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Solar/biomass hybrid cycles with thermal storage and bottoming ORC: System integration and economic analysis

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Background and motivations: biomass CHP

Bioenergy issues

- short biomass supply chains to improve economics, sustainability, logistics
- Use of heat (CHP) to maximize global efficiency
- minimum size is required for efficiency and costs

Bioenergy opportunities

- Programmable renewable energy resource
- Can be coupled to other resources (gas, solar, geothermal) to increase flexibility via hybridization

Innovation

biomass CC + CHP

increase global efficiency, operational flexibility (heat/power ratio), economics

Hybrid plants to increase flexibility and address trade-off size vs biomass supply chain

Biomass/natural gas cofiring

Biomass/concentrating solar power

Load following strategies (match with active DSM)

Optimal sizing and operation of hybrid CHP

Background and motivations: hybrid CSP

CSP technologies

- solar collectors
- heat transfer fluids
- max temperature
- Storage sizing (variable solar radiation)
- Heat to power cycles (steam turbine, ORC, bryton, stirling, etc)

Hybrid CSP

- Integration with gas, waste, geothermal
- Biomass-solar integration: biomass combustor as a partial thermal storage

Innovation

biomass and solar could:

Increase solar **dispatchability**, global efficiency, operational flexibility

Room for optimization:

Match biomass seasonality and solar resource

Optimize biomass/solar energy input ratio

Optimize thermal energy storage size

Biomass to biofuel processing through discharged heat

Modeling dynamic operation and regulation strategies (variable solar radiation - variable load - biomass seasonality - storage)

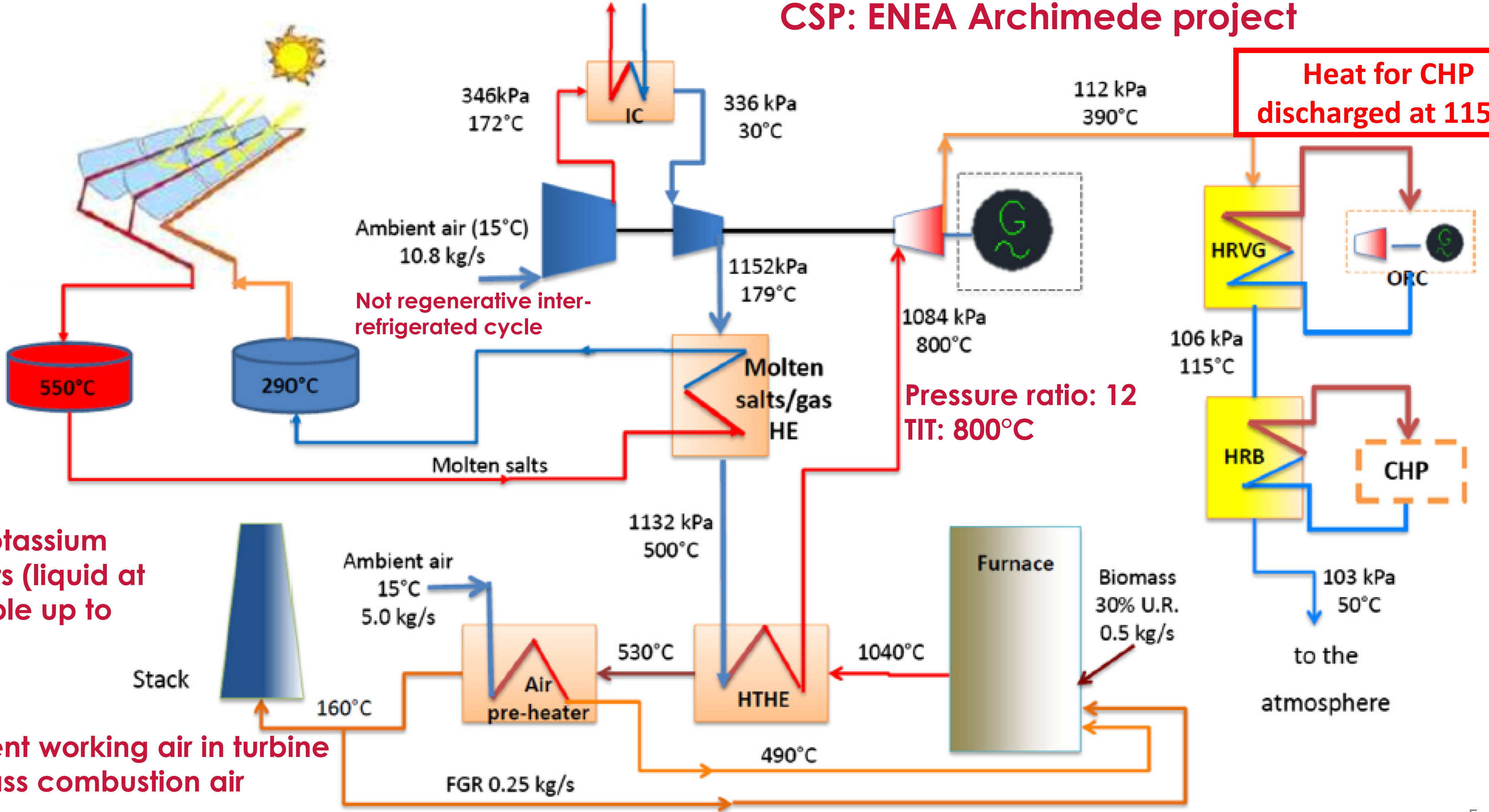
Objectives

- Conversion efficiency of a 2 MWe CC composed by EFGT (1.3 MWe) and ORC (0.7-0.8 MWe) for direct biomass combustion with CSP integration
- influence of solar/biomass thermal energy input ratio and thermal storage sizing on the plant performance
- Evaluate the economic profitability of the plant in different configurations

EFGT-ORC Combined Cycle layout (basic)

CSP: ENEA Archimede project

Heat for CHP discharged at 115°C



Not regenerative inter-refrigerated cycle

Pressure ratio: 12
TIT: 800°C

Sodium/potassium molten salts (liquid at 240°C, stable up to 600°C)

