Yearly performance of a cogeneration system with nanofluid-based thermal photovoltaic coupled to a heat pump

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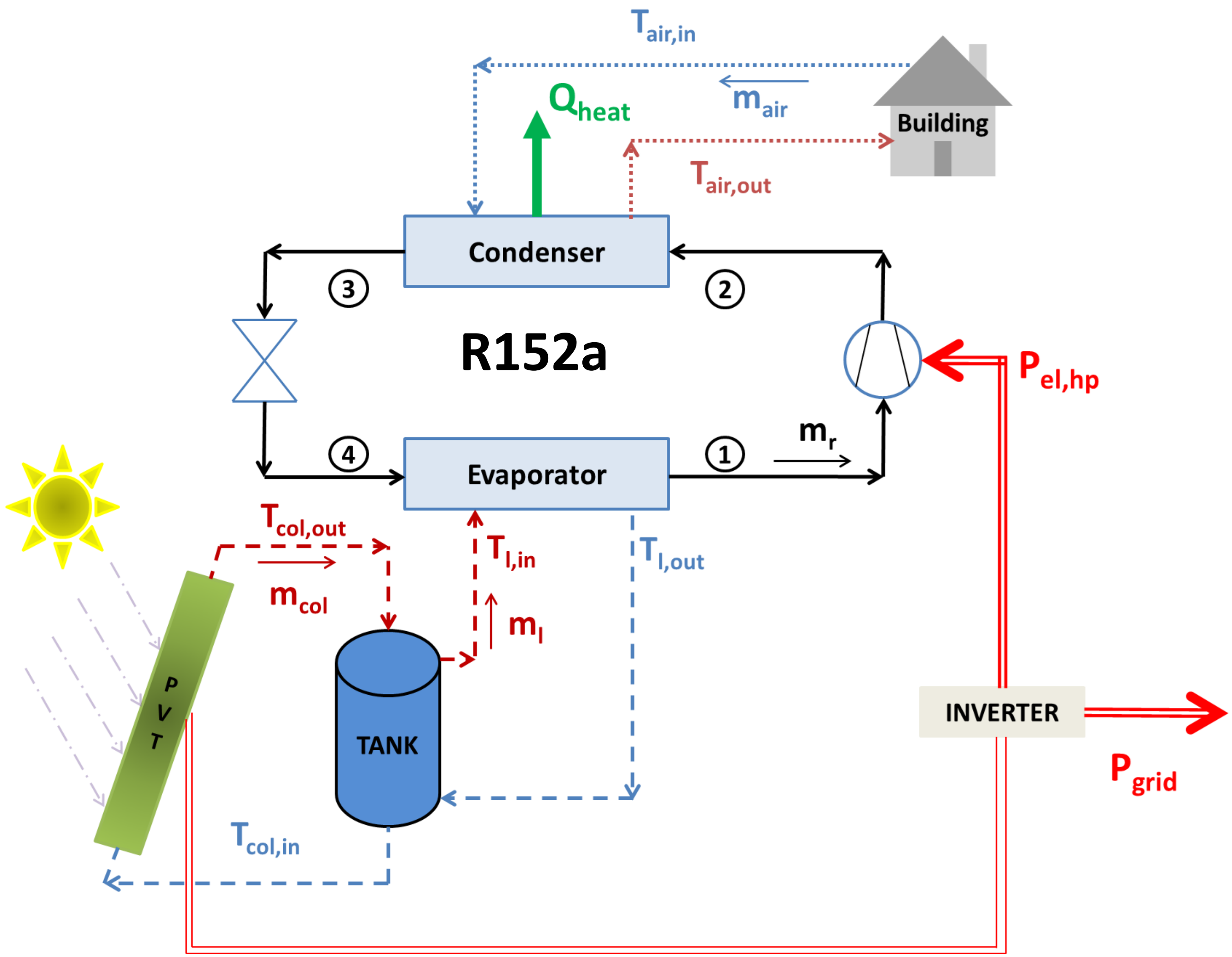
The examined system



The examined solar collector

Parameters	Values
Collector aperture (A_{col})	2 m^2
Volumetric flow rate (V_{col})	2 L/min
Collector length (L)	1.916 m
Number of water tubes (N_r)	10 tubes
Inner tube diameter (d_{in})	$7.72 \cdot 10^{-3}$ m
Outer tube diameter (d_{out})	$9.52 \cdot 10^{-3}$ m
Cover transmittance (τ)	0.83
Plate absorbance (α)	0.95
Cover emittance (ε_c)	0.88
Plate emittance (ε_p)	0.93
Reference efficiency of PV (η_{ref})	0.173
Packing factor (PF)	0.804
Reference temperature (T_{ref})	298 K
Reference temperature coefficient of PV (b)	0.00405 K^{-1}
Insulation layer thickness (L_{ins})	0.03 m
Collector slope (β_{col})	45^o
Insulation thermal conductivity (k_{ins})	0.034 W/mK

The examined nanofluid (water/Cu – 2%vol.)

