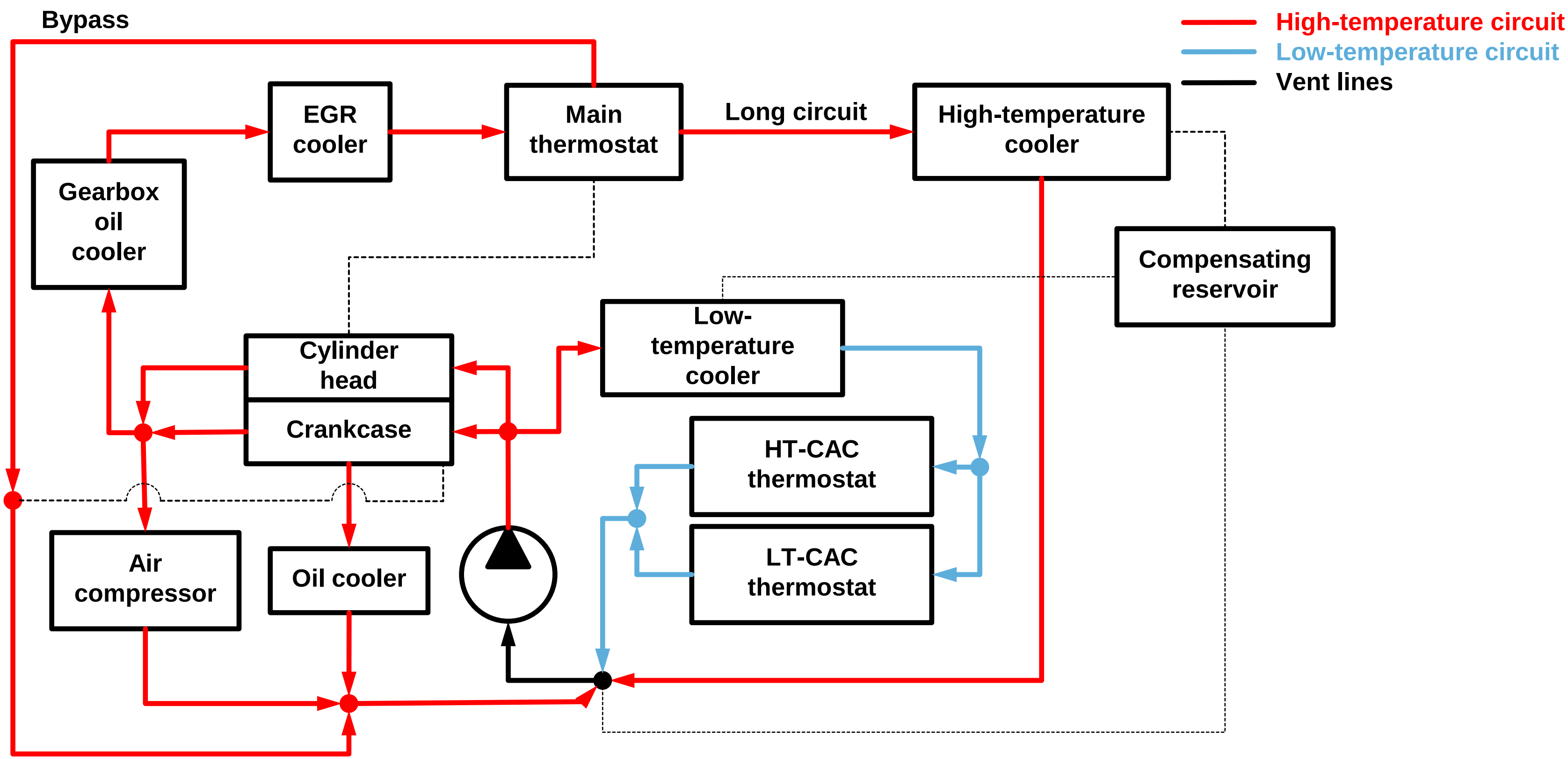
- Sequence of IAV long-haul cycles (~1 h each cycle)
- Total duration: 9 h including 45 minutes break