Independent working air in turbine and biomass combustion air

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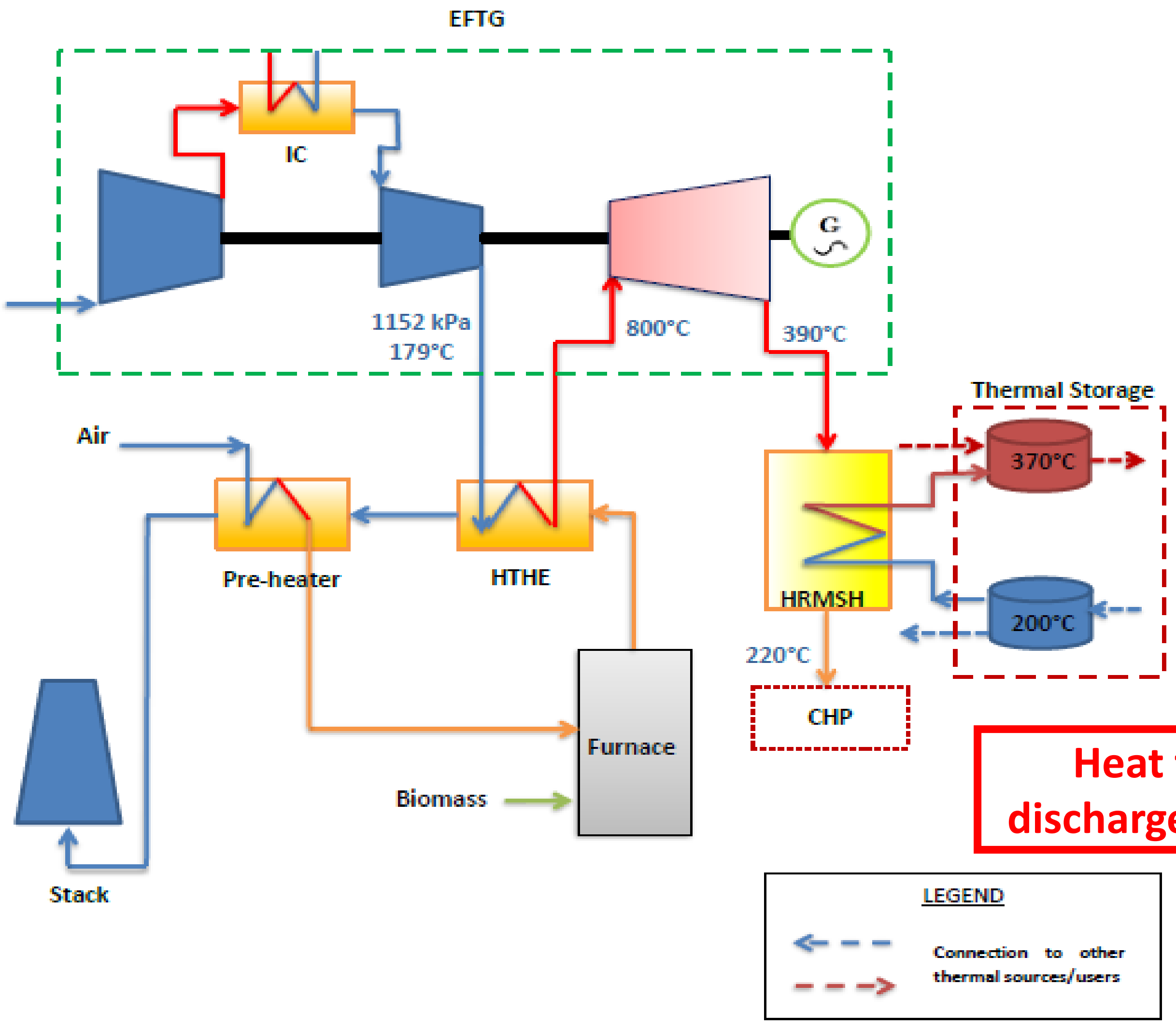
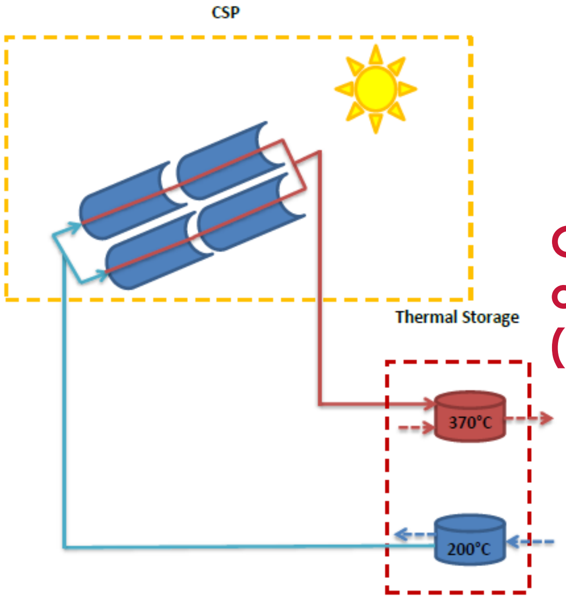
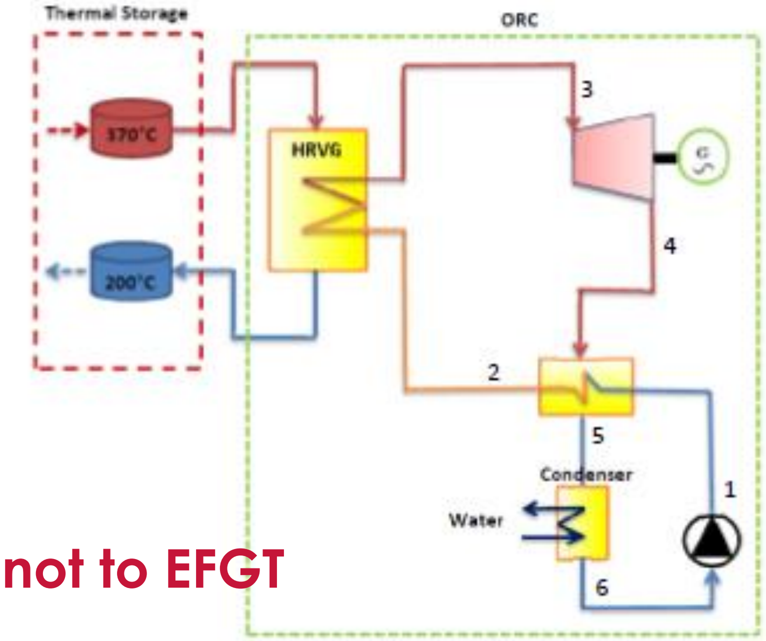
EFGT-ORC Combined Cycle layout (power blocks)





CSP sized to provide 30% of thermal input to ORC (900 kWt)

