Waste to Energy System Based on Solid Oxide Fuel Cells: Department Store Case

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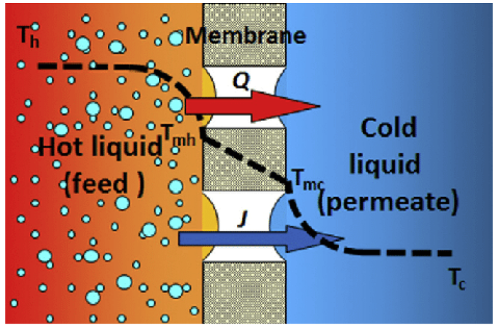
Motivation

- Municipal waste dispose is increasing significantly and must be taken care of.
- Waste to Energy after basic recycling and producing fuel through waste gasification.
- Multi generation systems is the most effective way from energetic/exergetic view.
- Decentralized trigeneration plants for producing electricity, cooling and freshwater.

Waste Gasifier

SOFC

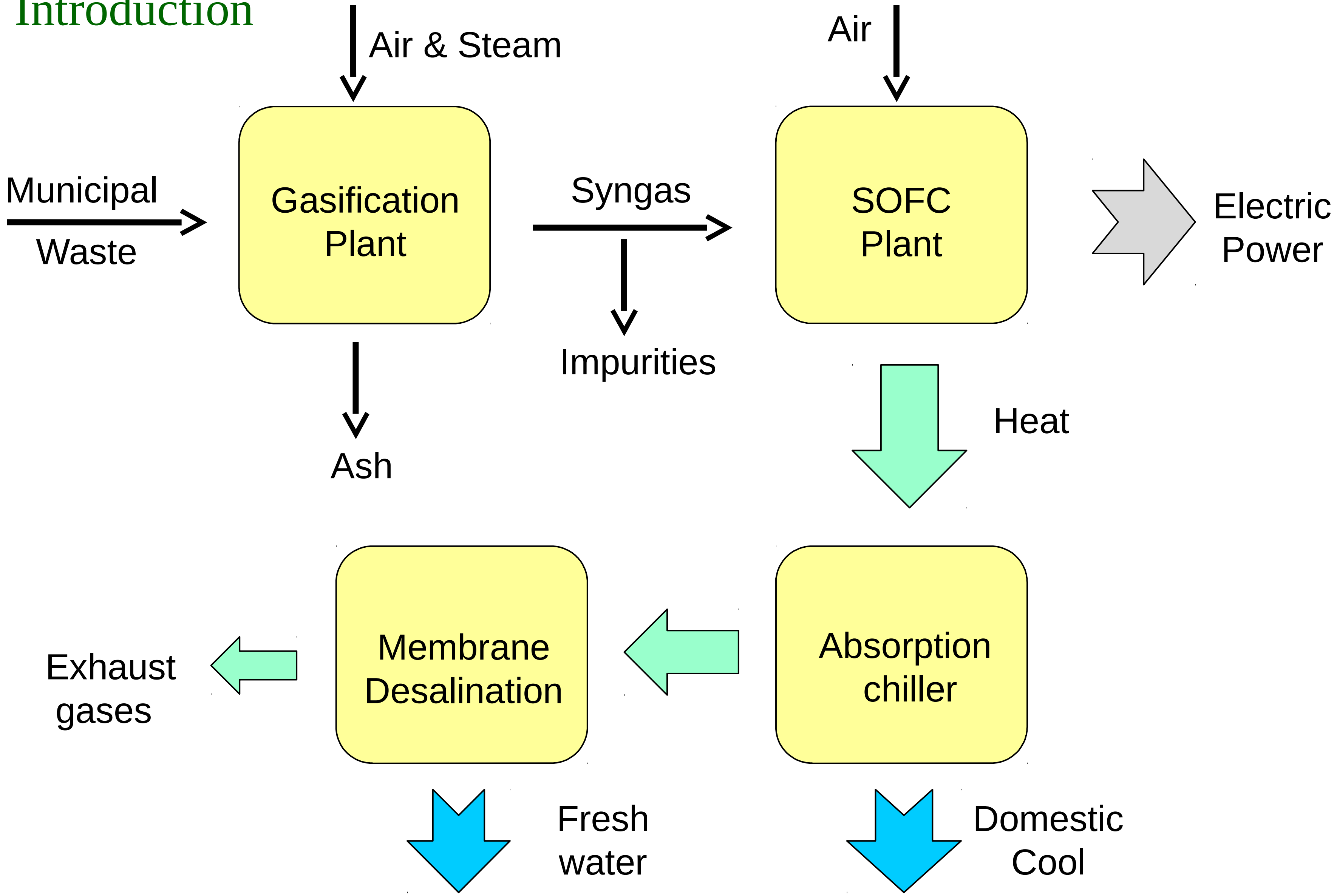
Freshwater



Absorption

SOFC = Solid Oxide Fuel Cell

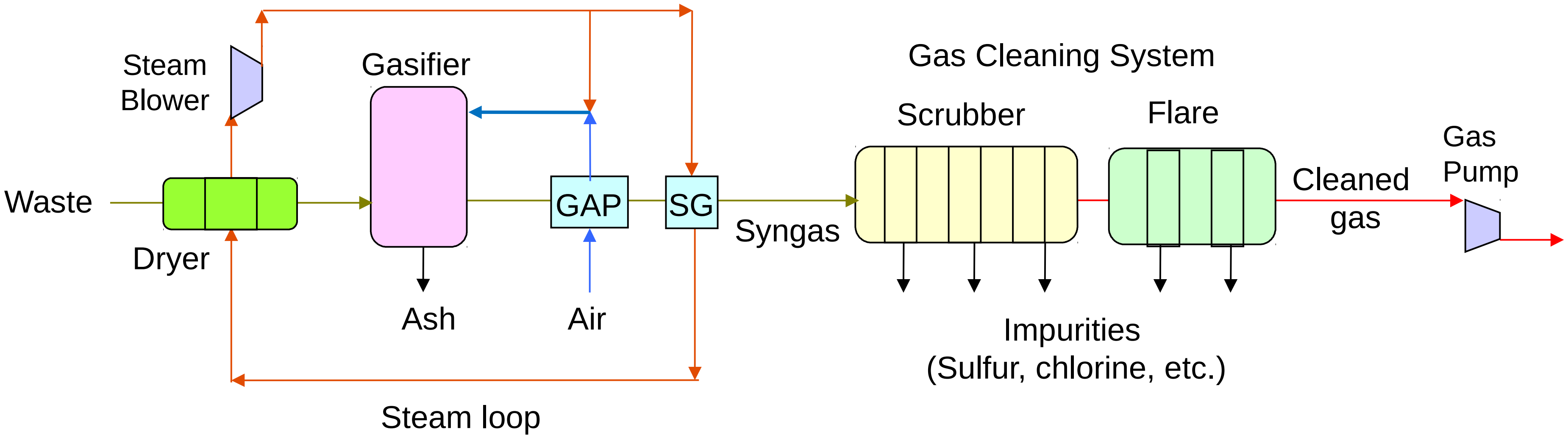
Introduction



GAP = Gasification Air Preheater
SG = Steam Generator

Gasifier Plant and its Modelling

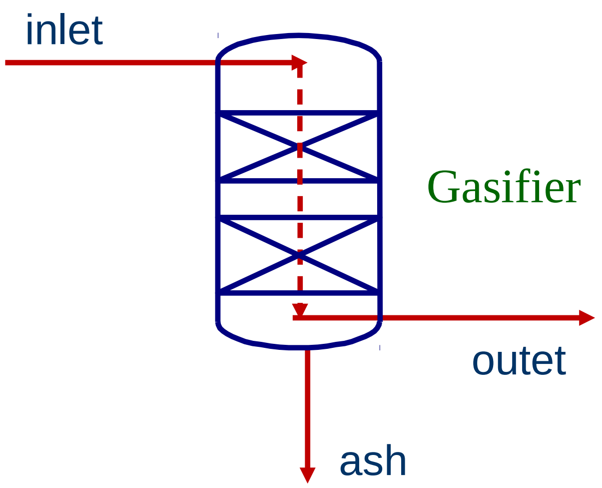
- Waste is dried and pyrolysis and then fed to the gasifier.
- Drying is made by steam generator (SG) in a steam–loop.
- Air is preheated in a gasifier preheater (GP) using the product gases from the gasifier.
- Preheated air and some of the steam from the drying process is fed to the gasifier
- Gasifier outlet temperature assumed 800°C, while inside temperature is around 1300°C.
- Syngas is cleaned in a gas cleaner system (such as sulfur and chlorine).



Modeling Gasifier (cont.)

- Equilibrium condition at outlet.
- Mixture of perfect gases.
- Minimizing the Gibbs energy at outlet, as described in Smith et al. (2005).
- Introduction of a parameter to account for methane bypass without undergoing chemical reactions (about 1%).

Parameter	***Value***
Waste temperature, (˚C)	15
Drying inlet temperature, (˚C)	150
Gasifier temperature, (˚C)	800
Gasifier pressure drop, (bar)	0.005
Gasifier carbon conversion factor	1
Gasifier non-equilibrium methane	0.01
Steam blower isentropic efficiency	0.8
Steam blower mechanical efficiency	0.98
Steam temperature in steam loop, (˚C)	150
Gas blower isentropic efficiency	0.7
Gas blower mechanical efficiency	0.95



Modeling Gasifier (cont.)