→ Boundary conditions were constant for all investigated variants

Simulation Submodel: Cooling Circuit

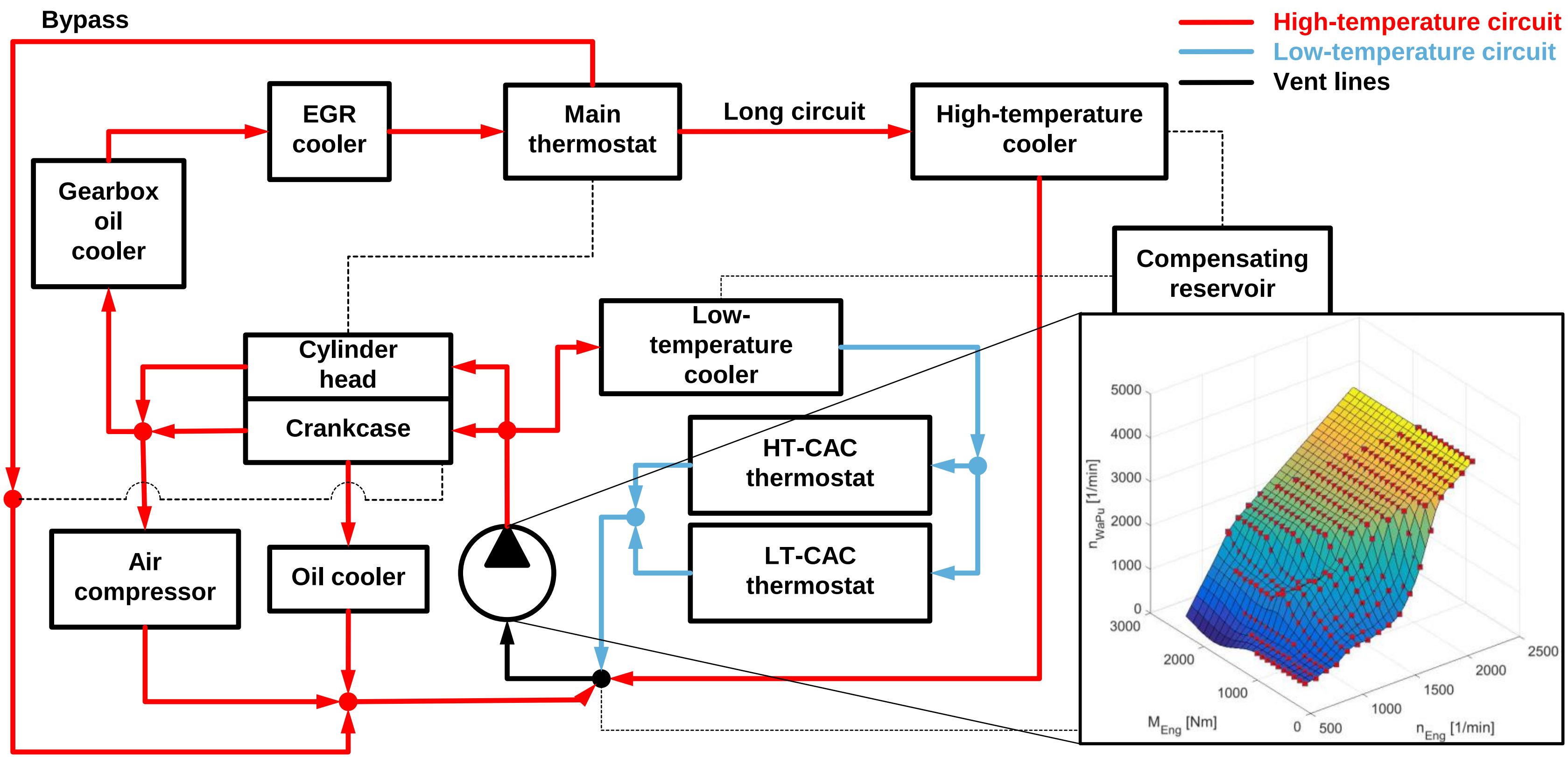


Engine Cooling Circuit



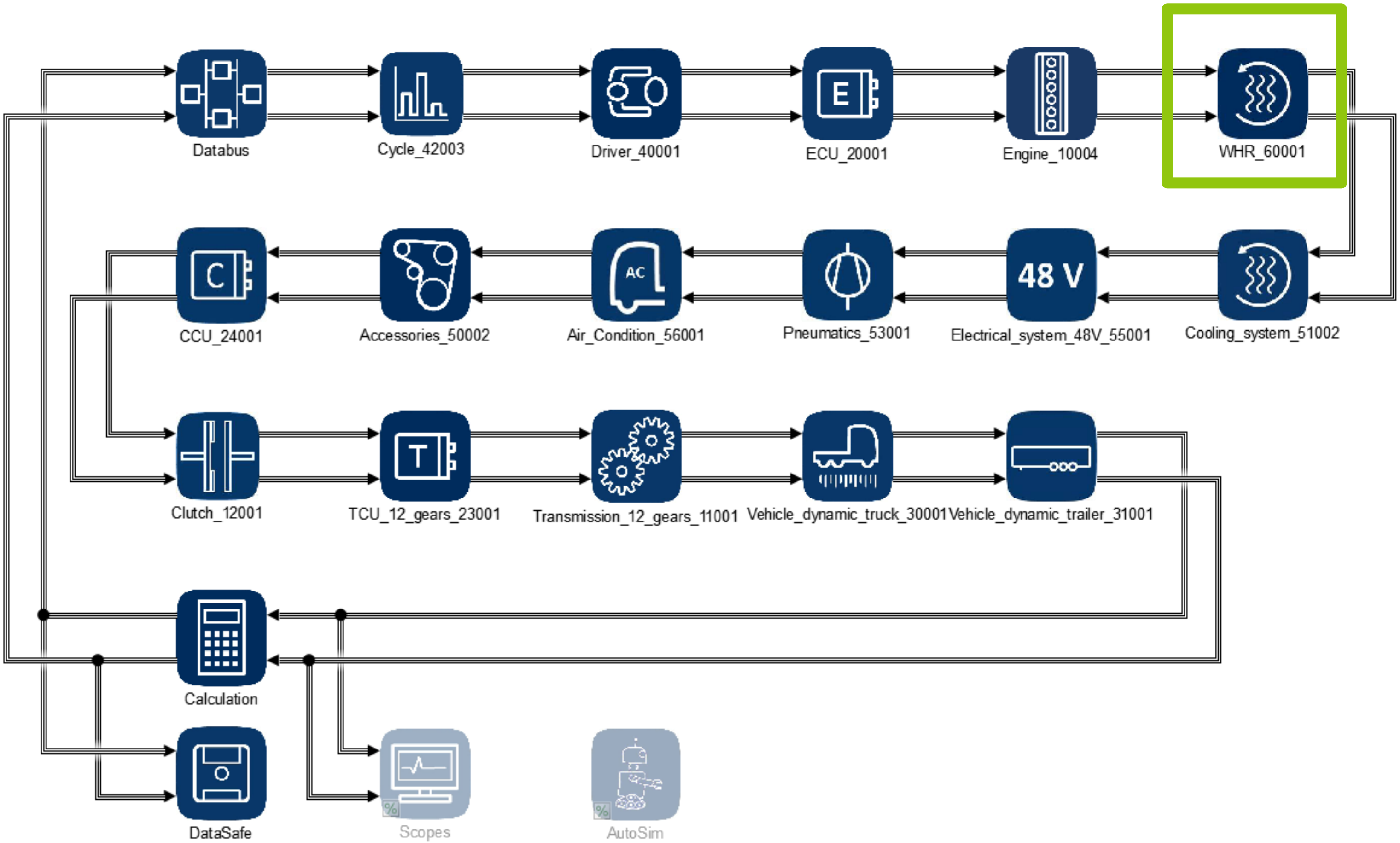
- Complex cooling system with HT / LT circuit
- Reference vehicle had rigid coupled water pump