Thermal input 2790 kWt-800 kWe



Heat for CHP discharged at 220°C

Independent power blocks with TES and CSP input only to ORC and not to EFGT

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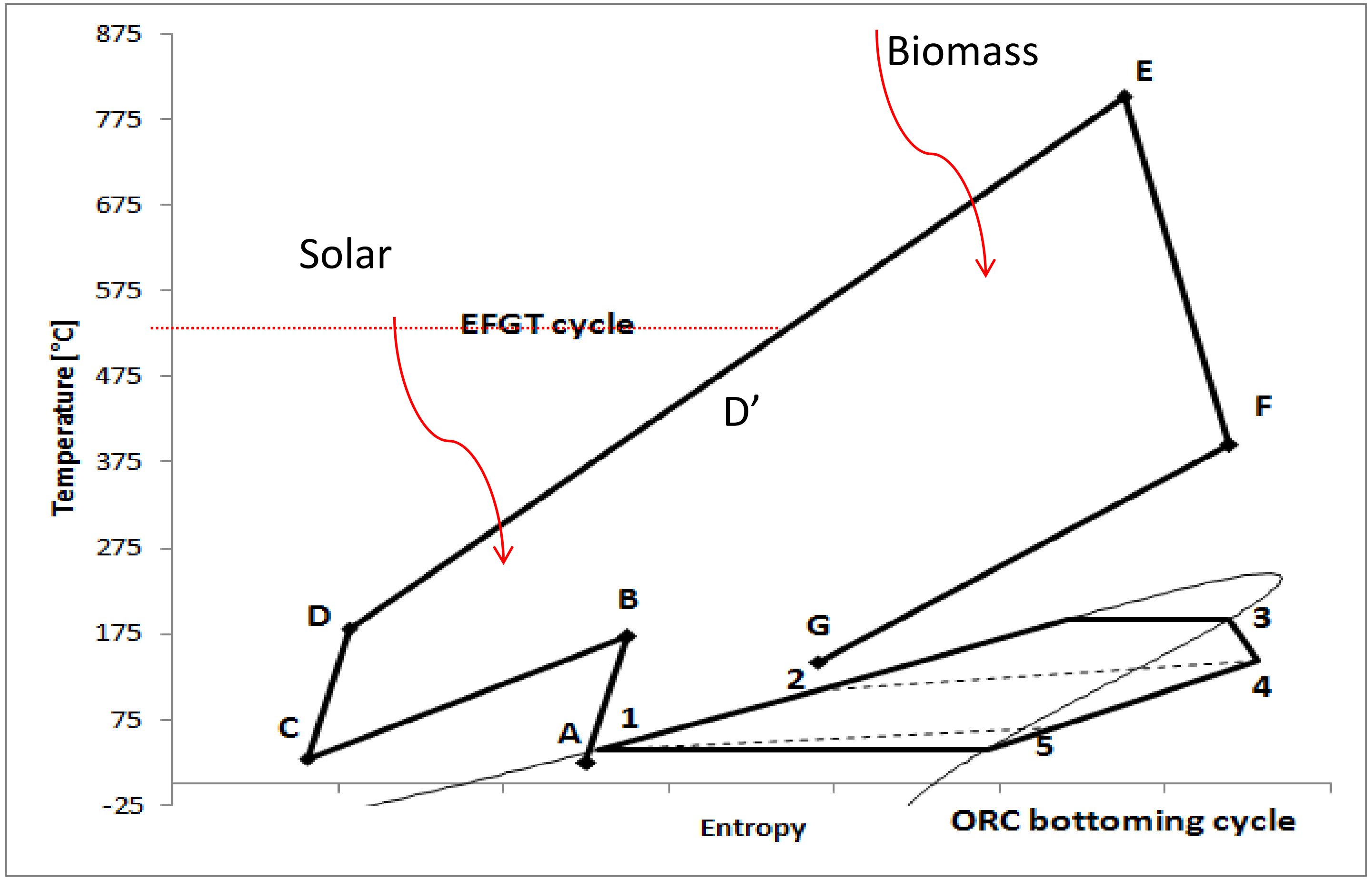
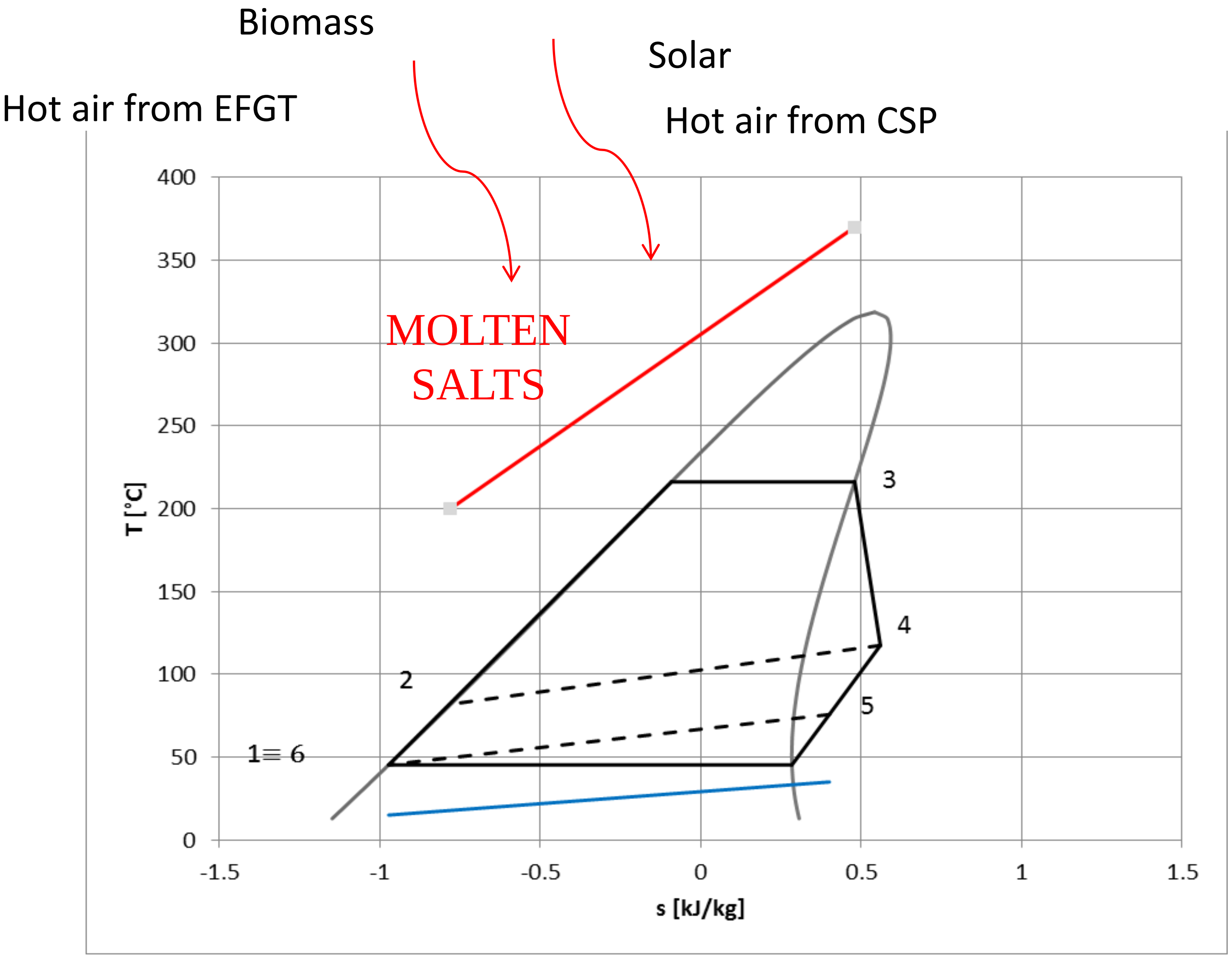
T-S chart : 50% input power from CSP (basic)