Nanoparticle	Density	Specific heat capacity	Thermal conductivity
Cu	8933 kg/m^3	397 J/kgK	393 W/mK

Nanofluid density

$$\rho_{nf} = \varphi \cdot \rho_{np} + (1-\varphi) \cdot \rho_{bf}$$

Nanofluid specific heat capacity

$$c_{p,nf} = \frac{\varphi \cdot \rho_{np} \cdot c_{p,np} + (1-\varphi) \cdot \rho_{bf} \cdot c_{pbf}}{\rho_{nf}}$$

Nanofluid thermal conductivity

$$k_{nf} = k_{np} \cdot (1 + 4.4 \cdot Re_d \cdot {}^{0.66}\mathrm{Pr} \cdot \left[\frac{T+273}{273}\right]^{10} \cdot \left[\frac{k_{np}}{k_{bf}}\right]^{0.03} \cdot \varphi^{0.66})$$

Nanofluid dynamic viscosity

$$\mu_{nf} = \mu_{np} \cdot \left(1 - 34.87 \cdot \left[\frac{d_f}{d_p}\right]^{0.3} \cdot \varphi^{1.03}\right)^{-1}$$

Nanofluid Nusselt number

$$\mathrm{Nu} = 0.4328 \cdot (1 + 11.285 \cdot \varphi^{0.754} \cdot [\mathrm{Re_d} \cdot \mathrm{Pr}]^{0.218}) \cdot \mathrm{Re}^{0.333} \cdot \mathrm{Pr}^{0.4}$$

Mathematical modeling

Collector thermal efficiency:

$$\eta_{th} = \frac{Q_u}{Q_s}$$

Collector electrical efficiency:

$$\eta_{el} = \frac{P_{el}}{Q_s}$$

Storage tank energy balance:

$$Q_{st} = Q_u + Q_{loss} - Q_{load}$$

Compressor isentropic efficiency:

$$\eta_{is} = 0.874 - 0.0135 \cdot (\pi_c)$$

Net electricity production:

$$P_{grid} = \eta_{inv} \cdot P_{el} - P_{el,hp}$$

Heat pump COP:

$$COP_{hp} = \frac{Q_{heat}}{Q_e}$$

System energy efficiency:

$$\eta_{en} = \frac{Q_{heat} + P_{grid}}{Q_{s,t}}$$

System energy efficiency:

$$\eta_{ex} = \frac{Q_{heat} \cdot (1 - \frac{T_o}{T_{air}}) + P_{grid}}{Q_{s,t} \cdot (1 - \frac{4}{3} \cdot \left(\frac{T_o}{T_{sun}}\right) + \frac{1}{3} \cdot \left(\frac{T_o}{T_{sun}}\right)^4]}$$