Engine Cooling Circuit

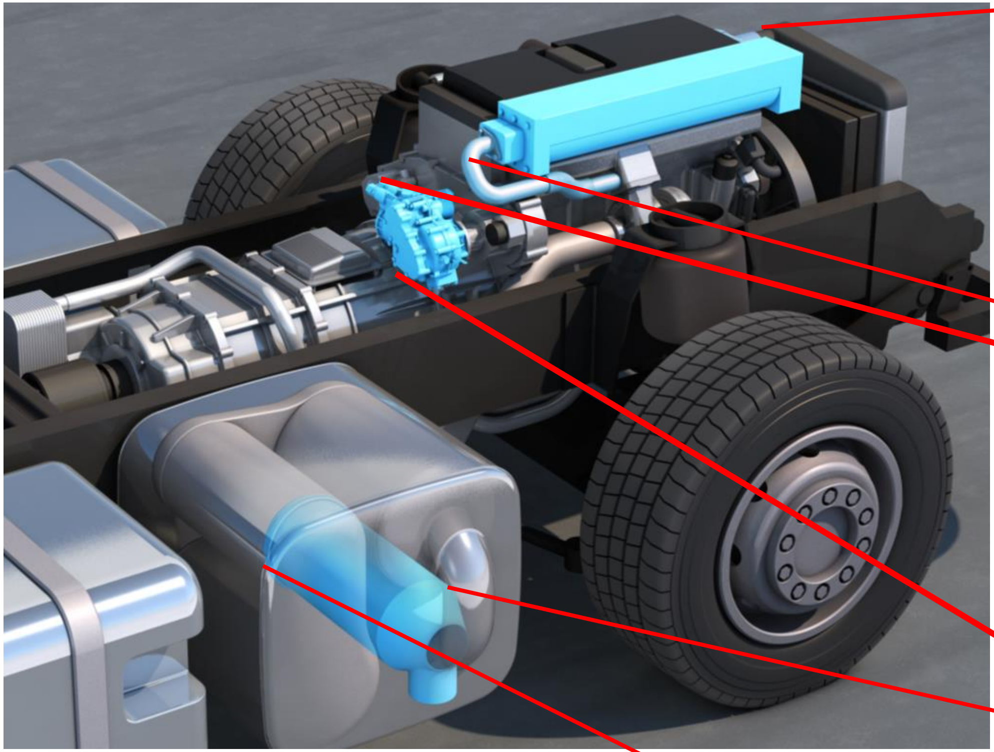


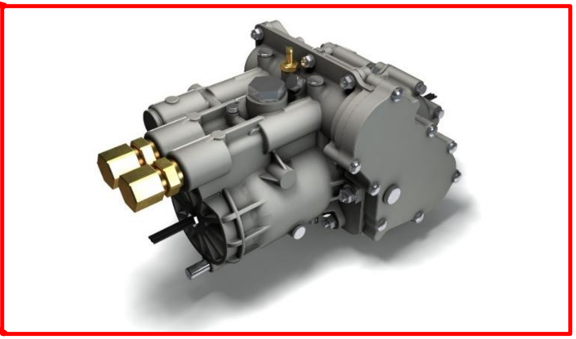
- At low engine loads pump speed was reduced by visco clutch or E-drive
- At high loads water pump switches back to ridged mechanical drive

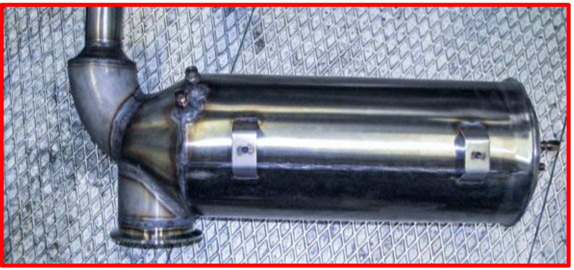
Simulation Submodel: ORC-System



IAV Main ORC Components

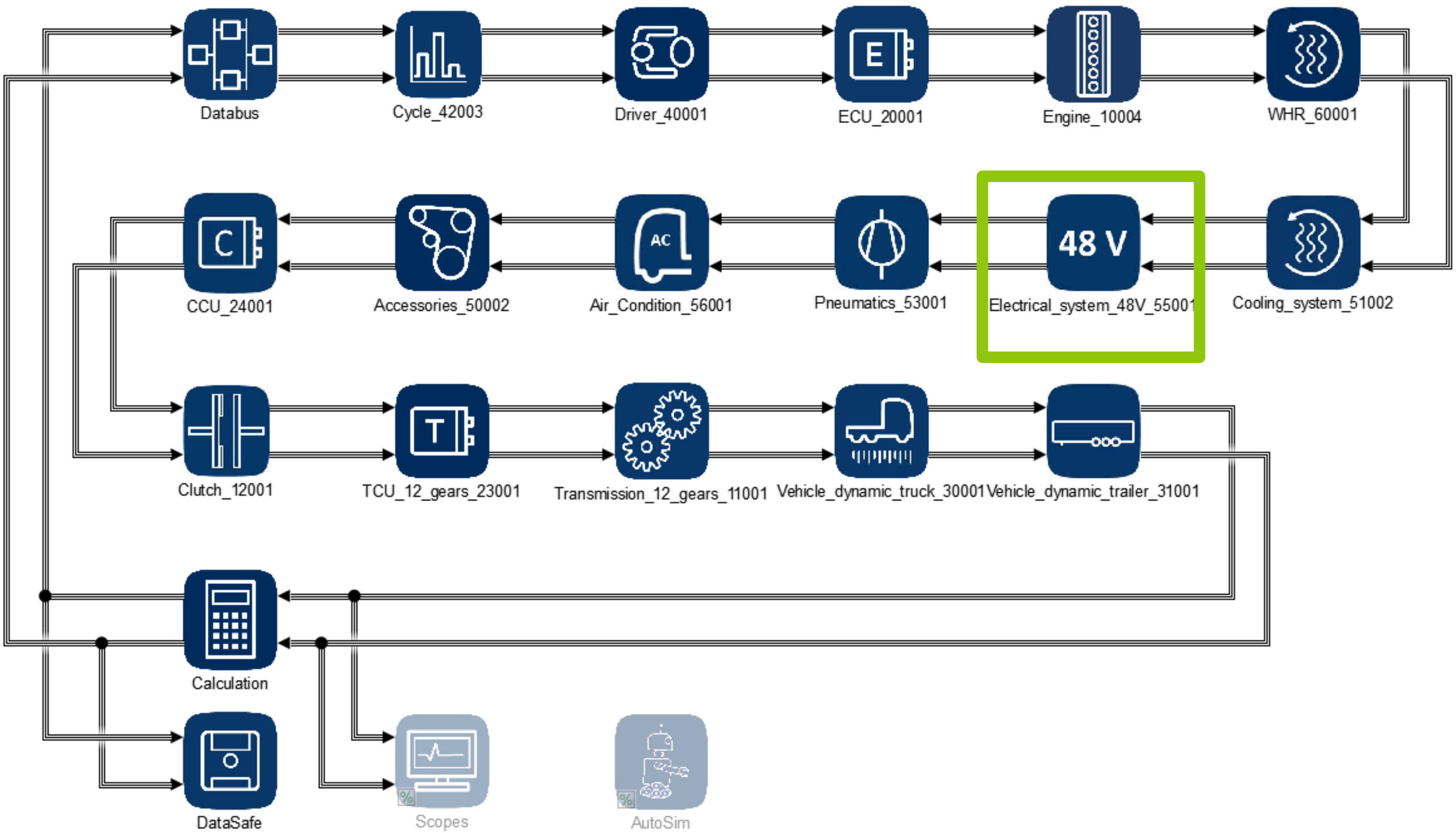






- Models of ORC components have been validated by test results from engine dyno
- Exhaust-HX can be bypassed