Hot air from CSP

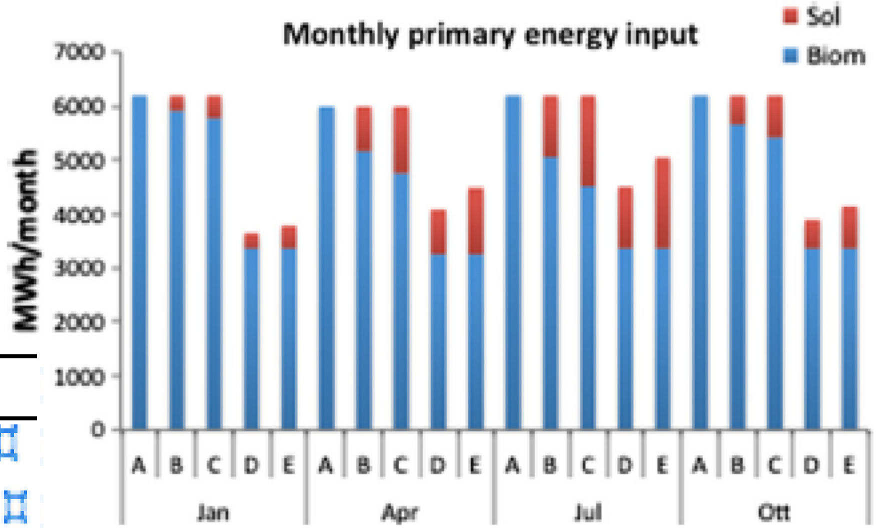


T-S chart of bottoming ORC (power blocks)



Case studies description and energy yield (basic)

Case A: baseload with fixed biomass input (100% biomass EFGT+ORC)
Cases B: baseload with modulating biomass boiler and low TES size;
Cases C: baseload with modulating biomass boiler and high TES size;
Case D: variable output with fixed biomass input, and low TES size;
Case E: variable output with fixed biomass input, high TES size;



Case study	A	B	C	D	E
Biomass furnace size (kW_t)	9,050	9,050	9,050	4,523	4,523
Biomass input (t/yr)	25,694	22,865	21,462	13,999	13,999
Net electric generation (MWh/yr)	15,741	15,741	15,741	10,761	11,818
Equivalent operating hours (hr/yr)	8,040	8,040	8,040	5,496	6,036

Priolo Gargallo site: DNI=2,256 kWh/m^2yr; discharged energy 12-13% at low/high TES
Electric efficiency case A: 23%, case B to E: 46% (part load efficiency neglected)
Biomass boiler efficiency 80%, LHV: 2.86 kWh/kg
Auxiliary consumption 6%; Thermal energy for cogeneration 980 kW – 104°C, condenser T: 40°

Case studies description and energy yield (power blocks)

Case A: baseload with fixed biomass input (100% biomass EFGT+ORC)
Cases B: baseload with fixed biomass input and low TES size;
Cases C: baseload with fixed biomass input and high TES size;

Case study	A	B	C
Biomass furnace (kW_t)	9,050	9,050	9,050
Biomass input (t/yr)	25,694	25,694	25,694
Topping EFGT net electric power (kW)	1,388	1,388	1,388
Bottoming ORC net electric power (kW)	700	800	800
Electric efficiency gas turbine	15.3%	15.3%	15.3%
Electric efficiency of the ORC(1),	21.5%	29%	29%
Solar share (solar/total energy input yearly basis)	0	6.9%	13.3%
Net electric generation (MWh/yr)	16,786	16,710	17,223
Equivalent operating hours (hr/yr)	8,039	7,568	7,805

(1). Ratio of electric power output and thermal power transmitted in the HRVG.
Case A: 100% biomass input; Cases B and C: CSP with different TES capacity

Sizing solar field and TES

DNI: 800 W/m^2; Solar Collector Assembly SCA: 8 Collectors of 5.9 x 12 m (67 m^2)
Net photo-thermal efficiency 65%;
Distance between Collectors of 2.5 times the PTC aperture

Priolo Gargallo site: DNI=2,256 kWh/m^2yr;
discharged energy 12-13%

Characteristics of the solar field and of the thermal energy storage.

Case study	Cases B and D	Cases C and E
Design TES capacity [h]	1.3	5.0
Number of lines – total SCAs [–]	2–16	3–24
Intercepting area [m^2]	8609	12,914
Required ground area [m^2]	21,523	32,300
Intercepted solar power [MWt]	6.89	10.33
Available thermal power [MWt]	4.48	6.72
Solar multiple [–]	1.22	1.83
Thermal power to the TES [MWt]	0.81	3.04
TES capacity [MWh]	4.8	18.3

basic

Power blocks

Solar field characteristics

Case study	B	C
Intercepting area (m^2)	3,228	6,457
Required ground area (m^2)	8,071	16,142
Thermal power output(MW)	1.808	3.616
Solar thermal power available for TES (MW)	0.887	2.6956
Design TES capacity (MWh)	5.178	16.02
Design TES discharge hours	5.48	16.96

