ACKNOWLEDGEMENT

"I am Carthikswami Sunil Thoniparambil declaring that this solution represents my individual work with no outside help. I will not share questions and solutions with anyone else until my instructors gives me explicit permission to do so."

SIGNATURE

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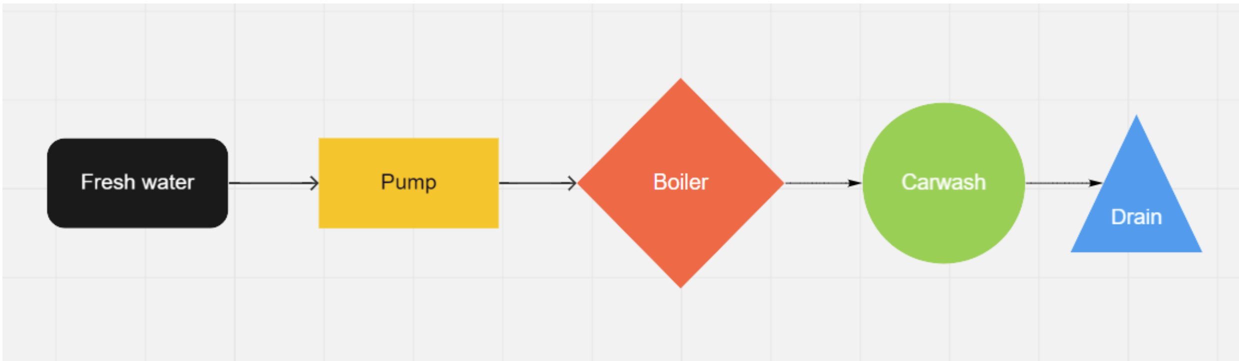