Parameter	*Waste*	Parameter	*Syngas*
C (vol %)	45.39	H_2 (vol %)	29.31
Ash (vol %)	20.26	N_2 (vol %)	32.39
S (vol %)	0.08	CO (vol %)	25.28
Cl (vol %)	0.08	CO_2 (vol %)	5.54
O (vol %)	26.56	H_2O (vol %)	5.67
H (vol %)	6.21	CH_4(vol %)	1.07
N (vol %)	1.42	Ar (vol %)	0.38
Moisture	18.12	HCl (ppmv)	< 10
Cp (kJ/kg)	1.84	H_2S (ppmv)	< 1
HHV (kW), dry basis	19990		

$$\dot{G} = \sum_{i=1}^{k} \dot{n}_i \left[g_i^0 + RT \ln(n_i p) \right]$$

$$\sum_{i=1}^{k} \dot{n}_{i,in} \mathbf{A}_{ij} = \sum_{m=1}^{w} \dot{n}_{m,out} \mathbf{A}_{mj} \qquad \text{for } j = 1, N$$

$\mathbf{A}_{ij}$; element *j* (H, C, O, N) entering in
i (H_2, CH_4, CO, CO_2, H_2O, O_2, N_2 and Ar)

$\mathbf{A}_{mj}$: element *j* of leaving compound
m (H_2, CH_4, CO, CO_2, H_2O, N_2 and Ar)

$$\phi = \dot{G}_{tot,out} + \sum_{j=1}^{N} \mu_j \left[\sum_{i=1}^{k} \dot{n}_{i,out} A_{ij} - \sum_{m=1}^{w} \dot{n}_{m,in} A_{mj} \right]$$

$$\frac{\partial \phi}{\partial \dot{n}_{i,out}} = \frac{\partial \dot{G}_{tot,out}}{\partial \dot{n}_{i,out}} + \sum_{j=1}^{N} \mu_j \mathbf{A}_{ij} = 0 \qquad \text{for } i = 1, k$$

$$\Rightarrow \quad g_{i,out}^0 + RT \ln(n_{i,out} p_{out}) + \sum_{j=1}^{N} \mu_j \mathbf{A}_{ij} = 0 \qquad \text{for } i = 1, k$$

Modelling of SOFC

- For planar SOFCs developed by DTU – Risø and TOPSØE Fuel Cell (Denmark).
- Zero-dimensional model allowing to be used for complex energy systems.
- Calibrated against experimental in the range of 650 to 800°C
- Keegan et al. (2002), Holtappels et al (1999), Kim and Virkar (1999), Peterson et al. (2005).

$$E_{FC} = E_{Nernst} - \Delta E_{act} - \Delta E_{ohm} - \Delta E_{conc}$$

$$\Delta E_{act} = \frac{RT}{(0.001698T - 1.254)F} \sinh^{-1}\left(\frac{i_d}{2(13.087T - 1.096x10^4)}\right)$$

$$\Delta E_{ohm} = \left(\frac{t_{an}}{\sigma_{an}} + \frac{t_{el}}{\sigma_{el}} + \frac{t_{ca}}{\sigma_{ca}}\right) i_d$$