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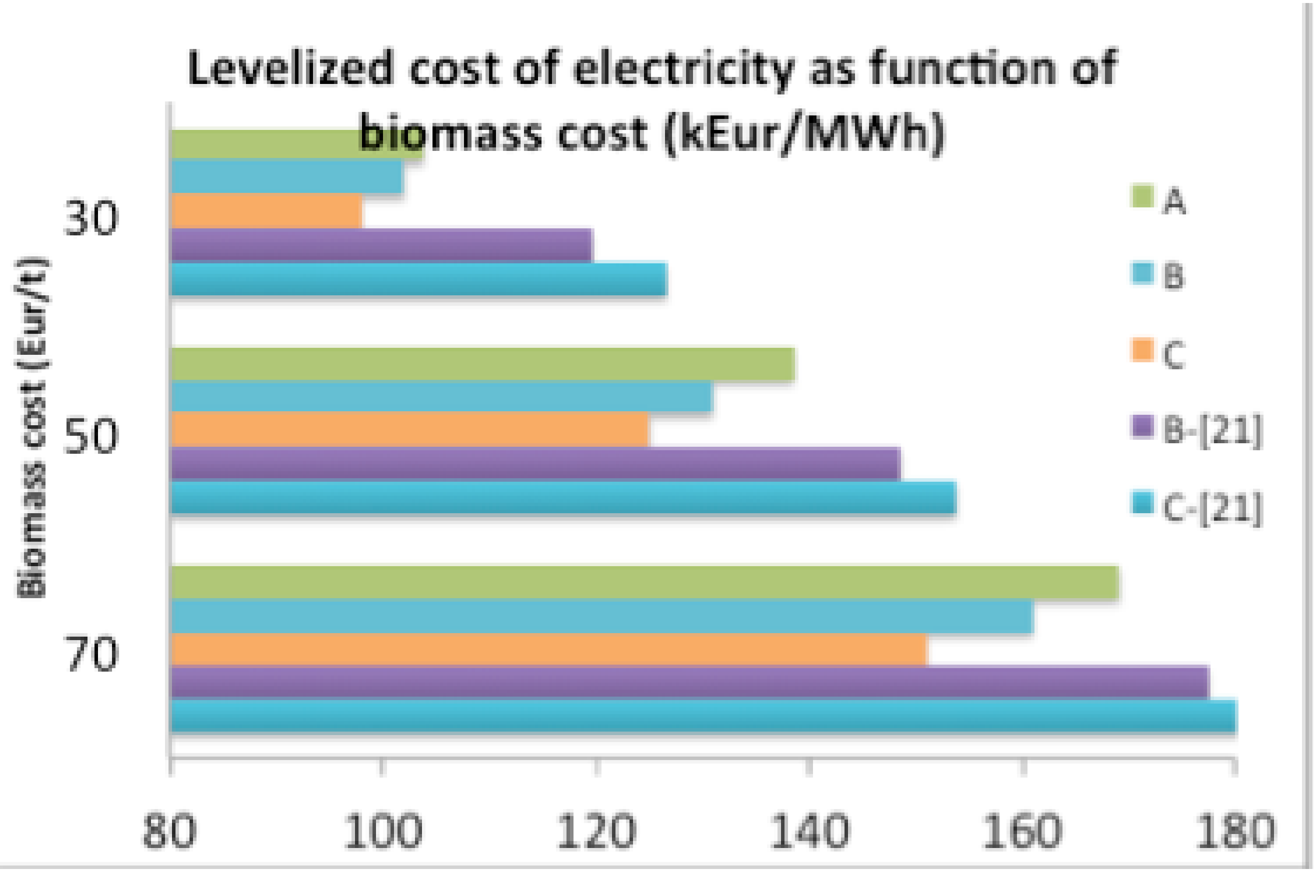
Performance of the plants considered for economic analysis

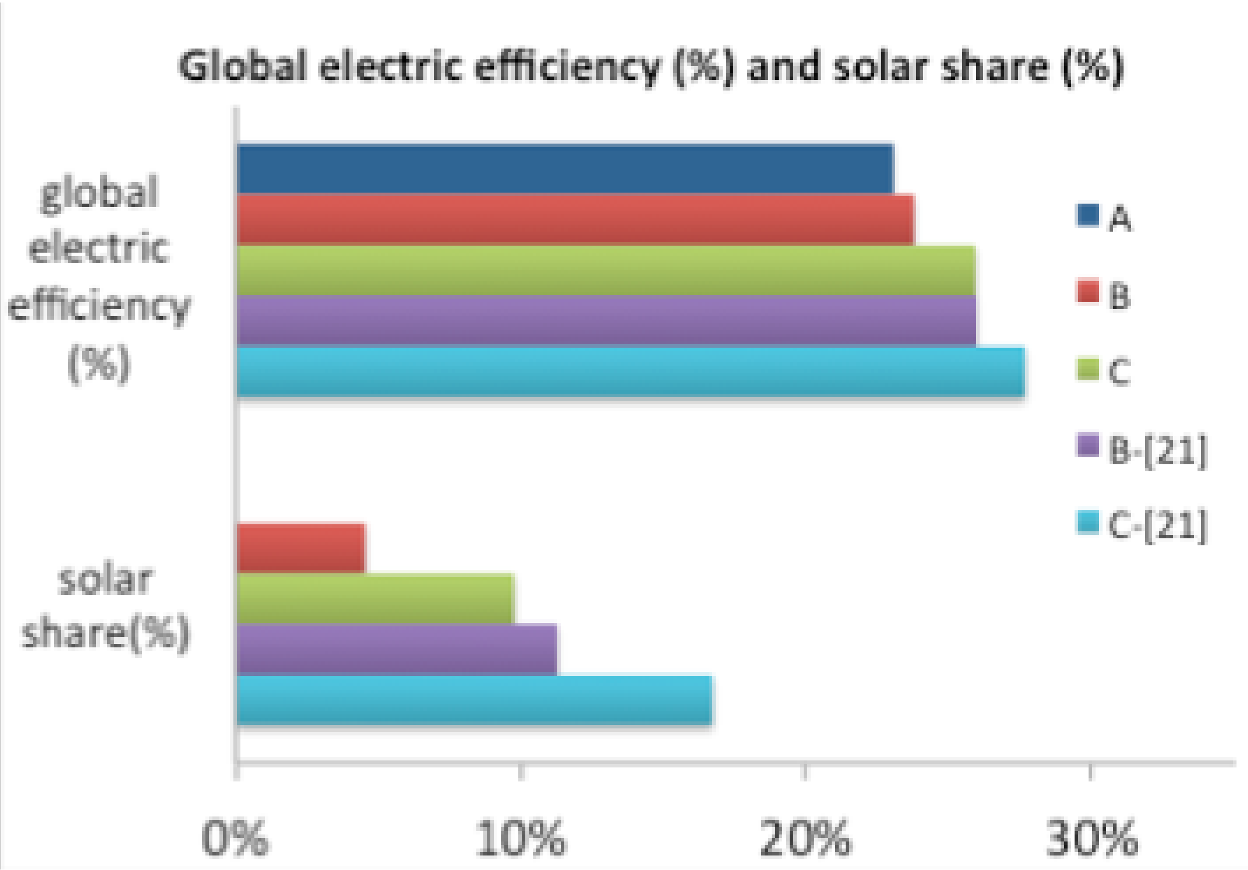
Parameter	Unit	EFGT	EFGT +ORC	EFGT+ORC +CSP (basic)	EFGT+ORC+CSP (power blocks)
Electric power output (ISO) PN	kW	1,383	2,083	2,083	2,183
Auxiliary consumpt. % PN	%	5	6	6	6
Thermal Power output (for CHP)	kW	4,083	963	963	2106
Gas temperature (for CHP)	°C	394	104	104	220
Net-electric efficiency (ISO)	%	15.3	23.0	46.0	32.0