Fig1. Flow chart of system

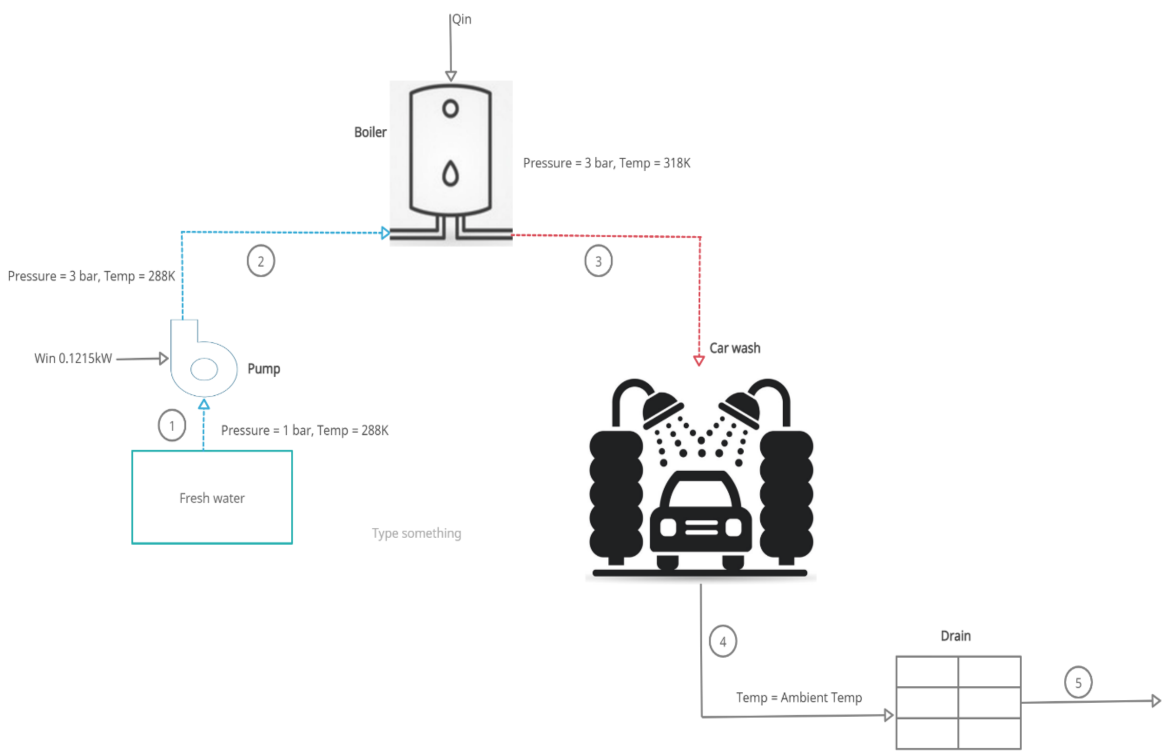


Fig 2. System diagram

Introduction

The aim of the project is to analyze a car wash based on two heating options.

a. Natural gas
b. Solar thermal collector

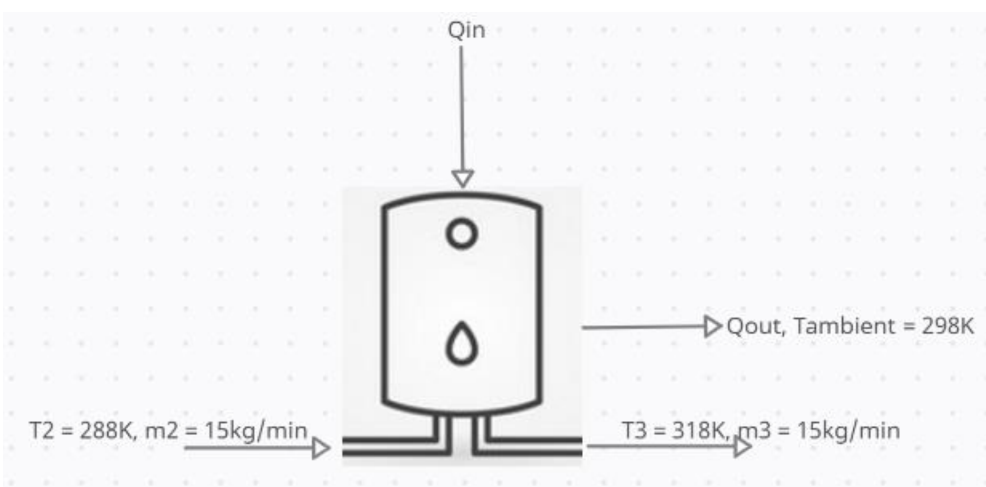
The system I must analyze washes 400 cars per day. There are 10 lanes present and washes 10 cars a time for 40 times. It requires 150L/10min to wash a car. After the analysis I must decide which is a better option both with respect to cost as we as for the environment.

For natural gas

1. Heat and power required

   Here the calculations are done for 10 lanes and 10 cars are being washed at once for 10 minutes this is simultaneously continued for 40 times, and this leads us to 400 minutes of working time.

   Hence 15kg/min is mass flow rate for 1 lane and here I am considering 150kg/min for the 10 lanes.



Electrical power needed = Pump power + 5kW

Power required by pump = (Volume flow rate * Pressure drop)/Efficiency

= ((39.626gallon/minute*2bar)/0.85)*6.3W

Pump power needed = 0.595kW

Electrical power needed = 5.595kW

Using energy balance for pump we get,

$$\Delta E = W_{in} - W_{out} + Q_{in} - Q_{out}$$

$$\Delta E = \Delta KE + \Delta PE + \Delta CE + \Delta U \text{ [Only change in internal energy]}$$

$$\Delta U = W_{in}$$

$$m*c_w*(T2 - T1) = W_{in}$$

$$150kg/min*4.182kJ/kgK*(T2 - 288K) = 0.595kW$$

$$T2 - 288K = 0.595kW/(2.5kg/s*4.182kJ/kgK)$$

$$\mathbf{T2 = 288.056K}$$

Using energy balance for boiler, we get

$$W_{in} + Q_{in} + \sum mi(h + KE + PE + CE)_i = W_{out} + Q_{out} + \sum mo(h + KE + PE + CE)_o$$

$$W_{in} + Q_{in} + + \sum mi\ (h_i) = Q_{out} + \sum mo(h_o) \ldots\ldots\ldots\ldots\ldots (1)$$