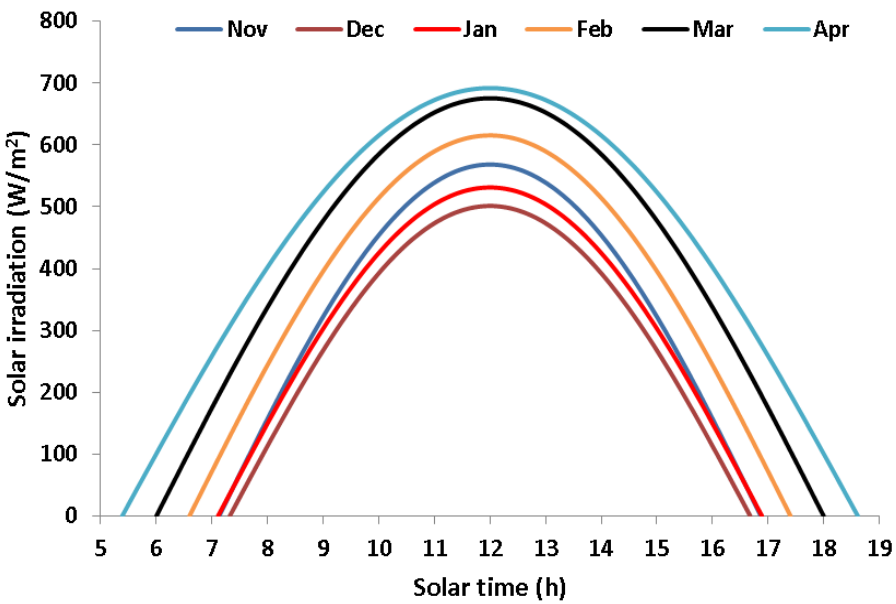
Methods – System parameters

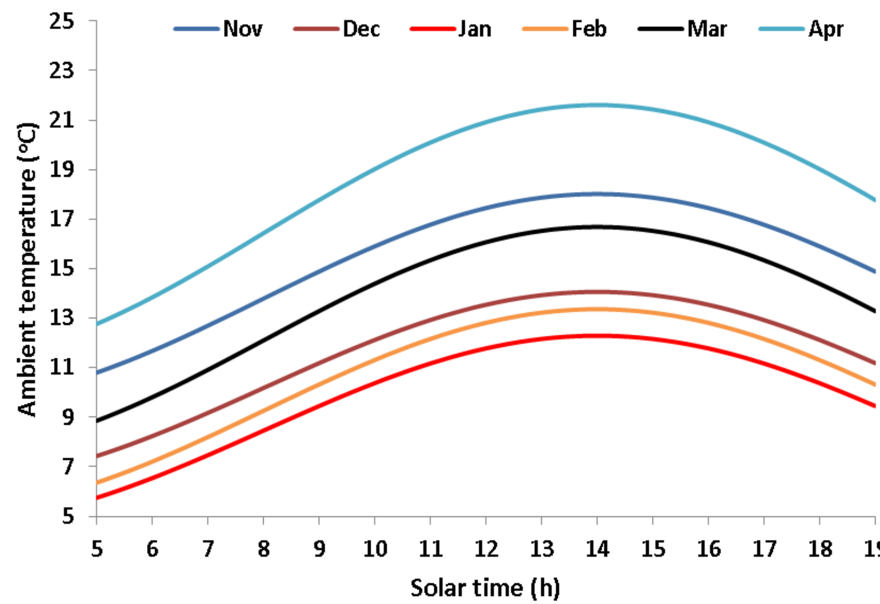
Parameter	Symbol	Value
Total collecting area	$A_{col,t}$	20 m^2
Storage tank volume	V_T	1 m^3
Tank thermal loss coefficient	U_T	0.5 W m^{-2} K^{-1}
Inverter efficiency	η_{inv}	90%
Compressor shaft efficiency	η_{com}	85%
Overall heat transfer coefficient in the condenser	$(UA)_{con}$	1 kW m^{-2} K^{-1}
Evaporator heat exchanger - tube diameter	dt_{ube}	0.01 m
Evaporator heat exchanger - coil diameter	d_{coil}	0.1 m
Evaporator heat exchanger - coil length	L_{coil}	12 m
Inlet air temperature	$T_{air,in}$	20°C
Outlet air temperature (calculated)	$T_{air,out}$	~30°C
Condenser temperature	T_c	35°C
Nominal solar irradiation	G_T	800 W m^{-2}
Nominal ambient temperature	T_{am}	10°C
Reference temperature	T_o	298.15 K
Sun temperature	T_{sun}	5770 K

The analysis is conducted with a developed model in Engineering Equation Solver (EES).