Simulation Submodel: 48 Volt Boardnet

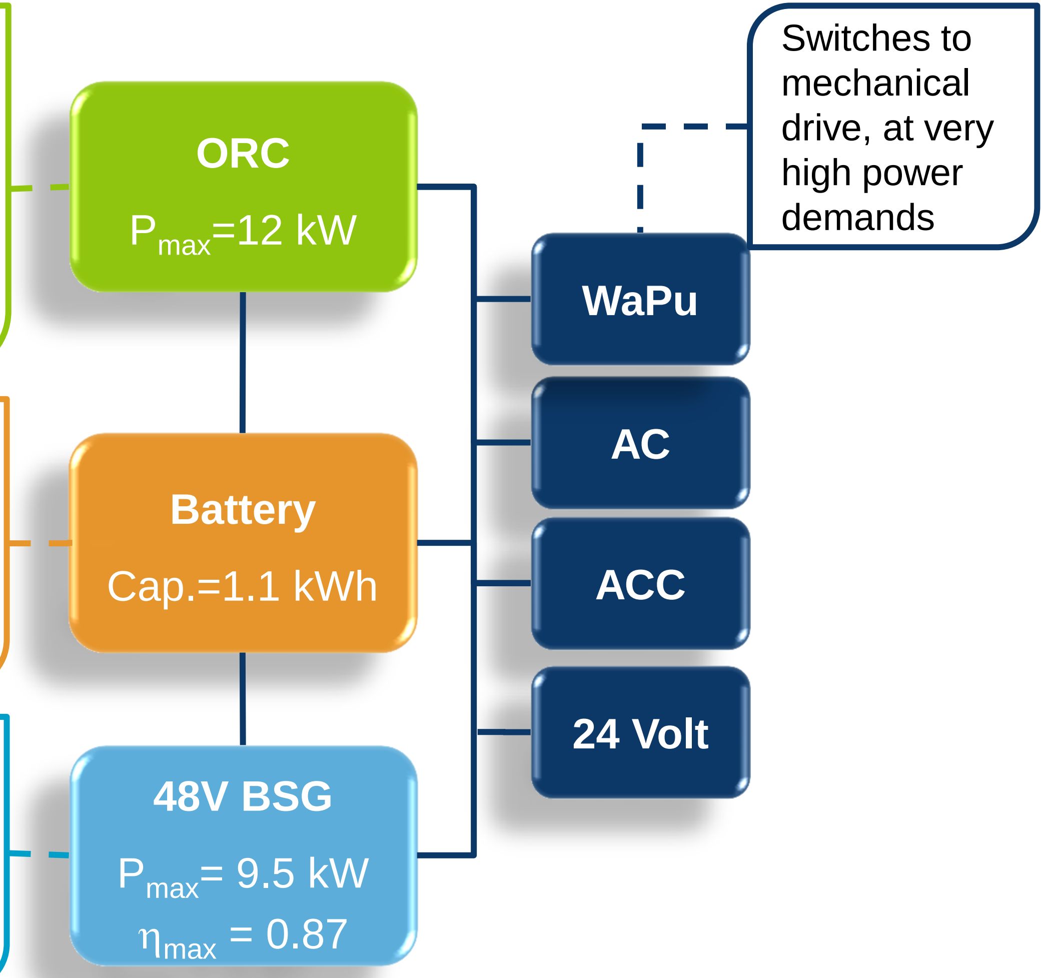


Electric Architecture and Operating Strategy

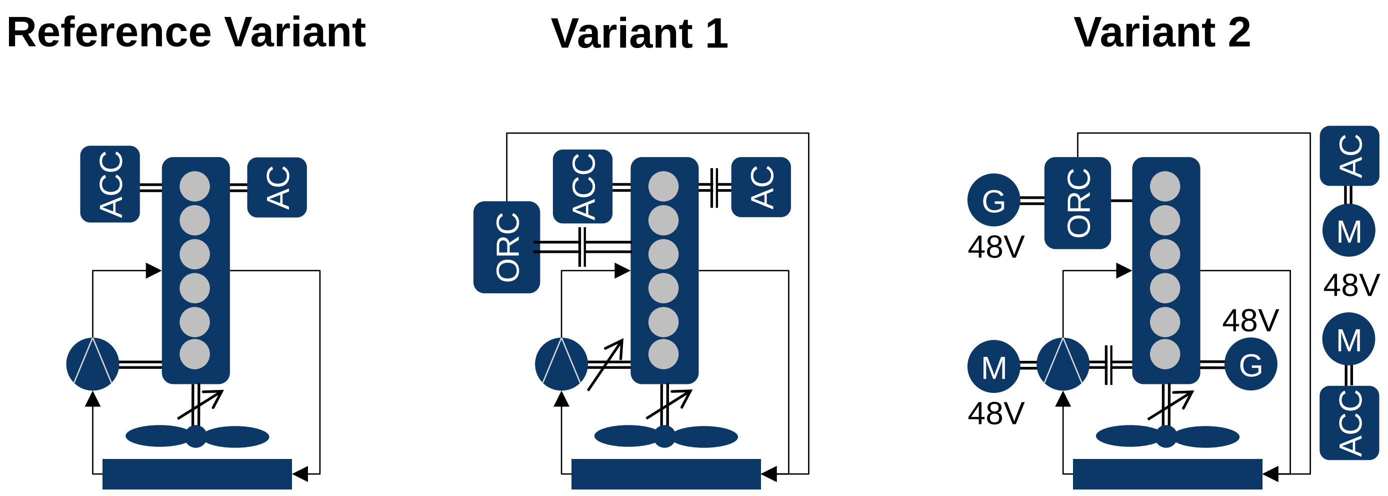
- Use of electric power from ORC has highest priority
- Limitation of ORC power, when there is restricted demand from electrical consumers
- Max. ORC power limited by power demand of fan

- Battery is charged up to max. SOC when sufficient ORC power is available
- Discharging of battery when ORC-power is too low