$$m_i = m_o = m \ldots\ldots\ldots (2)$$

$$W_{in} + Q_{in} = E_{in} \ldots\ldots\ldots (3)$$

Substituting (2) and (3) in equation (1), we get

$$E_{in} = m*(h3 - h2) + Q_{out}$$

$$Q_{out} = h_{out}A_{out}(T_{st} - T_o)$$

$$R_{Total} = 1/\ h_{out}A_{out} = 0.834K/W \text{ (Assuming)}$$

$$Q_{out} = (T_{st} - T_o)/R_{Total}$$

$$= (318K - 298K)/0.834K/W$$

$$Q_{out} = 23.98W$$

$$E_{in} = m*(h_3 – h_2) + Q_{out} = m*c_p*(T_3 – T_2) + Q_{out}$$

$$= 150kg/min*4.182kJ/kgK*(318K – 288.056K) + 23.98W$$

$$E_{in} = 18783.8712kJ/min + 23.98W$$

$$= 18783.8712kJ/min + 1.4388kJ/min$$

$$\mathbf{E_{in} = 18766.491kJ/min}$$

The above E_{in} is for 10 lanes and to was 10 cars per minute. Hence multiplying it with the time needed to wash we get the total Ein for washing 10 cars each time in all the 10 lanes combined. This means that every round where the 10 cars are lined up the boiler must be supplied with this much heat.