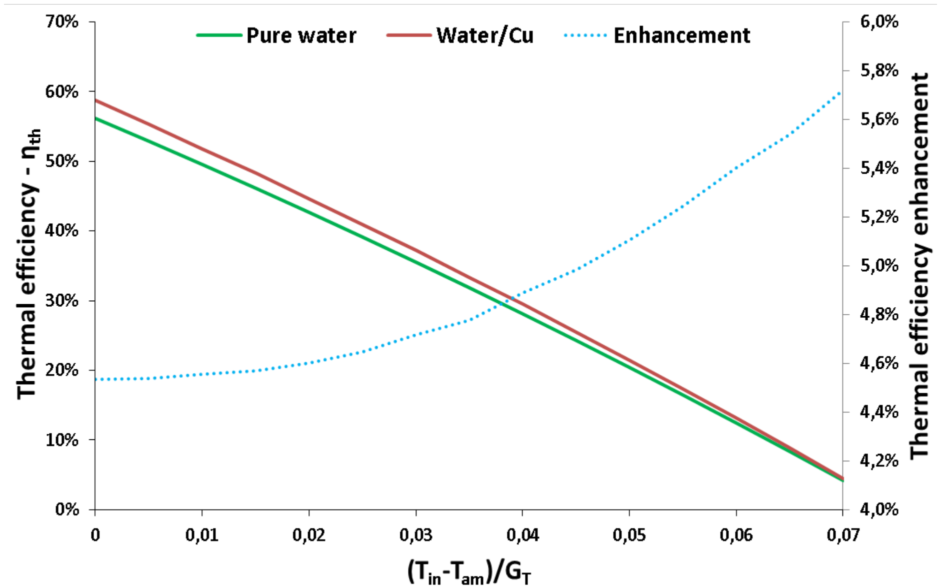
Methods – Weather data

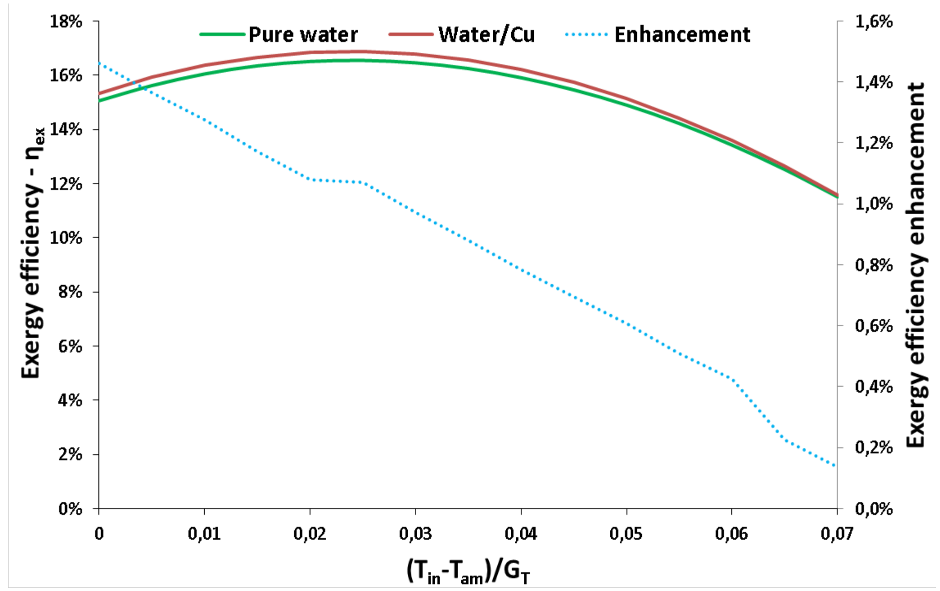
The weather data regard the location of Athens (Greece) for the winter period.





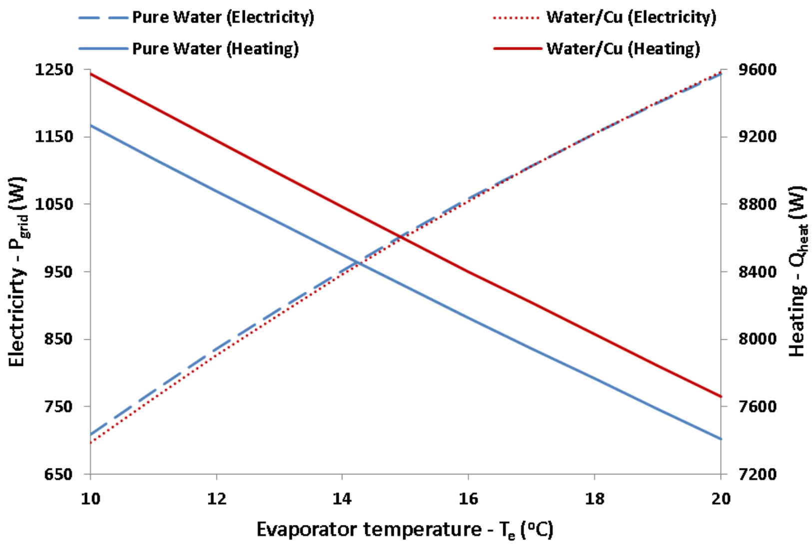
Results -Steady-state analysis (solar collector performance)