CAPEX and OPEX costs (basic)

Description	EFGT	EFGT+ORC (A)	B	C	D	E
Turn Key cost (kEur)	**3,500**	**4,700**	**7,684**	**9,450**	**7,284**	**9,050**
- PTC and CSP	-	-	2,863	4,294	2,863	4,294
- Gas Turbine	1,200	1,200	1,200	1,200	1,200	1,200
- ORC genset	-	1,200	1,200	1,200	1,200	1,200
- Biomass furnace	1,000	1,000	1,000	600	600	600
- HTHE for EFGT	600	600	600	600	600	600
- Civil works,grid conn, eng and devel	700	700	700	700	700	700
Unit upfront cost (kEur/kWe)	**2.53**	**2.26**	**3.69**	**4.54**	**3.50**	**4.34**
Opex (included fuel) (kEur/yr)	**2,285**	**2,285**	**2,186**	**2,099**	**1,532**	**1,549**

Global electric efficiency and LCE

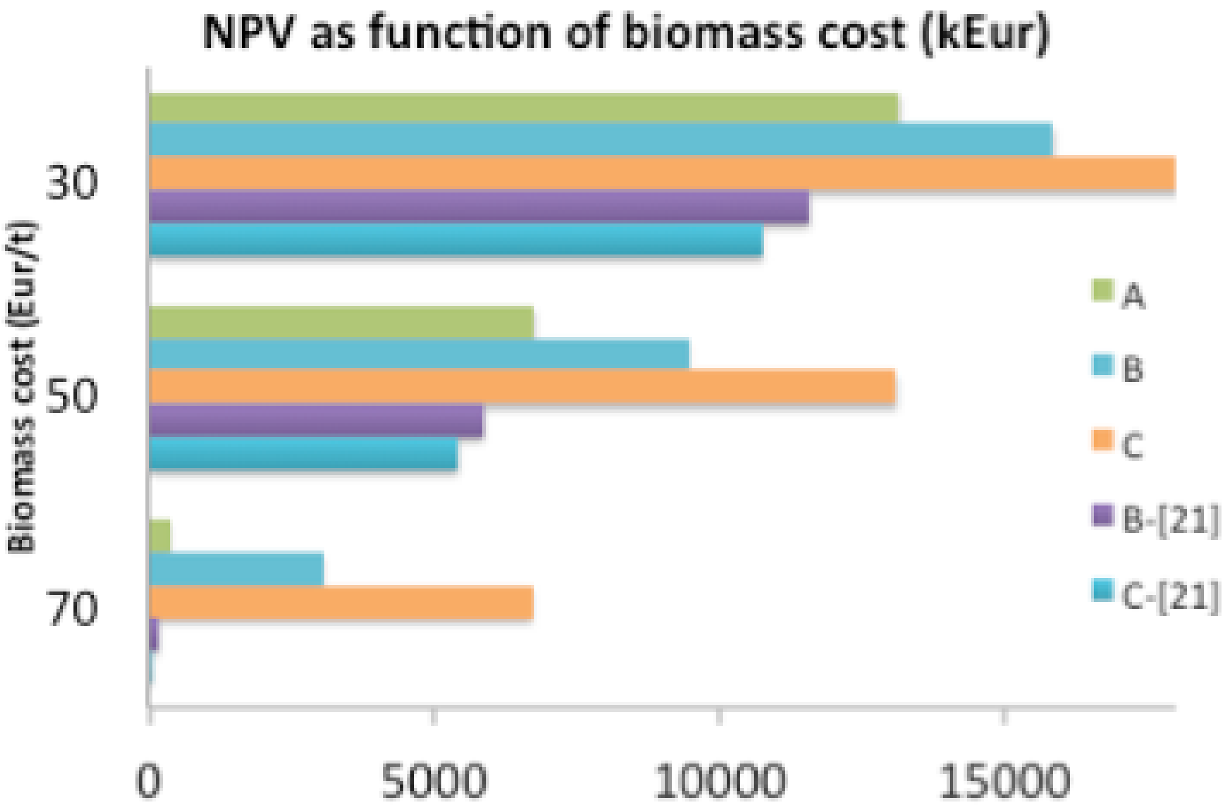


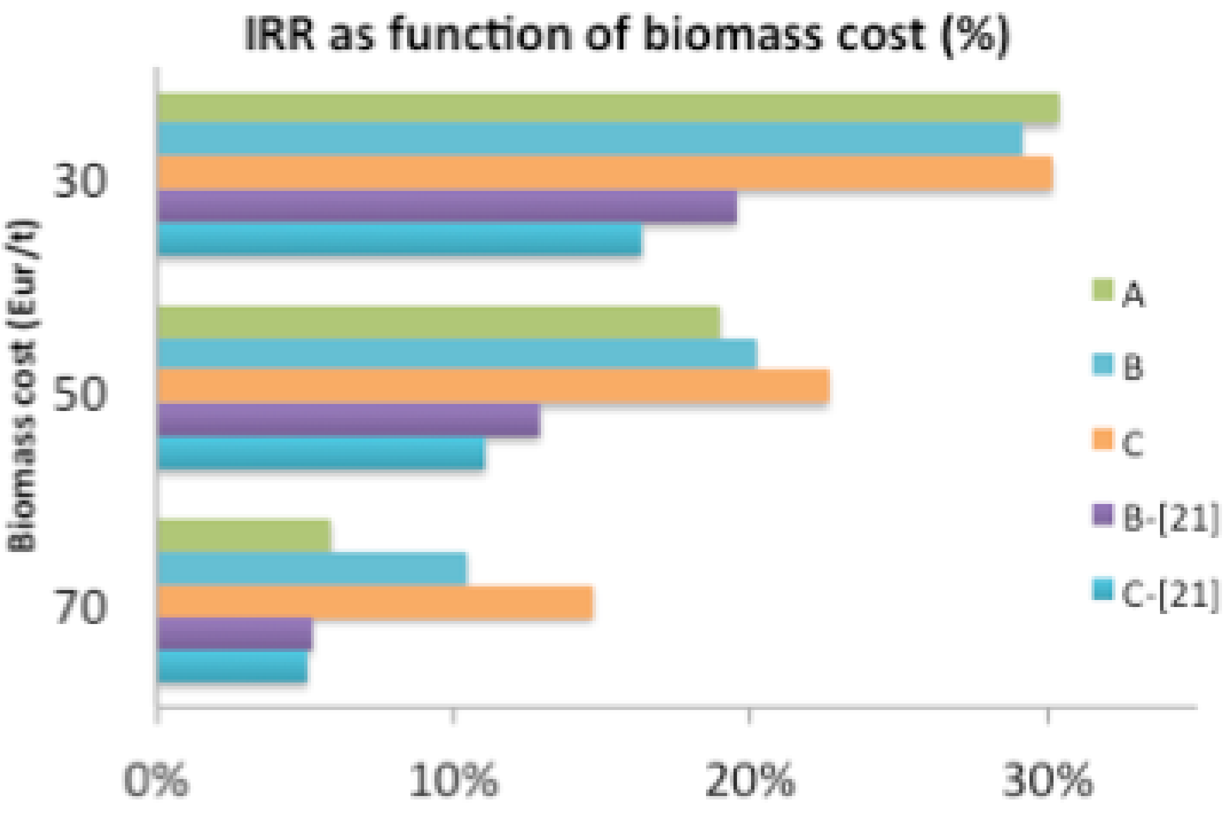


Global electric efficiency = ratio electricity / thermal energy input from biomass (annual basis)