- 48V BSG is activated during braking and when ORC- and battery power too low and/or if 50% < SOC < 30%
- BSG only operated if $\eta \geq 80\%$



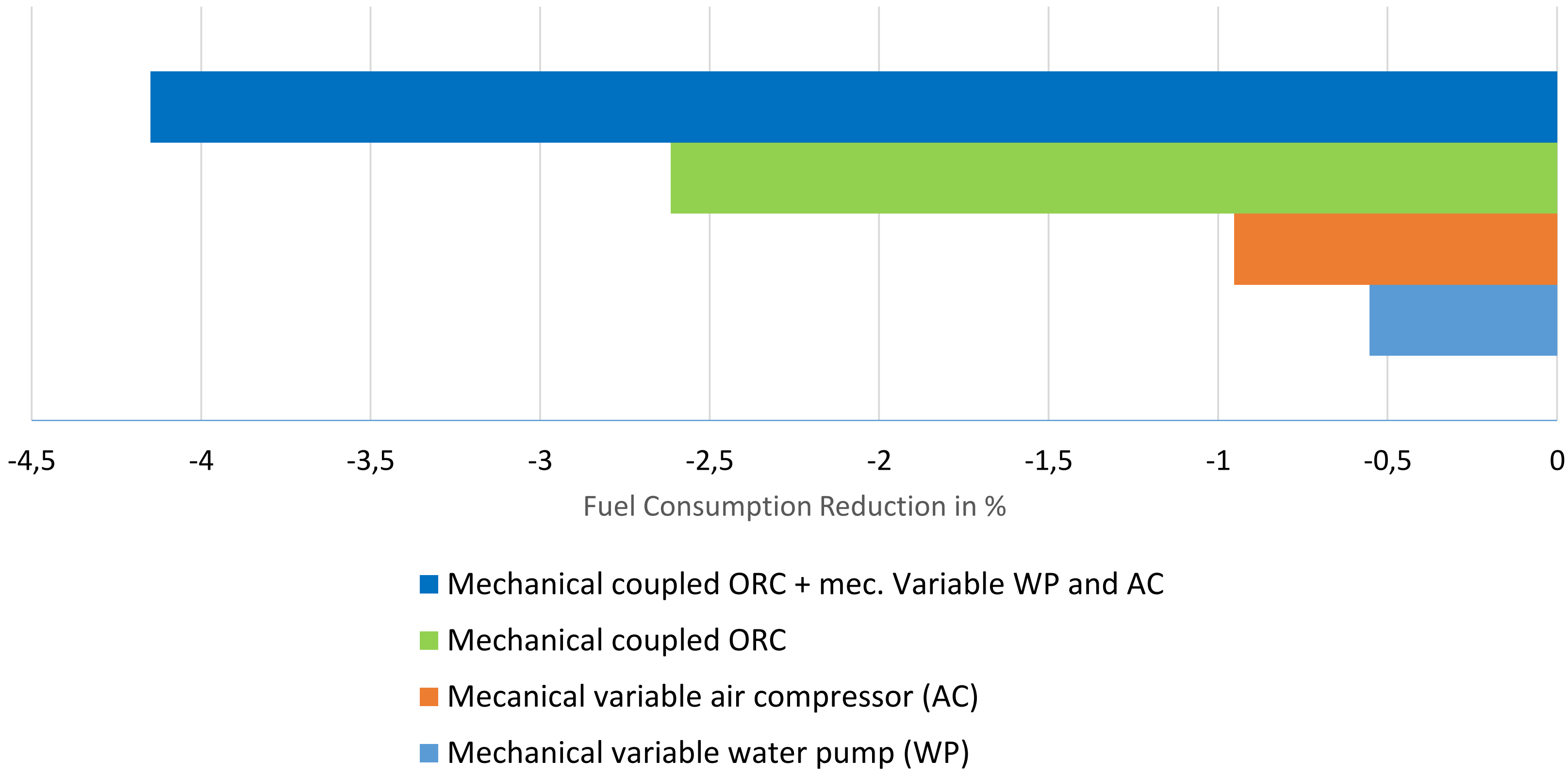
Fundamental System Variants



ORC	no	yes / no	yes / no
48 Volt	no	no	yes
WaPu, AC	mech. rigid	mech. variable	electro-mech. variable
ACC	mech. variable	mech. variable	electrically variable

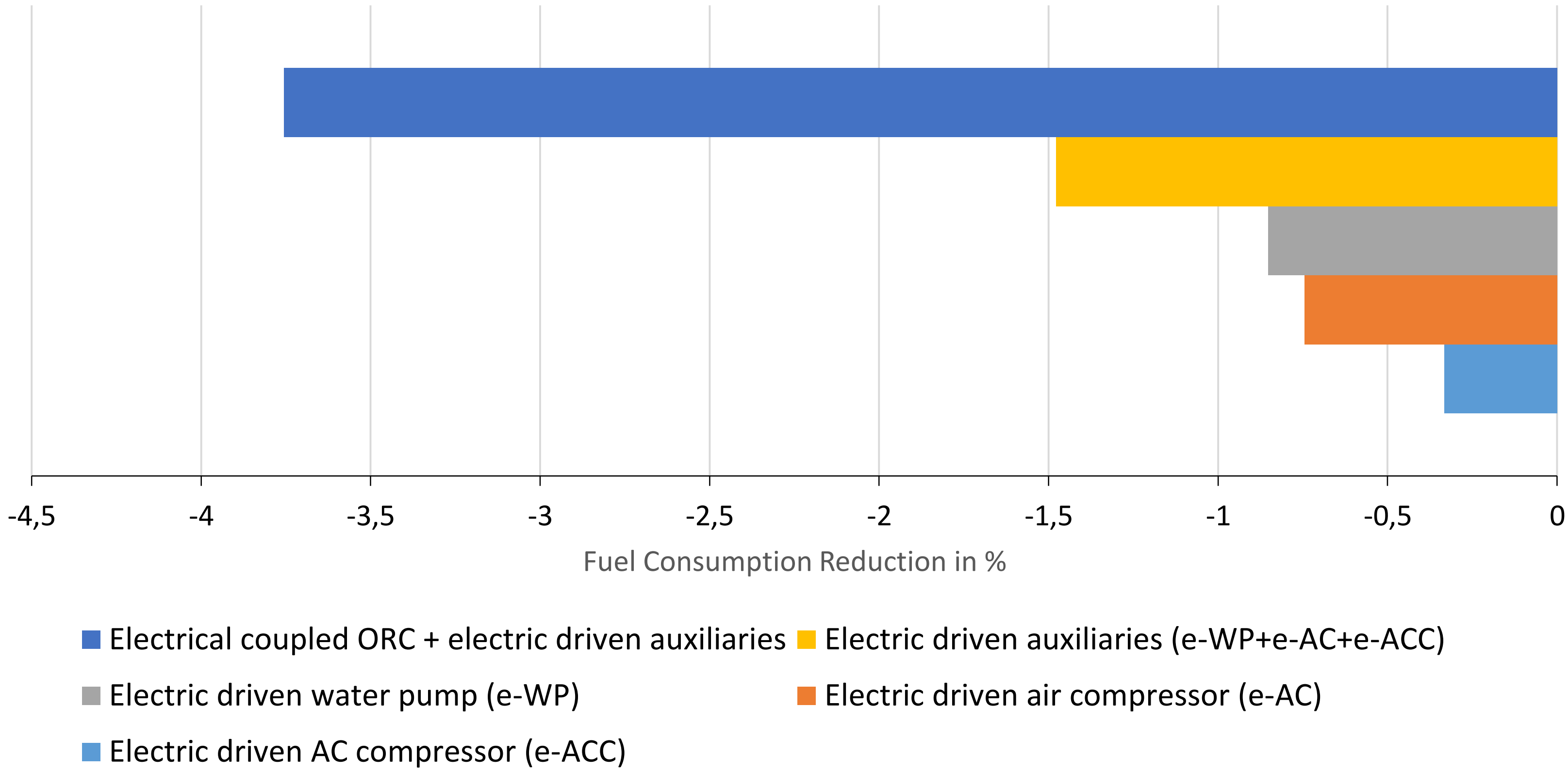
→ Entire matrix is result of fundamental variants in different combinations with subsystems (total of 82 variants)