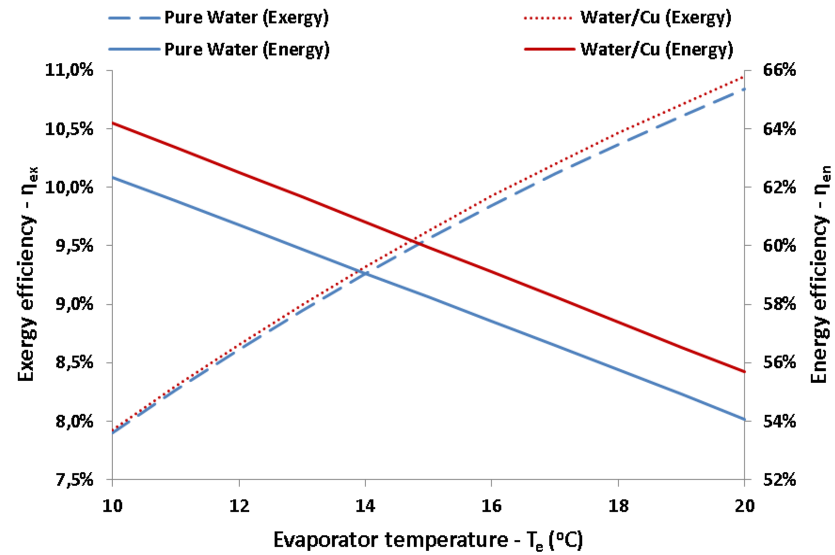


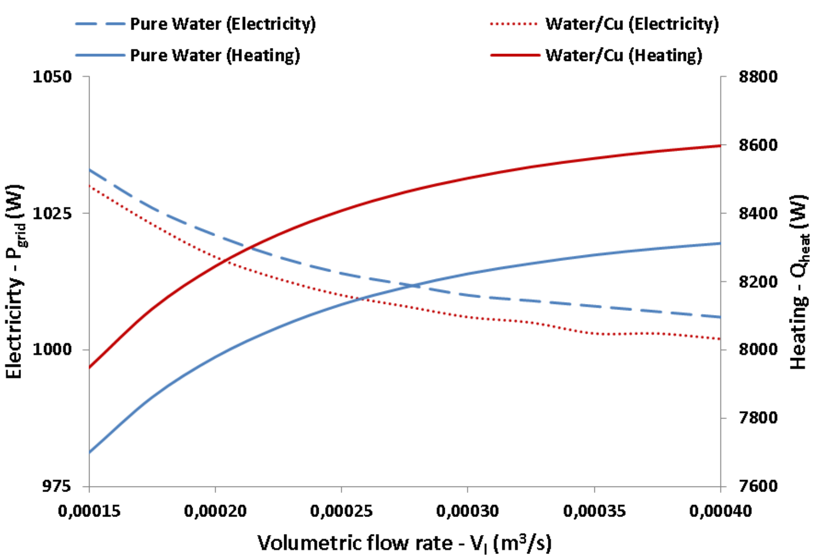


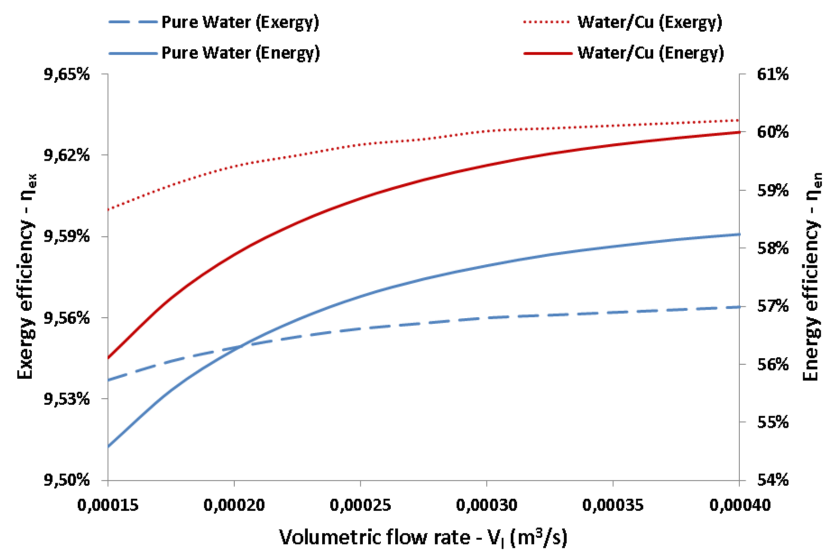
The results indicate that there is an enhancement in both useful outputs. The enhancement of the thermal efficiency is higher (around 5%) than the enhancement of the electrical efficiency which is close to 1%.

Results - Steady-state analysis (parametric analysis)