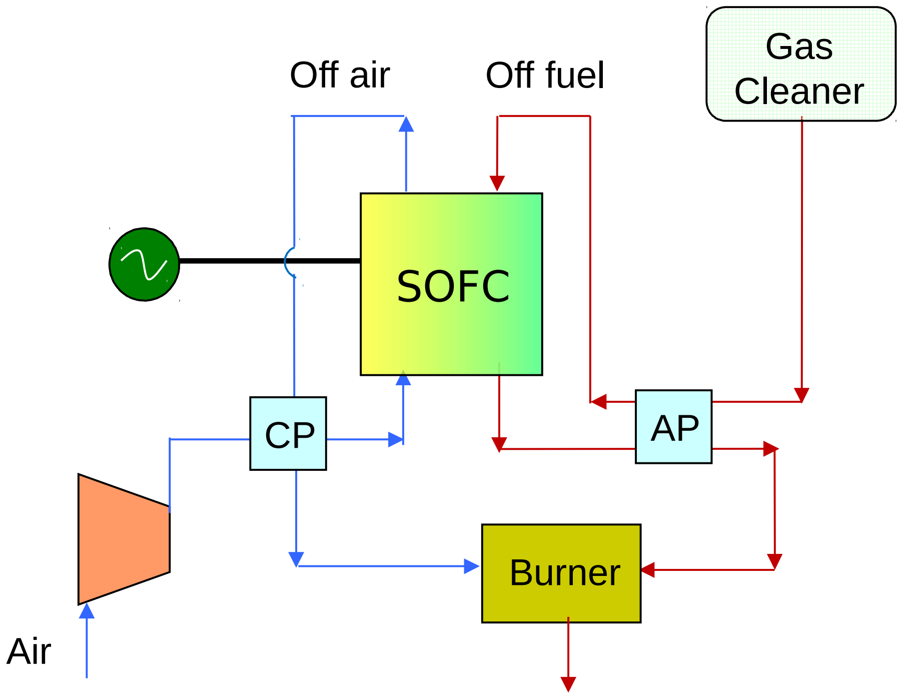
t = thickness, σ = conductivity

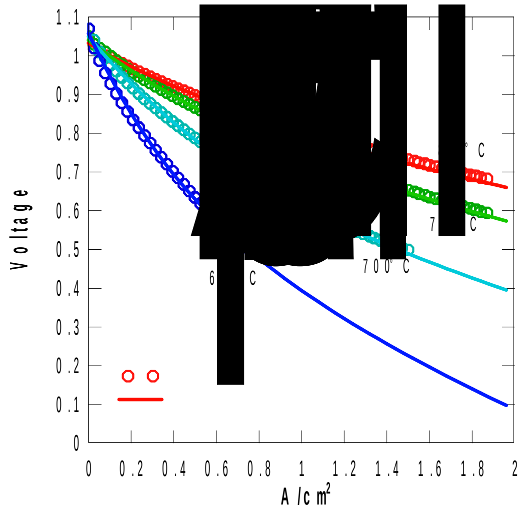
$$\Delta E_{conc} = B\left[-\ln\left(1 + \frac{p_{H2}\, i_d}{p_{H2O}\, i_{as}}\right) - \ln\left(1 - \frac{i_d}{i_{as}}\right)\right]$$

i_d = current density,
i_{as} = anode limiting current

Design of SOFC Plant Fed by Syngas

- Gas cleaner (Desulfurization)
- Gas pump
- Anode preheater (AP)
- Anode side of SOFC
- Burner
- Air compressor
- Cathode preheating (CP)
- Burner



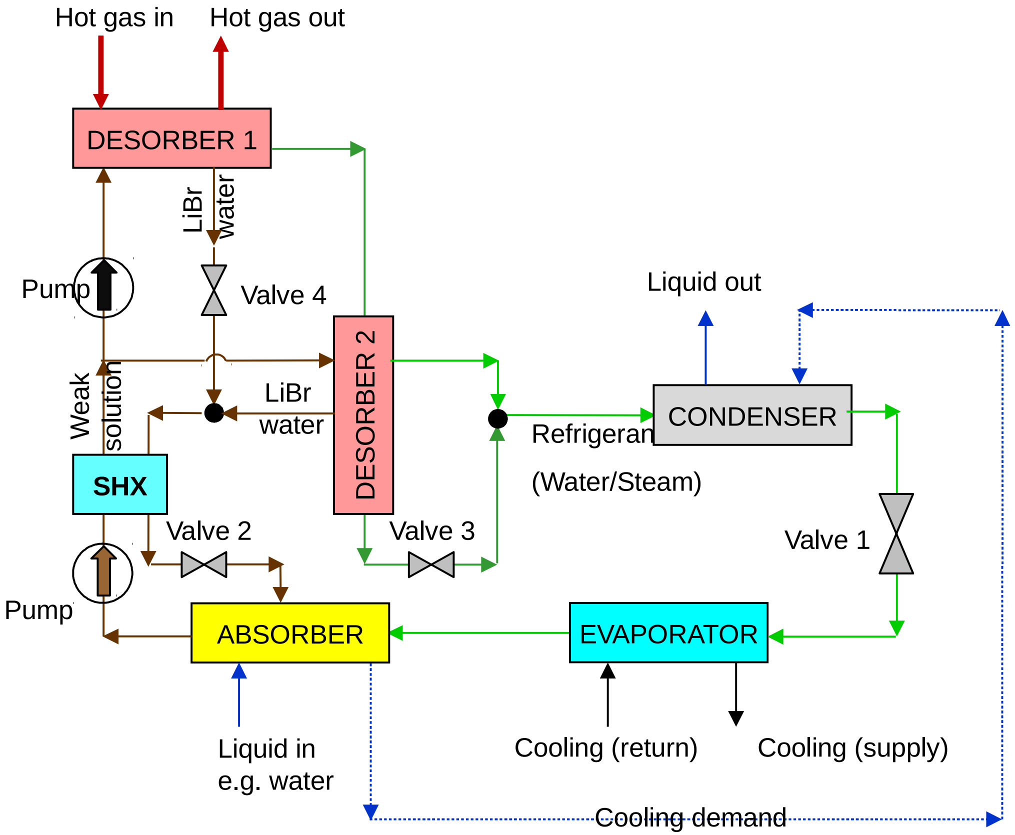


Parameter	*Value*
Fuel utilization factor	0.7
Number of cells in stack	75
Number of stacks	160
Cathode pressure drop ratio, [bar]	0.04
Anode pressure drop ratio, [bar]	0.01
Cathode inlet temperature, [°C]	600
Anode inlet temperature, [°C]	650
Outlet temperatures [°C]	780
DC/AC convertor efficiency	0.97

SHX = Solution Heat eXchanger

Absorption Chiller

- LiBr (Lithium Bromide) is used as absorbent.