Results of Mechanical Coupled Variants



→ **Max. of 4.1% can be achieved by combining all measures**

Results of Electrical Coupled Variants



→ Combination of ORC and electrified auxiliaries provides 3.8% FE benefit

→ Electric conversion losses and demand for BSG limit FE benefit

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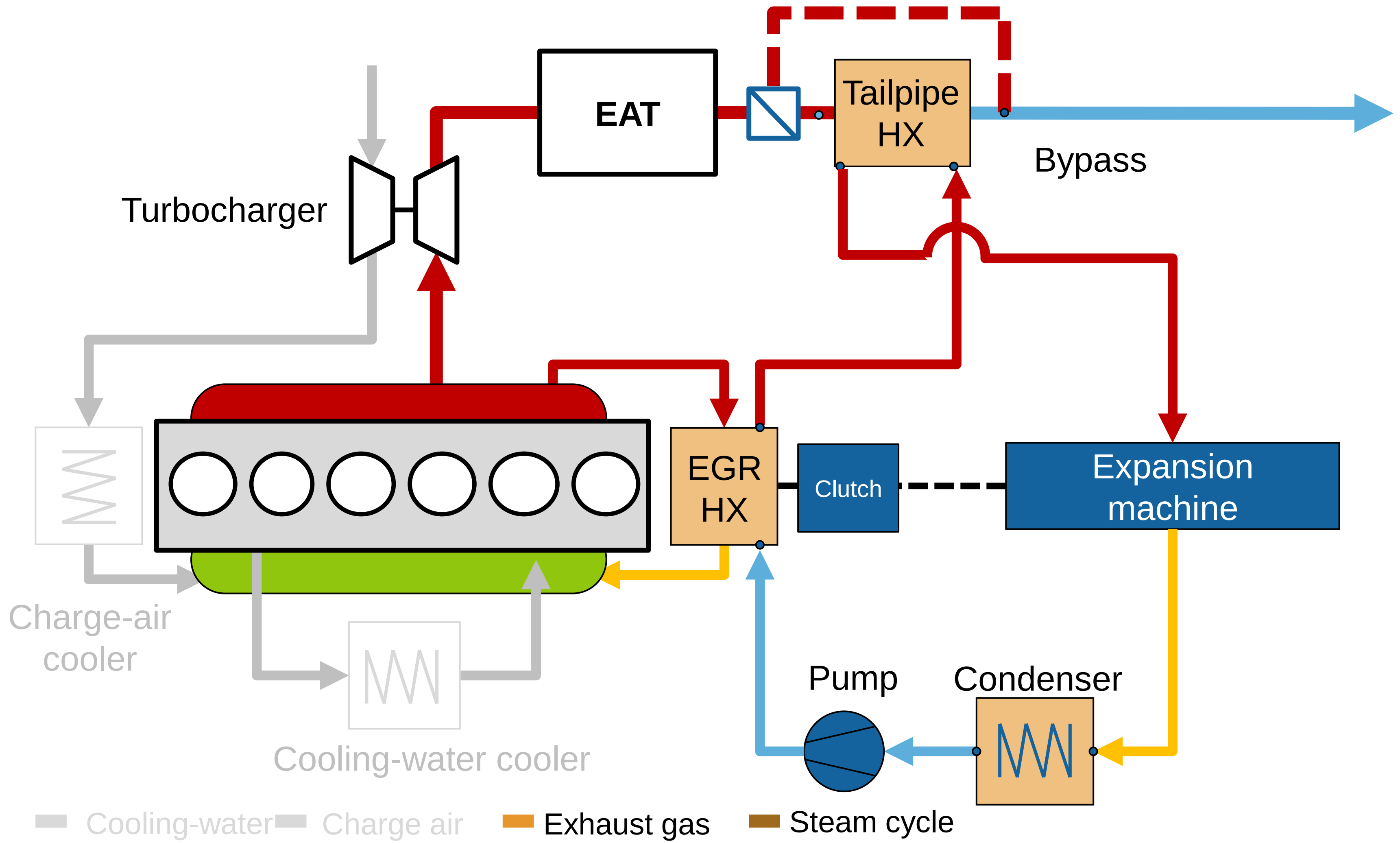
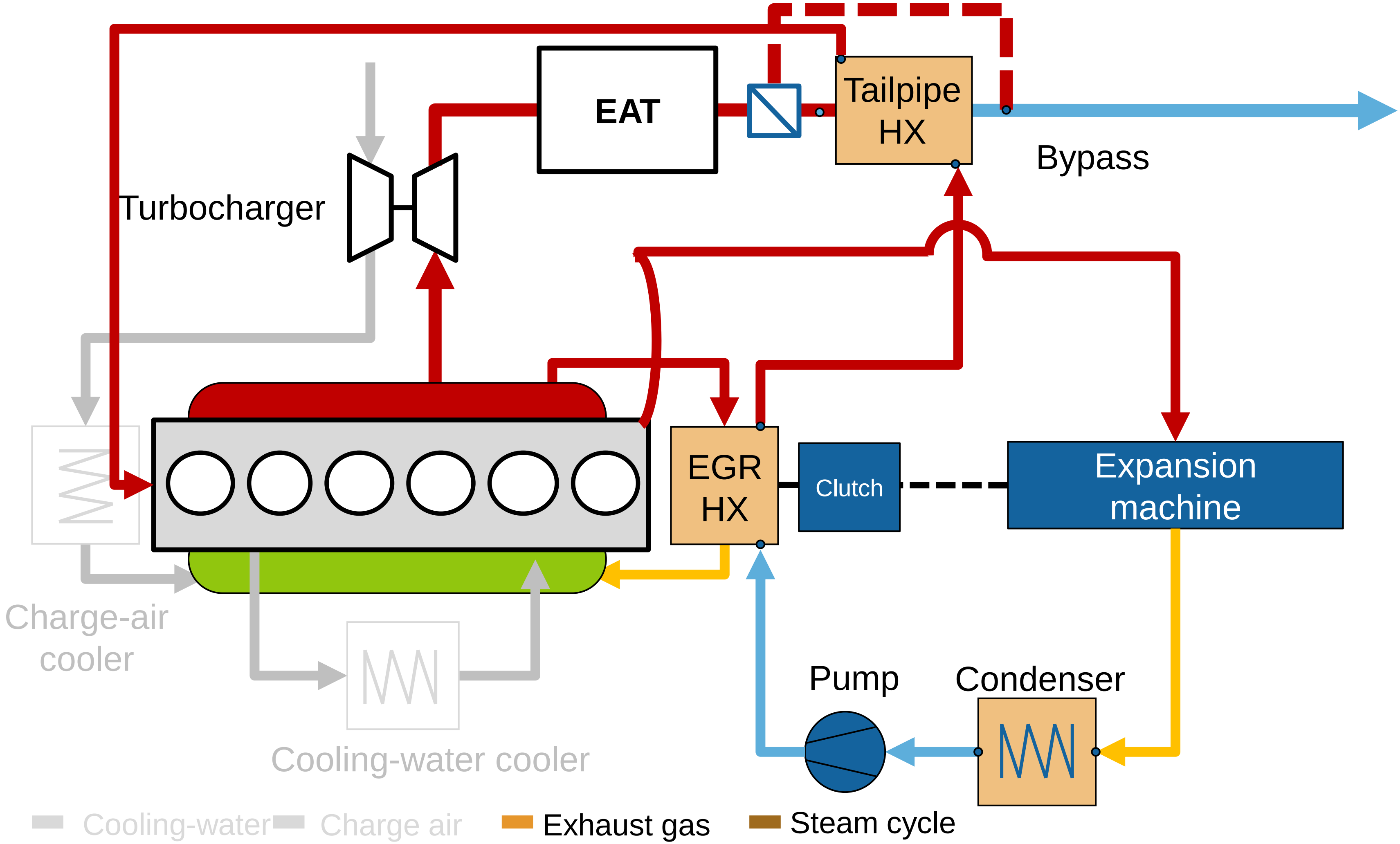
Summary