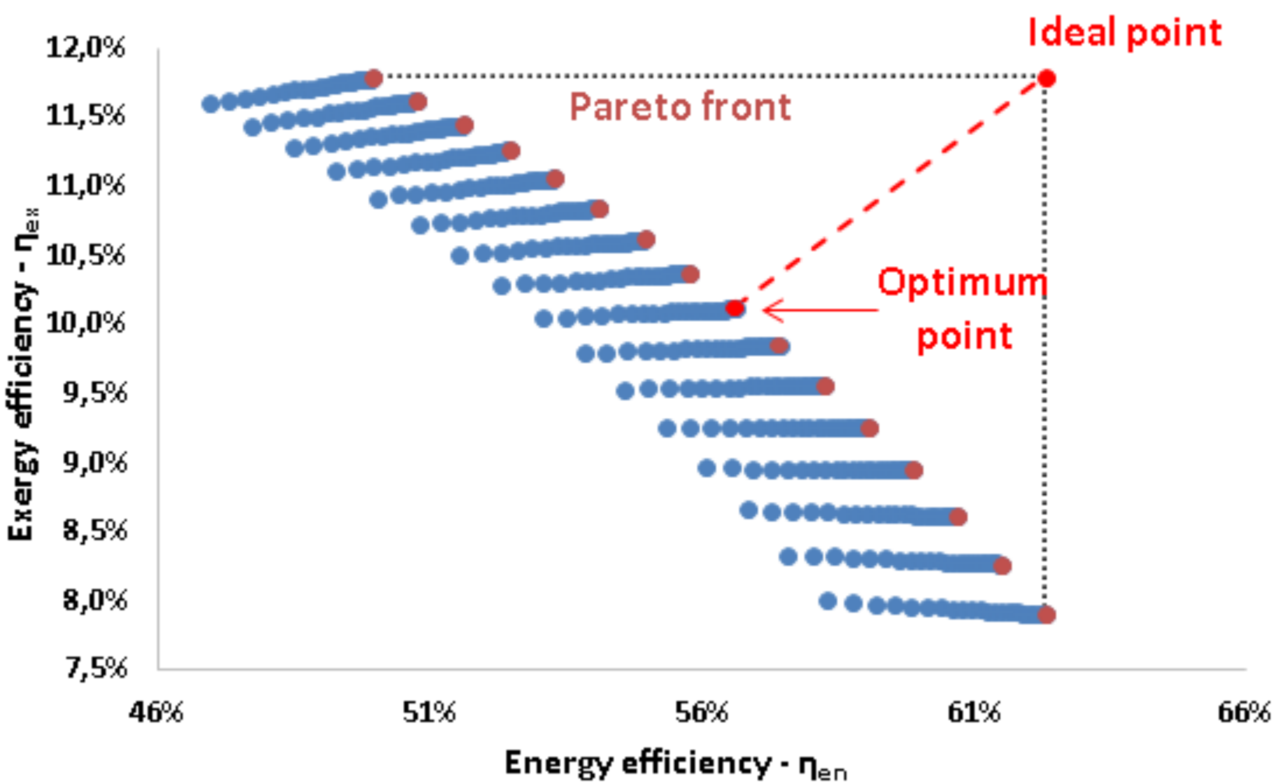






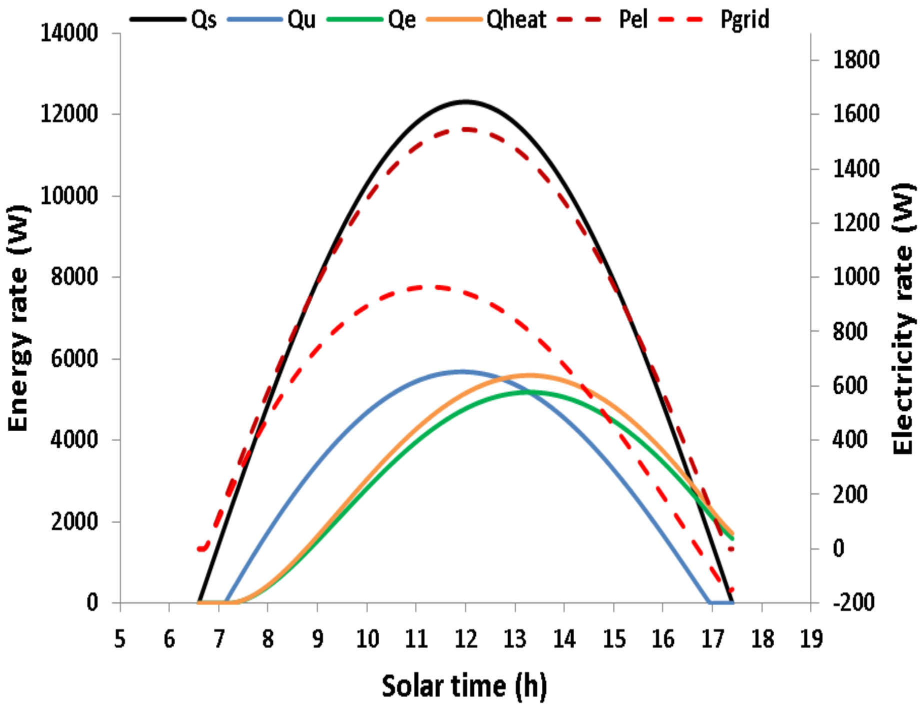


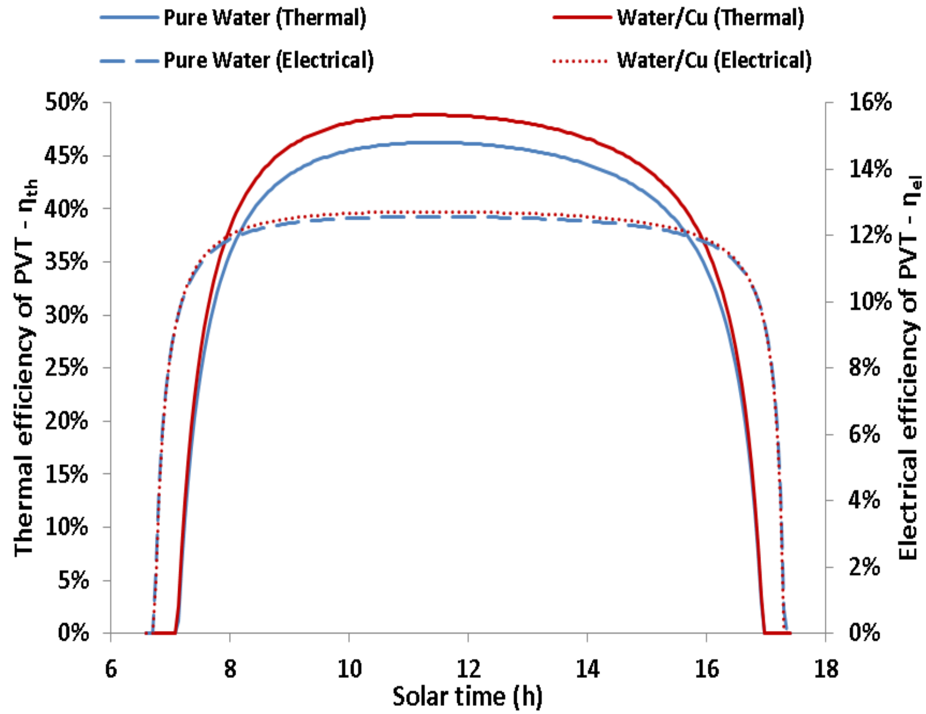
Results - Steady-state analysis (Multi-objective optimization)



The optimum case has 17°C evaporator temperature, 0.0004 m^3/s flow rate, while the grid production and the heating production are 1108 W and 7948 W respectively. The energy efficiency is 56.60% and the exergy efficiency is 10.12%.

Results - Dynamic analysis (Typical day of February)