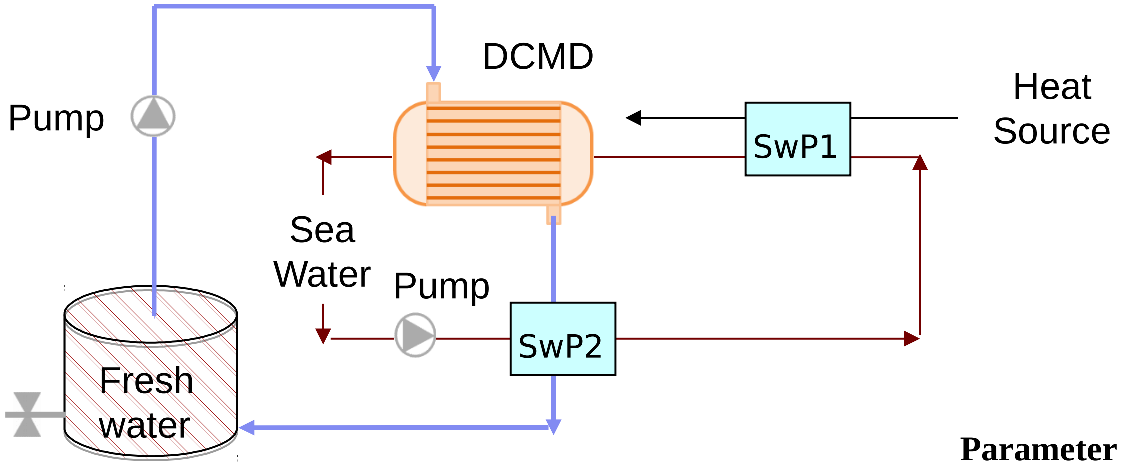


Parameter	Value
Desorber gas outlet temp. (°C)	90
Rich solution (–)	0.6195
Week solution (–)	0.548
Condenser outlet temp. (°C)	32
Pressure after valve 1 (bar)	0.008
Pressure after valve 3 (bar)	0.05
Absorber cooling inlet temp. (˚C)	20
Absorber cooling inlet pressure (bar)	16
Hot side outlet temp. for SHX (˚C)	70
Solution pump pressure high/low (bar)	0.8/0.05

SwP = Sea Water Preheater

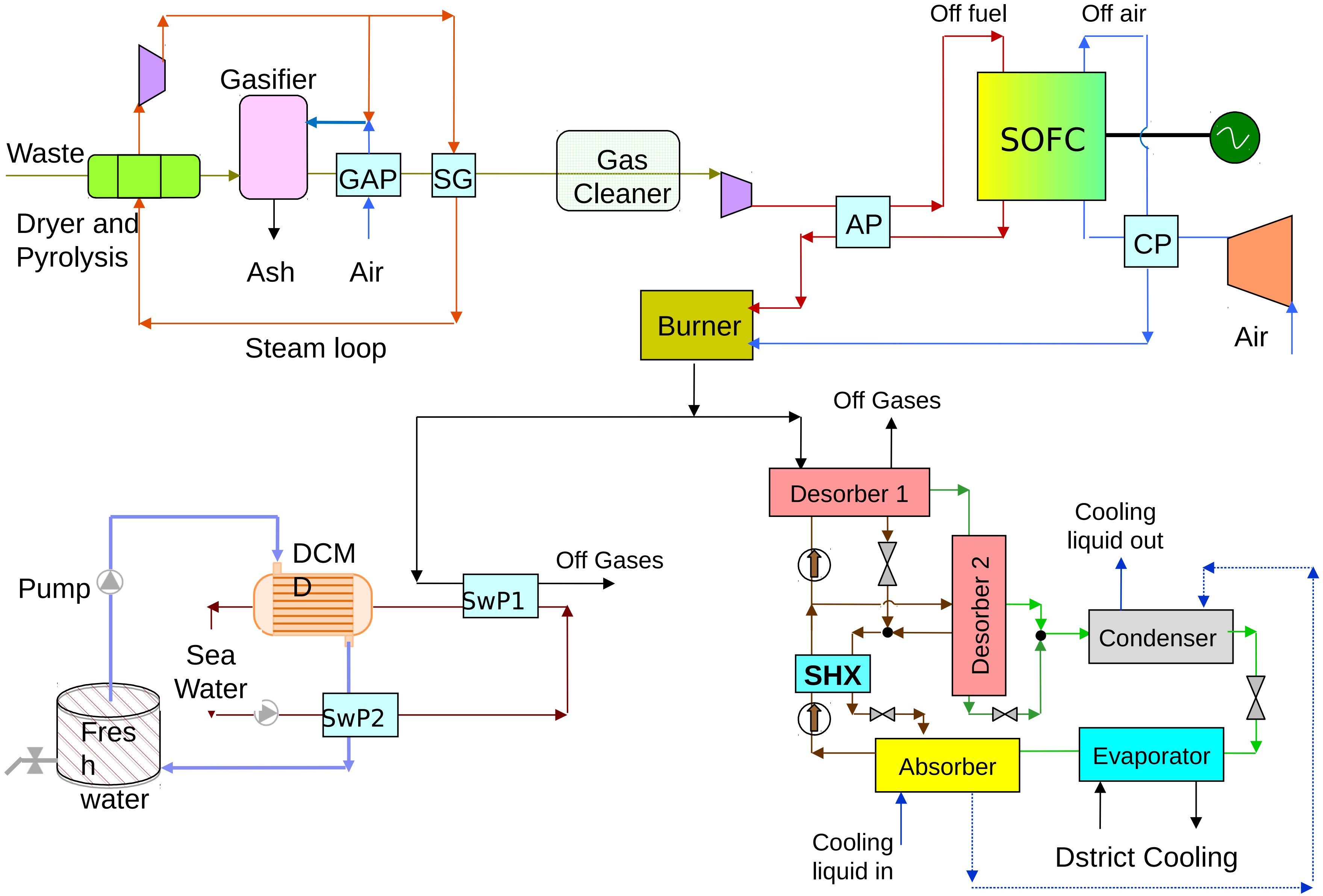
DCMD (Membrane Desalination)

- LiBr (Lithium Bromide) is used as absorbent.