$$\text{For 10 minutes} = E_{in}*10min$$

$$\mathbf{E_{in}\ for\ 10\ minutes = 187664.91kJ\ or\ 187.664MJ}$$

2. <u>Exergy destruction</u>

Flow exergy for each inlet/exit state carrying water

$$e_f = (h - h_o) – T_o(s – s_o) +0.5v^2 + gz + ce$$

Assuming water is incompressible

$$h – h_o = c_w*(T – T_o) + v(p – p_o)$$

$$s – s_o = c_w*ln(T/T_o)$$

$$e_f = c_w*[(T – T_o) – T_oln(T/T_o)] + v(p – p_o)$$

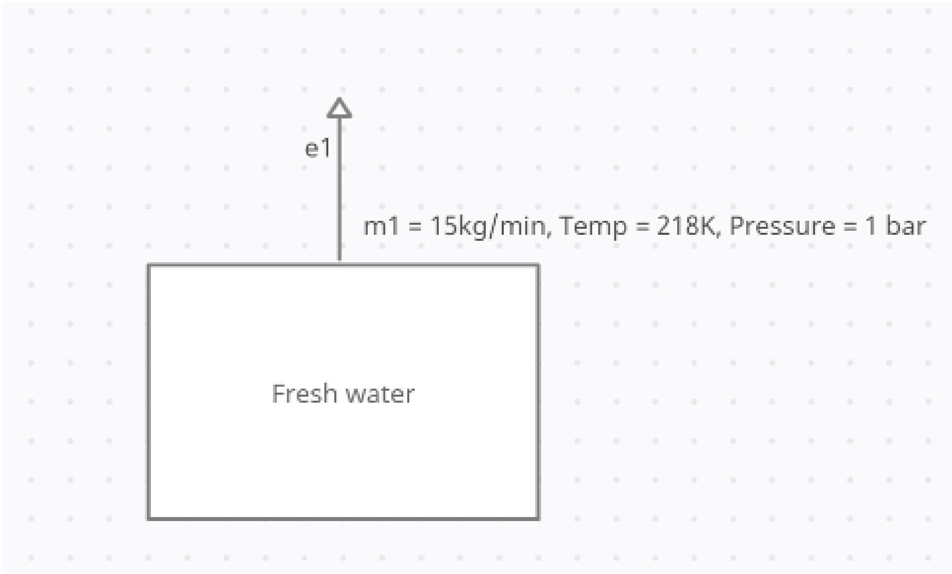
For ground water

$$T_o = 298K \text{ and } T_1 = 288K$$

$$p = p_o = 1bar$$

$$e_1 = 4.182kJ/kgK*[(15 – 25)K – 298K*ln(288K/298K)]$$

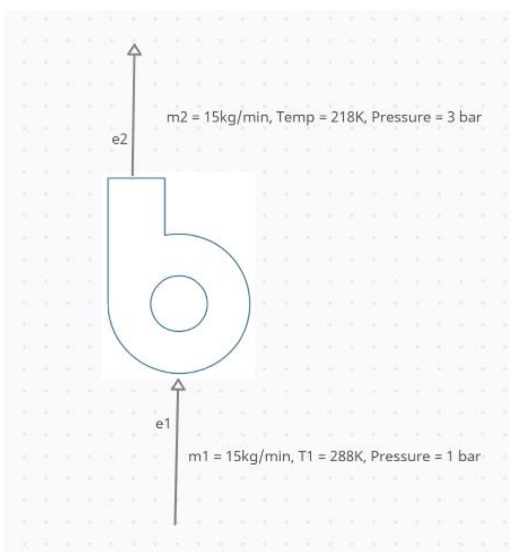
$$\mathbf{e_1 = 0.7177\ kJ/kg}$$



For pump

$$p_o = 1\text{bar and } p_1 = 3\text{bar}$$

$$T_o = 298\text{K and } T_2 = 288.056\text{K}$$



$$e_2 = 4.182\text{kJ/kgK}*[(15.056\text{K} – 25)\text{K} – 298\text{K}*\ln(288.086\text{K}/298\text{K})] + 1.005\text{L/kg}*(3 – 1)\text{bar}$$

$$= 0.7098\text{kJ/kg} + 0.2\text{kJ/kg (Converting Lbar/kg to kJ/kg)}$$

$$\mathbf{e_2 = 0.9098\ kJ/kg}$$

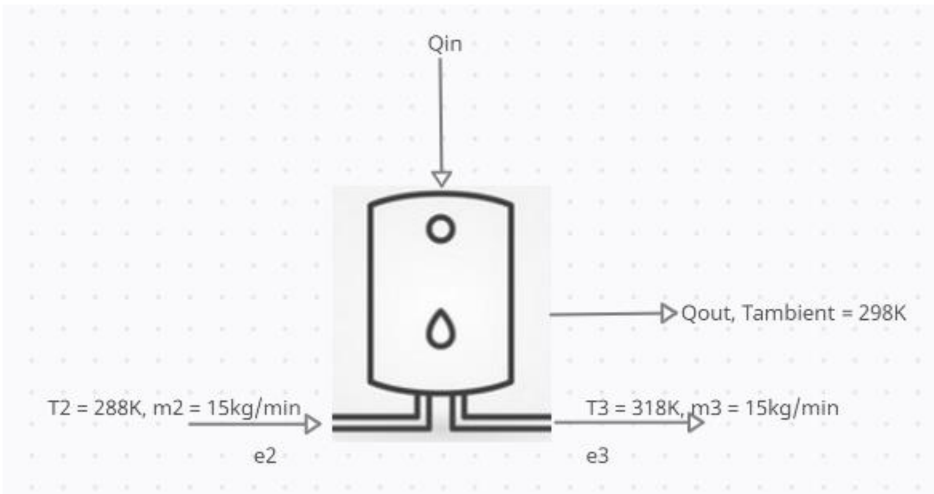
For Boiler/Storage

$$p_o = 1\text{bar and } p_1 = 3\text{bar}$$

$$T_o = 298\text{K and } T_3 = 318\text{K}$$

$e_3 = 4.182\text{kJ/kgK}*[(45 – 25)\text{K} – 298\text{K}*\ln(318\text{K}/298\text{K})] + 1.005\text{L/kg}*(3 – 1)\text{bar}$