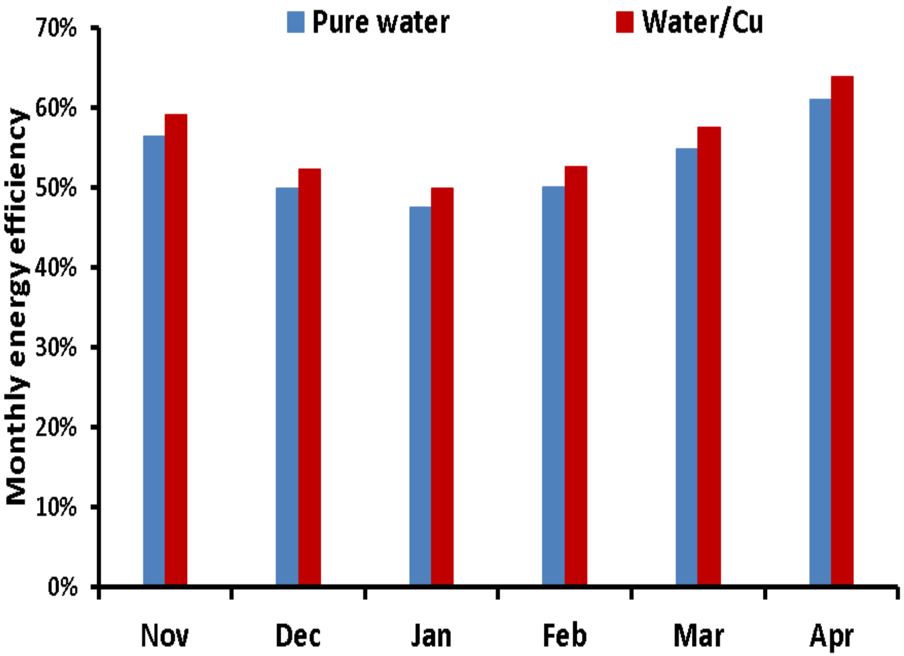


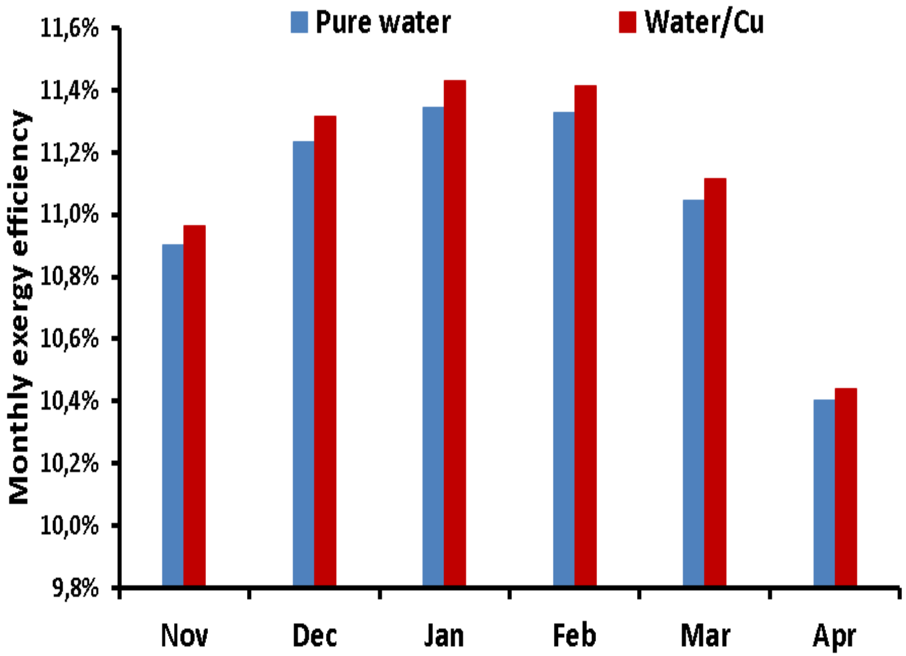


The heating production is maximized about two hours later than the solar noon because of the existence of the storage tank. Also, during the last hours of the day, the system consumes electrical energy from the grid.

There is an important increase in energy efficiency with the nanofluid and a small increase in electricity production.

Results - Dynamic analysis (monthly results)





The results prove that the use of nanofluid is beneficial in all cases. The months with the highest electric efficiency are November and April, while the maximum exergy efficiency is obtained in January and February.

Results - Summary

Month	Pure water				Water/Cu			
	E_{heat} (kWh)	E_{grid} (kWh)	η_{en} (%)	η_{ex} (%)	E_{heat} (kWh)	E_{grid} (kWh)	η_{en} (%)	η_{ex} (%)
Nov	34.5	5.1	56.48	10.90	36.5	5.0	59.17	10.96
Dec	25.3	4.4	49.88	11.24	26.8	4.4	52.34	11.32
Jan	26.4	4.9	47.52	11.34	28.0	4.8	49.90	11.43
Feb	36.1	6.2	50.17	11.33	38.3	6.1	52.63	11.42
Mar	49.0	7.4	54.91	11.05	51.8	7.3	57.53	11.12
Apr	62.7	8.1	61.06	10.41	66.1	8.0	63.88	10.44
Year	7020	1082	54.18	11.11	7423	1068	56.78	11.19
Deviation (%)	-	-	-	-	5.75	-1.38	4.80	0.66

The energy efficiency is enhanced by 4.80% on a yearly basis while the exergy efficiency of 0.66%. The heating production is enhanced by 5.75% while there is a reduction in the grid electricity production by about 1.75%.

The use of nanofluids increases the heating production so higher work is needed in the compressor and this is the reason for the grid electricity production. However, both energy and exergy efficiencies are enhanced and so the total system performance is improved with the use of nanofluid.

Conclusions

In this work, a cogeneration system with thermal photovoltaics and the heat pump is examined. This system produces space-heating and net electricity. Moreover, the use of water/Cu nanofluid in the solar collector is examined. The analysis is conducted in Engineering Equation Solver in steady-state conditions and on a daily basis. The most important conclusions of this study are summarized below:

- The use of nanofluid in the PVT enhances both the thermal and the electrical production.
- The heating production of the system is enhanced, while the electricity production is reduced. The reason for the lower grid electricity production is based on the greater compressor demand for electricity due to the higher heating load production with the nanofluid.
- The yearly system energy efficiency is enhanced by 4.80% and the exergy efficiency is enhanced by 0.66%. These enhancements prove that the overall system is improved with the use of nanofluids.
- The heating production is maximized round two hours later than the solar noon.

In the end, it has to be stated that the use of nanofluids makes the system generally more efficient. However, the application faces difficulties because of the high cost of them and due to the stability problems. So, a lot of research has to be made before the nanofluids to be made a reliable choice for real applications.

Future research

- **Investigation of other nanofluids, for example with MWCNT.**

- **Investigation of concentrating thermal photovoltaic systems.**

- **Investigation of heat pumps with environmentally friendly refrigerants such as CO_2.**

- **Optimization of the system with realistic building loads.**

- **Experimental investigation of solar-driven heat pumps and nanofluids.**

Thank you very much for your attention!

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