Parameter	Value
Fiber length	0.4 m
Inner diameter of fiber	0.3 mm
Membrane thickness	60 µm
Porosity	75%
Membrane conductivity	0.25 W/mK
Shell diameter	0.003 m
Number of fibers	3000
Packing density	60%
Inlet temperature	80°C
C_k (individual contribution of Knudsen diffusion)	15.18×10^{-4} [–]
C_m (individual contribution of Molecular diffusion)	5.1×103 m^{-1}
C_p (individual contribution of Poiseuille flow)	12.97×10^{-11} m

The Complete Plant

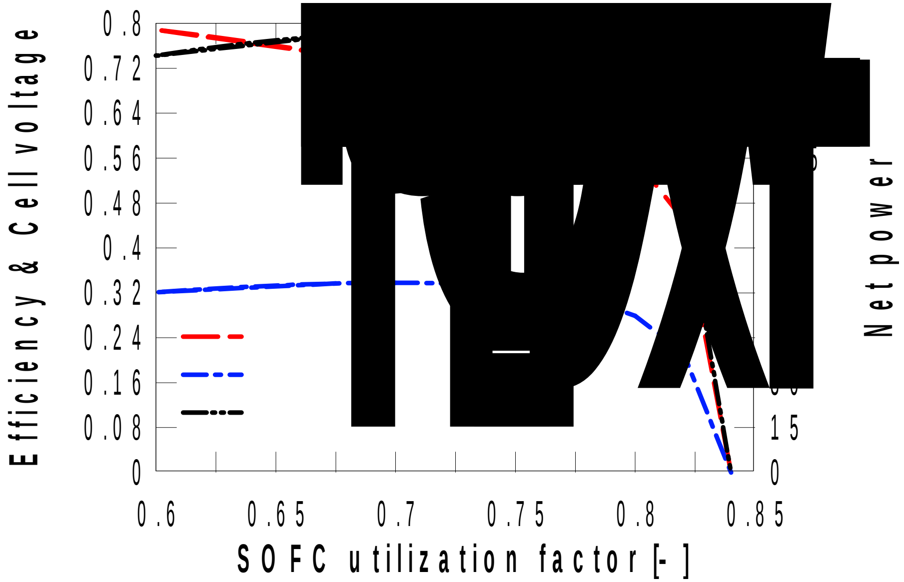


Plant Performance

Parameter	Values
Net electric production (kW)	146.56
Freshwater production (kg/h)	179.94
Heat input to DCMD, Q_{FW} (kJ/s)	125.66
DCMD efficiency (%)	59.30
Cooling production (kJ/s)	145.34
Fuel consumption (LHV) (kW)	433.35
Total power consumption (kW)	16.394
Off-gases temp. (°C)	90
Electric efficiency, Eq. (2) (%)	33.82
Plant energy efficiency, Eq. (1) (%)	84.55

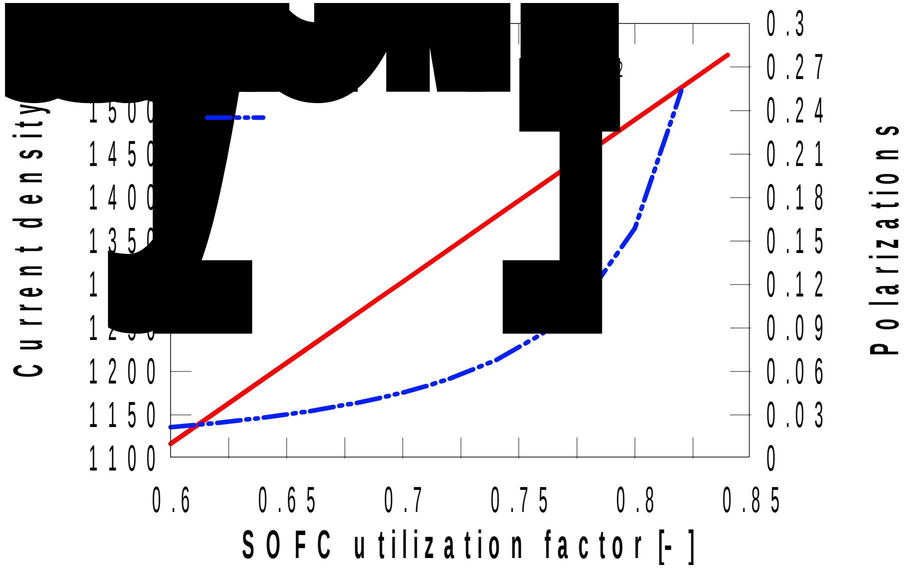
Parameter	Value
MW mass flow (kg/h)	105.3
MW temperature (°C)	15
Drying temperature (°C)	150
Gasifier outlet temperature (°C)	800
Gasifier pressure (bar)	1
Gasifier pressure drop (bar)	0.005
Gasifier carbon conversion factor	1
Gasifier non-equilibrium methane	0.01
Steam blower isentropic efficiency	0.8
Steam blower mechanical efficiency	0.98
Air temperature into gasifier (°C)	15
Syngas blower isentropic efficiency	0.7
Syngas blower mechanical efficiency	0.95
Syngas cleaner pressure drop	0.0049
Blower air intake temperature (°C)	15
Blower isentropic efficiency	0.7
Blower mechanical efficiency	0.95
Gas heat exchangers pressure drop (bar)	0.01
Cathode preheater pressure drop (bar)	0.04
Anode preheater pressure drop (bar)	0.01
Burner inlet-outlet pressure ratio (efficiency)	0.95