Solar share = ratio of thermal energy from CSP vs total thermal energy input (annual basis)

Profitability analysis: influence of biomass supply cost





Electricity only production scenario
Power block is more profitable system configuration than basic scenario
Higher revenues from electricity sales from CSP increase the NPV in comparison to only biomass fuel (more evident at high biomass supply cost)
High investment cost for CSP makes it less profitable than only biomass in BASIC scenario (IRR)

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Conclusions

- A hybrid biomass/CSP combined cycle composed by EFGT (non regenerative) + ORC cycle is examined
- The combined cycle EFGT+ORC results more profitable than the simple EFGT option, because of its higher electric efficiency.
- Only in case of high temperature of heat demand, and high thermal demand load, the simple EFGT is the most profitable one
- CSP with PTC and molten salt can be a valuable option for hybrid solar/biomass cycles and such hybrid cycle allows increasing global electric efficiency from 23% to 26-32%
- The integration with CSP increases NPV for the higher feed-in tariff (Italian scenario) but reduces IRR for the high investment costs (in the basic scenario)
- In power block scenario the integration of CSP is optimized and economic profitability is higher than the basic CSP scenario and the only-biomass scenario
- Part load and dynamic modeling is required to optimize operational strategies (load following), energy storage sizing, solar to biomass ratio

Thank you! Any question?

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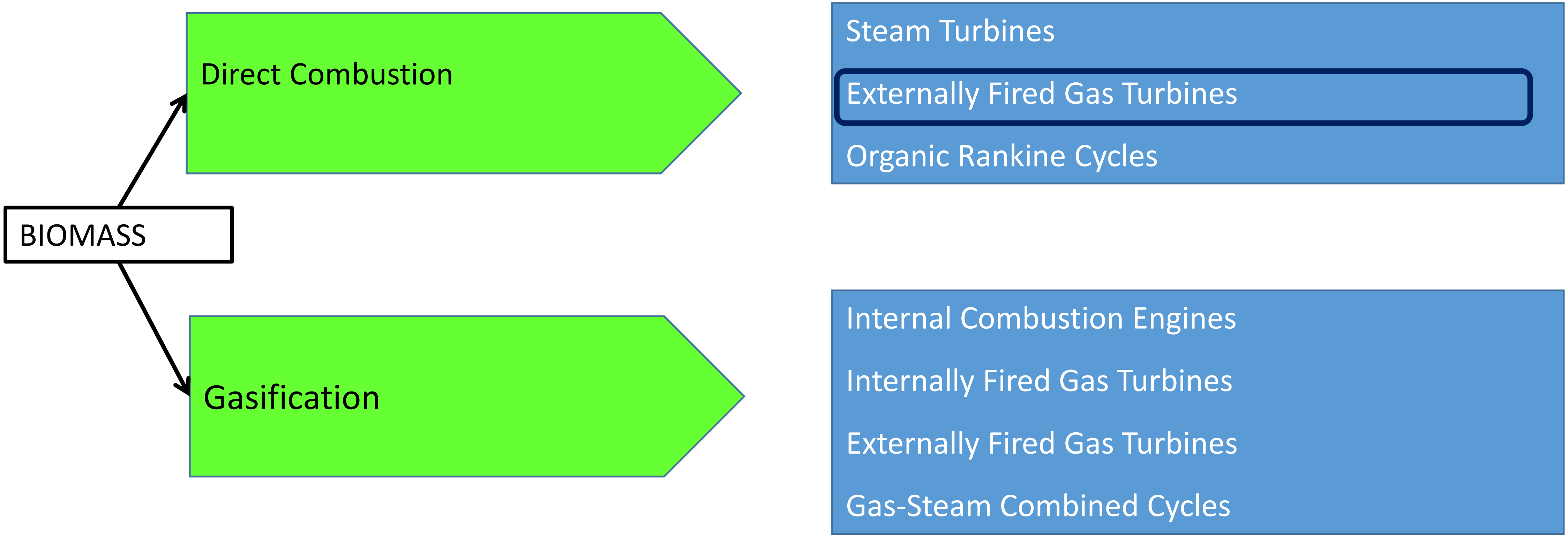
Biomass CHP generation



CSP generation and hybridization

Solar collectors (required T level, space constraints)	Linear Fresnel Parabolic through Solar dishes Solar tower
Heat transfer fluid	Steam Diathermic oil Compressed air Molten salts (with T of 500-550 °C)
Biomass/solar hybridization	Steam/Rankine cycle Gasified biomass into bryton cycle Hot air for Externally Fired Gas Turbines Gas-Steam Combined Cycles