- Due to the higher transmission efficiency, mechanical coupled auxiliaries and ORC expander show slightly bigger potential to reduce fuel consumption compared to electrical coupled variants.
- Electrified auxiliaries only make sense in combination with an electrically coupled ORC system
- By optimizing the operating strategy of the electrical system, enlarging the battery capacity and improving the efficiency of the electric components a further improvement of the electrical coupled approach is expected.
- A combined mechanical/electrical coupling could combine the advantages of both concepts but increases complexity
- Enhanced power supply from the ORC system would lead to less use of the 48-Volt BSG during engine operation and could therefore also improve the electrical approach.
- This can be achieved by integrating the engine coolant circuit into the ORC!

Serial Heat Exchanger Arrangement for Conventional HER-Concept



Serial Heat Exchanger Arrangement for ATM + HER-Concept



Thank You

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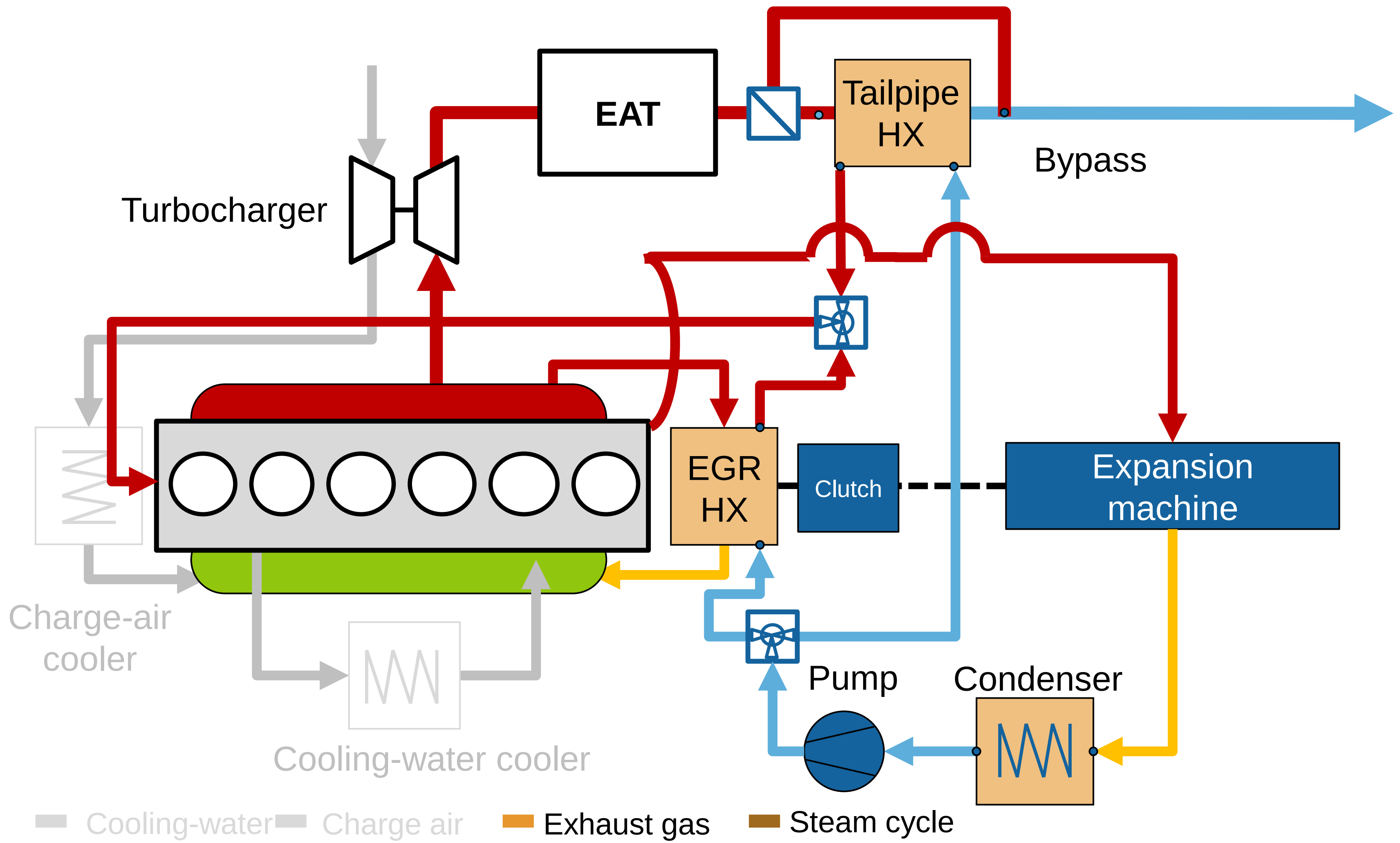
Parallel Heat Exchanger Arrangement for EHR + ATM Concept