Effect of SOFC Utilization Factor

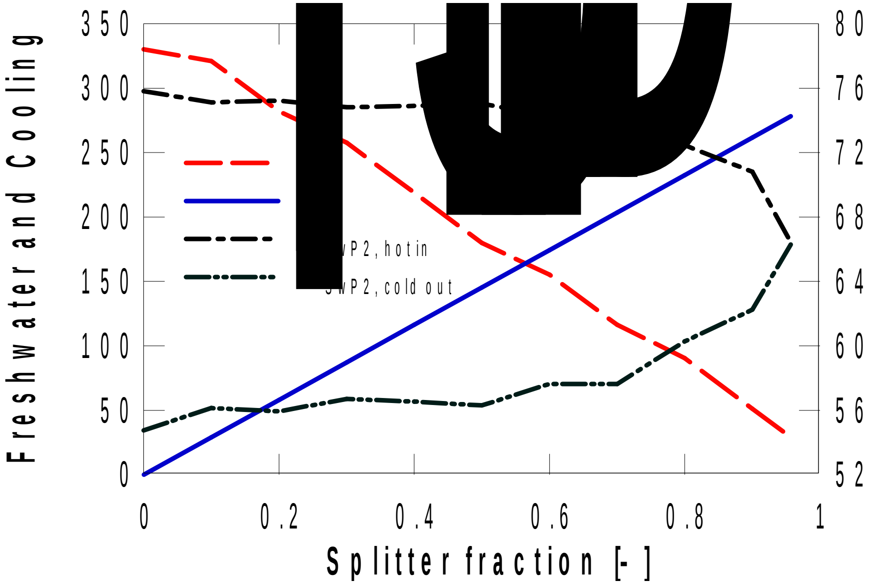


- There exist a point where plant efficiency and power maximizes.
- This optimum value is 0.7.

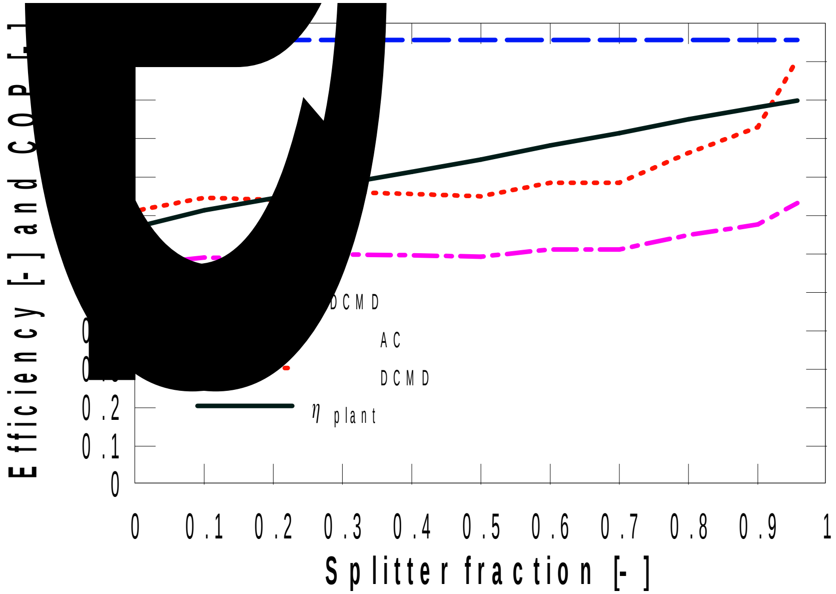
- Increasing utilization factor increases current density.
- At a certain current density, the concentration losses increases exponentially and thereby decreases cell voltage as ell as power.