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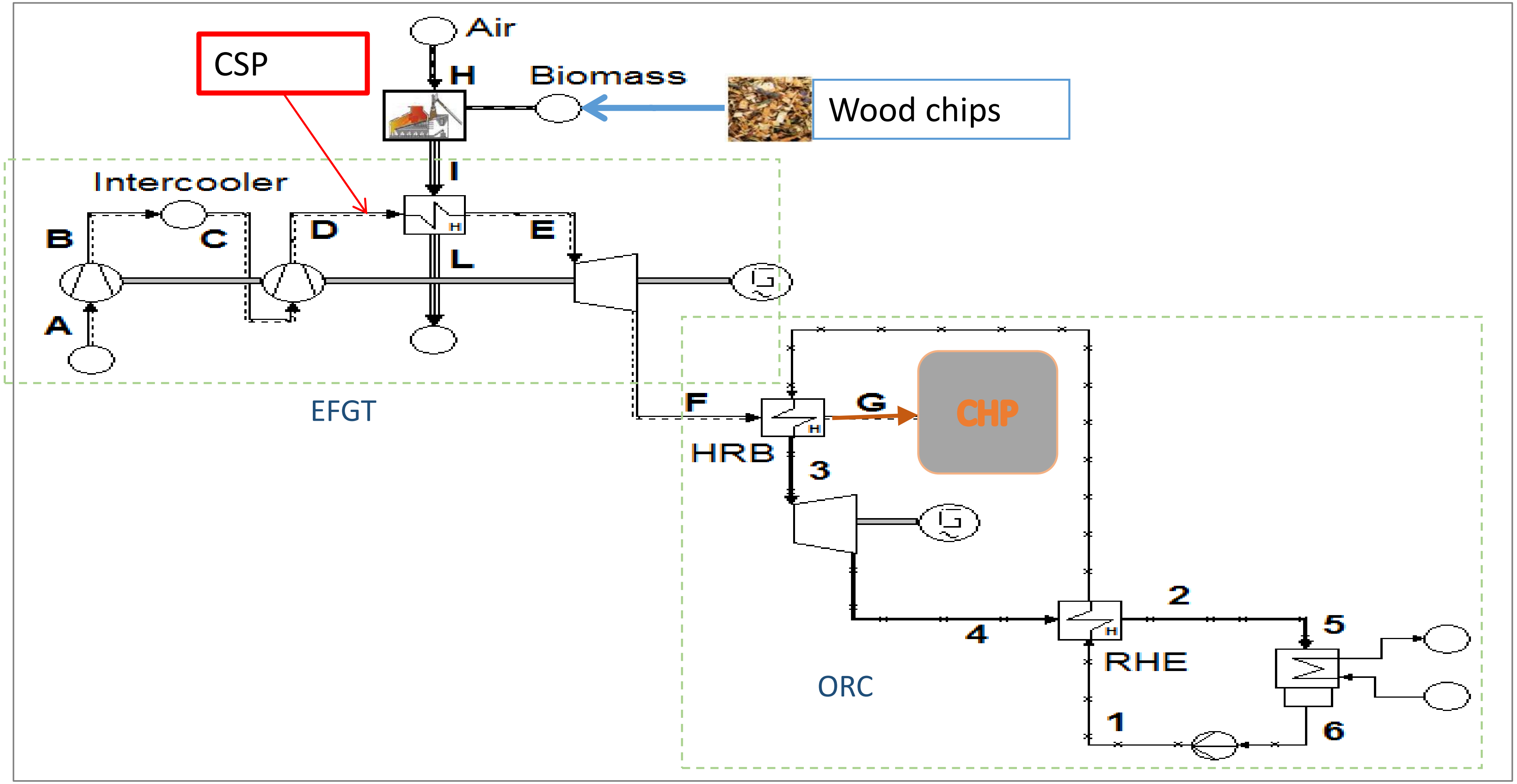
Plant layout modeled in cycle-tempo



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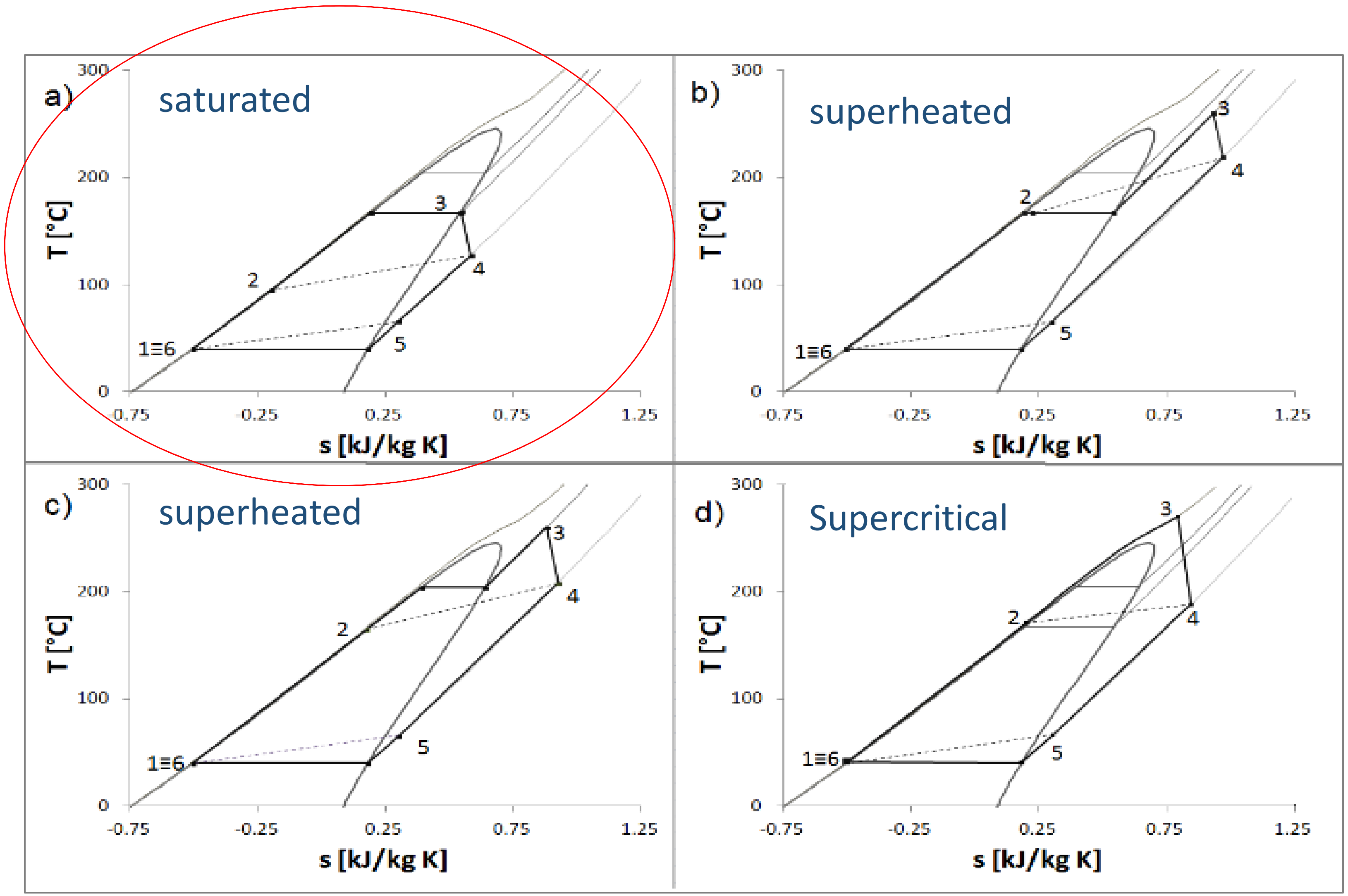
ORC cycle selection

Toluene -dry fluid-



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Profitability analysis: heat demand

Different heat demand intensities

Thermal energy selling price 80 Eur/MWh