Sensitivitätsanalyse

Parameter-Matrix

	SIM.name	m Truck [kg]	m Trailer [kg]	truck tyre no.	trailer tyre no.	Inertia Tyre [kgm²]	Rolling drag	cW	A [m²]	ES48V.Sig_on	Battery Num Series	Battery Num Parallel	Battery SOC Init [%]	Battery SOC min [%]	Battery SOC max [%]	CS mode	P eWaPu limit [W]	Factor WaPu map	WHR mode	AC mode	Pneumatic mode	Air_req [Nl/min]	Start Stop	eta Visco cl WaPu
Variante 1 (mechanisch)	001_HD_40_0t_IAV_Berlin_mid_standard_St_St_off	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	0	0,8
	002_HD_40_0t_IAV_Berlin_mid_standard	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	1	0,8
	003_HD_40_0t_IAV_Berlin_mid_standard_Visco_Cl	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	2	2000	2	0	1	1	60	1	0,8
	004_HD_40_0t_IAV_Berlin_mid_standard_Visco_Cl_eta_red	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	2	2000	2	0	1	1	60	1	0,5
	005_HD_40_0t_IAV_Berlin_mid_standard_Compr_Cl	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	2	60	1	0,8
	006_HD_40_0t_IAV_Berlin_mid_standard_WHR_Compound	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	2	1	1	60	1	0,8
	007_HD_20_0t_IAV_Berlin_mid_standard_St_St_off	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	0	0,8
	008_HD_20_0t_IAV_Berlin_mid_standard	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	1	0,8
	009_HD_20_0t_IAV_Berlin_mid_standard_Visco_Cl	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	2	2000	2	0	1	1	60	1	0,8
	010_HD_20_0t_IAV_Berlin_mid_standard_Visco_Cl_eta_red	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	2	2000	2	0	1	1	60	1	0,5
	011_HD_20_0t_IAV_Berlin_mid_standard_Compr_Cl	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	2	60	1	0,8
	012_HD_20_0t_IAV_Berlin_mid_standard_WHR_Compound	8000	12000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	2	1	1	60	1	0,8
	013_HD_40_0t_IAV_Berlin_col_standard_St_St_off	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	0	0,8
	014_HD_40_0t_IAV_Berlin_col_standard	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	1	0,8
	015_HD_40_0t_IAV_Berlin_hot_standard_St_St_off	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	0	0,8
	016_HD_40_0t_IAV_Berlin_hot_standard	8000	32000	6	6	14,9	0,00537	0,53	10	0	13	4	80	20	80	1	2000	2	0	1	1	60	1	0,8
ariante 2 (48V-System)	017_HD_40_0t_IAV_Berlin_mid_48V_WHR	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	4	80	20	80	3	2000	2	1	3	3	60	1	0,8
	018_HD_40_0t_IAV_Berlin_mid_48V_WHR_WaPu_adapted	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	4	80	20	80	4	2000	2	1	3	3	60	1	0,8
	019_HD_40_0t_IAV_Berlin_mid_48V_WHR_WaPu_13_8	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	8	80	20	80	3	2000	2	1	3	3	60	1	0,8
	020_HD_40_0t_IAV_Berlin_mid_48V_WHR_WaPu_13_12	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	12	80	20	80	3	2000	2	1	3	3	60	1	0,8
	021_HD_40_0t_IAV_Berlin_mid_48V_WHR_WaPu_13_16	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	16	80	20	80	3	2000	2	1	3	3	60	1	0,8
	022_HD_40_0t_IAV_Berlin_mid_48V_WHR_WaPu_13_2	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	2	80	20	80	3	2000	2	1	3	3	60	1	0,8
	023_HD_40_0t_IAV_Berlin_mid_48V_WHR_all_func	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	16	80	20	80	4	2000	2	1	3		60	1	
	024_HD_40_0t_IAV_Berlin_col_48V_WHR_all_func	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	16	80	20	80	4	2000	2	1					
	025_HD_40_0t_IAV_Berlin_hot_48V_WHR_all_func	8000	32000	6	6	14,9	0,00537	0,53	10	1	13	16	80	20	80	4	2000	2						
	026_HD_20_0t_IAV_Berlin_mid_48V_WHR_all_func	8000	12000	6	6	14,9	0,00537	0,53	10	1		16	80	20	80	4	2000	2						
	027_HD_20_0t_IAV_Berlin_col_48V_WHR_all_func	8000	12000	6	6	14,9	0,00537	0,53	10					20	80	4	2000							
	028_HD_20_0t_IAV_Berlin_hot_48V_WHR_all_func		12000	6	6	14,9	0,00537	0,53								4	2000							
	029_HD_40_0t_IAV_Berlin_mid_48V_all_func				6	14,9																		
	…30_HD_40_0t_IAV_Berlin_col …nc																							
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