Effect of SOFC Operating Temperature and Utilization Factor

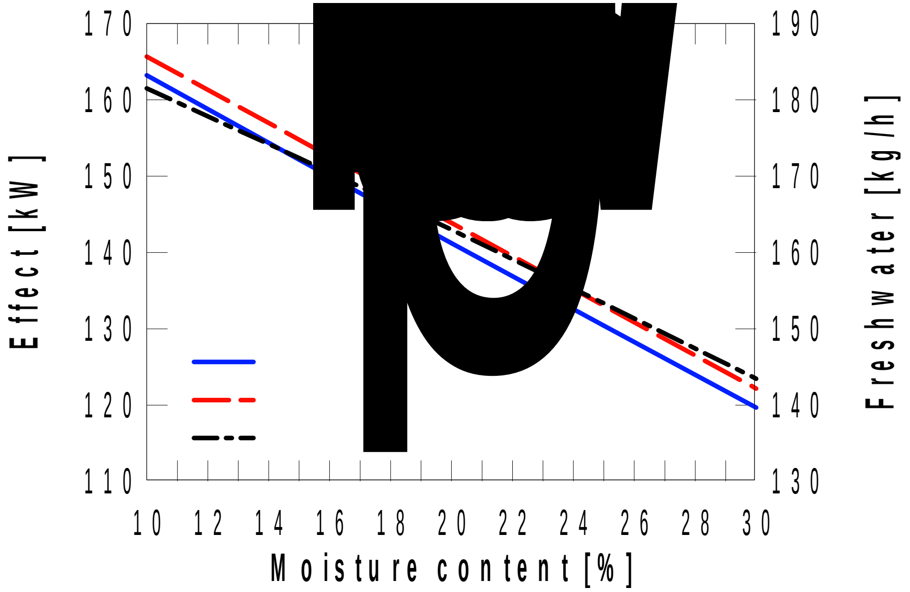


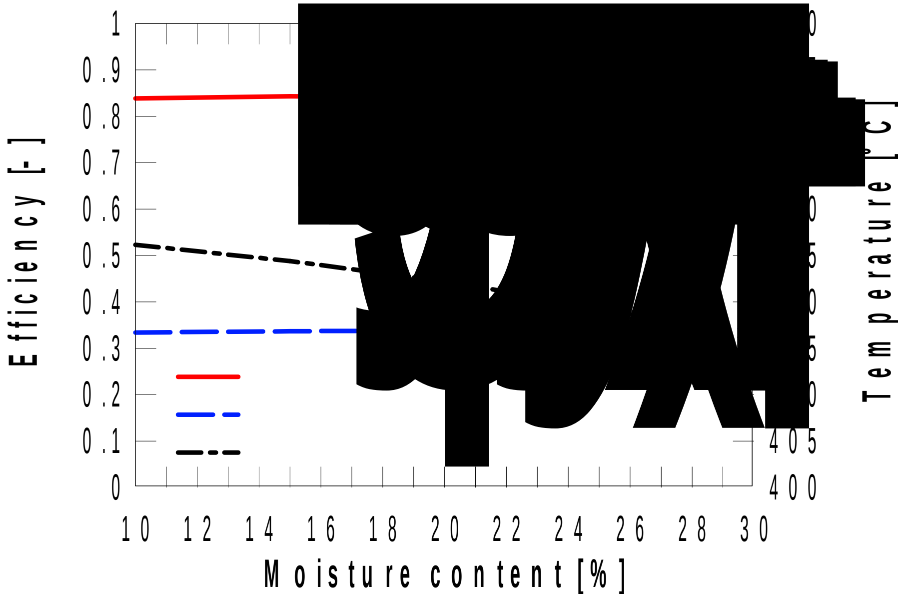
- Opening the valve for chiller increases plant efficiency because chiller performance is higher than the desalination performance.
- Even though desalination performances increases with opening the chiller valve.



- Opening the valve for chiller increases cooling production (more off-gases to chiller);
- Thereby, freshwater production decreases.
- Opening the valve beyond 95% , then the freshwater device (DCMD) must be decoupled. This is due to the pinch temp associated with the DCMD heat exchanger.

Effect of Moisture Content





- Waste moisture may changes significantly from day to day.
- Increasing moisture content results in decreasing plant performance. All production decreases.
- Higher moisture content means also lower fuel energy (LHV) and therefore plant performance remains unchanged.

$$\eta_{plant} = \frac{P_{net} + Q_{FW} + Cool}{\dot{m}_{fuel} \cdot LHV_{fuel}} \quad (1)$$

$$\eta_{plant} = \frac{P_{net}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \quad (2)$$

Conclusions

- The electrical efficiency of the plant is about 34% with a net power of 145 kW.
- Connecting the absorption chiller and seawater desalination systems in parallel as bottoming cycle for the fuel cell plant then freshwater and cooling productions will be about 180 liter/hour and 145 kW respectively when waste heat from SOFC plant divides equally between AC and DCMD plants.
- The suggested designs offer the possibility to regulate freshwater and cooling productions after demand.
- Effect production (electricity, cooling and freshwater) depends on the moisture of the feed waste while plant total efficiencies (electrical and energy) does not change significantly.

Thank you for your attention.