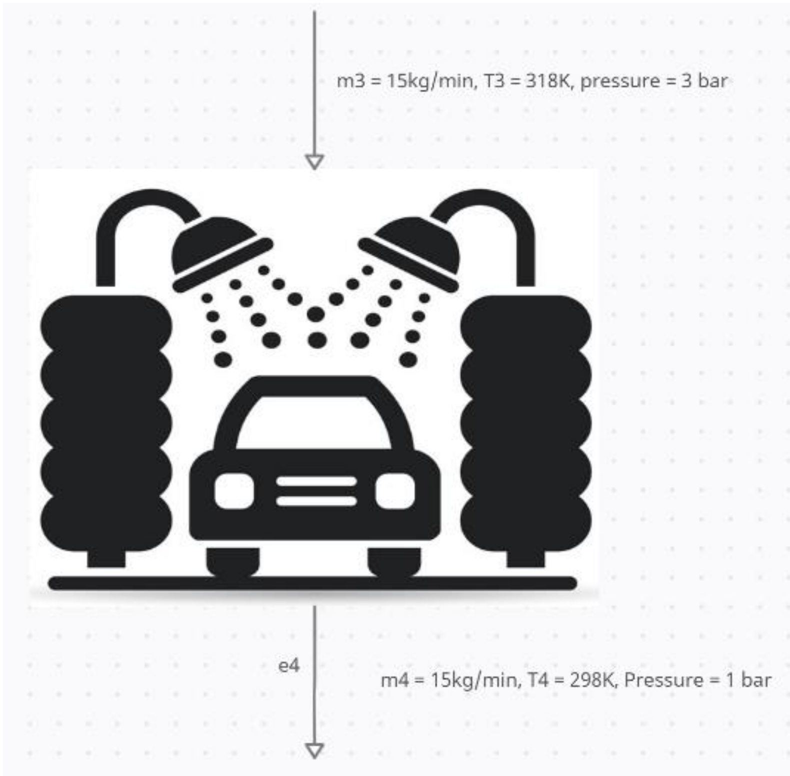
$$\mathbf{e_3 = 2.887kJ/kg}$$



For car wash

$$p_o = p_1 = 1bar$$

$$T_o = 298K \text{ and } T_4 = 318K$$



$$e_4 = 4.182kJ/kgK*[(45 – 25)K – 298K*ln(318K/298K)]$$

$$\mathbf{e_4 = 2.687kJ/kg}$$

For drain

$$e_5 = c_w*(T_6 – T_o) – T_o*ln(T_6/T_o)$$

Here at some point of time the temperature of the water reaches the same as ambient temperature

$$T_6 = T_o$$

Therefore

$$\mathbf{e_5 = 0}$$

Exergy destruction in the boiler

$$\text{Exergy destroyed} = (1-(T_o/T_{in}))*Q_{in} + m_3*(e_2 - e_3)$$

$$(1 - (298K/2230K))*18766.491kJ/min + 150kg/min(0.9098 - 2.887)kJ/kg$$

$$= 16258.68kJ/min - 296.58kJ/min$$

Exergy destroyed = 15962.1kJ/min

Exergy destroyed for 10 minutes

Exergy destroyed = 159621kJ 0r 159.62MJ

Exergy destruction in car wash

$$\text{Exergy destruction} = m*[e_5 - e_6]$$

$$= 150kg/min*[2.687kJ/kg - 0]$$

Exergy destruction = 403.05kJ/min

Exergy destroyed for 10 minutes

Exergy destruction = 4030.5kJ

Exergy destruction in pump

$$m*(e1 - e2) + Win$$

$$150kg/min*(0.7177 - 0.9098)kJ/kg + 35.7kJ/min$$

Exergy destroyed= 6.88kJ/min

Exergy destroyed for 10 minutes

Exergy destruction = 68.8kJ/min

5. Exergetic efficiencies

Exergetic efficiency = Useful exergy output/Required input

For car wash

Exergetic efficiency = 0%

Since there in no useful exergy output and hence exergetic efficiency 0%

For Pump

Exergetic efficiency = m_2*e_2/(m_1*e_1 + W_{in})

= ((150kg/min*0.9098kJ/kg)/(150kg/min*0.7177kJ/kg) + 35.7kJ/min)

Exergetic efficiency = 95.1%

For Boiler/Storage

(m_3*(e_3 – e_2))/(Eq_{in} + W_{in}))

Eq_{in} = (1 – T_o/T_{in})*Q_{in}

= (1 – 298K/2230K)*18766.491kJ/min

Eq_{in} = 16258.681kJ/min

Exergetic efficiency = 150kg/min*(2.887kJ/kg – 0.9098kJ/kg)/(16258.681kJ/min + 0)

Exergetic efficiency = 1.82%

For the entire system

Exergetic efficiency = (E_5 – E_1)/(Eq_{in} + Ew_{in})

= (me_5 – me_1)/(Eq_{in} + Ew_{in})

= (150kg/min*2.687kJ/min)/(16258.681 + 35.7)kJ/min

Exergetic efficiency = 1.99%

4. Yearly CO2 production

For the boiler

$$CH_4 + a(O_2 + 3.76N_2) = bCO_2 + cH_2O + dN_2$$

n in Reactant	n in Products	
C	B	b = 1
H	2c	c = 2
O	2b+c	a = 2
N	2d	d = 7.52

$$CH_4 + 2O_2 + 7.52N_2 = CO_2 + 2H_2O + 7.52N_2$$

1CH_4 in reactants = 1CO_2 in the products

M_{CH4} = 16.04g/mol MCO$_2$ = 44.01g/mol

(1 mol CH_4) (16.04g/mol CH_4) (1 mol CO_2) (44.1g/mol CO_2)

$$m_{CO2}/m_{CH4} = 2.743kg_{CO2}/kg_{CH4}$$

$$mCH_4/m_{ng} = 1$$

Therefore, we get

$$mCH_4/m_{ng} = 2.743kg_{CO2}/kg_{ng}$$

This means that burning 1 mole of natural gas gives 2.743kg of CO_2

Heating value of natural gas is = 55.5MJ/kg

Thermal efficiency of the boiler = 90%

$$m_{CO2}/W_{ng} = m_{CO2}/m_{ng}/\eta_{ng}HV_{ng} = 2.743kg_{CO2}/0.9*(55.5MJ/kg_{ng})$$

$$= 0.055kg_{CO2}/MJ$$

CO_2 for 1 wash = 0.055kg_{CO2}/MJ *187.664MJ = 10.3213kg_{CO2}

CO_2 for 400 washes/per day = 10.321kg_{CO2}*40 = 415.852 kg_{CO2}

CO_2 production per year = 415.852kg_{CO2}*360

CO_2 production per year = 148626.72kg_{CO2}/year

For the Utility

Total power needed by car wash = 5.595kW

The car wash operation time = 400 minutes

CO_2 produced = 5.595kW*(400/60hrs)*360

= 13428kWh

From the above energy needed only 90% comes natural gas therefore

= 13428*0.9kWh

Energy from natural gas = 12085.2kWh

Assuming plant efficiency is 50%

CO_2 production per year by the utility = $m_{CO2}/W_{ng} = m_{CO2}/m_{ng}/\eta_{ng}HV_{ng}$ = $2.743kg_{CO2}/0.5*(55.5MJ/kg_{ng})$

= $0.366kg_{CO2}$/kWh * 12085.2kWh

CO_2 production per year by the utility = **$4423.1832kg_{CO2}$**

Total CO_2 production = $148626.72kg_{CO2}$/year + $4423.1832kg_{CO2}$/year

Total CO_2 production = 153049.9032kgCO_2/year

5. <u>Thermoeconomic cost</u>

Natural gas

$c_{wash} = (c_{gw}*m_{gw}*e_1*\Delta t_{w,year}) + Z_{ST} + Z_{pump}/(m_w*e_4*\Delta t_{w,year})$

$\Delta t_{w,year} = \Delta t_w$*no.of wash*$n_{days}$

= 10min*40*360

$\Delta t_{w,year}$ = 144000min/year

$$\text{Total water cost} = \text{Cost of ground water} + \text{Cost of drain water}$$

$$= \$2.591/m^3 + \$3.639/m^3$$

$$\text{Total water cost} = \$6.23/m^3$$

$$\text{Cost of water} = \$6.23/m^3 * 1.005 L/kg * (1m^3/10^3 L)$$

$$\text{Cost of water} = \$0.00626/kg$$

$$c_{gw} = \text{Cost of water} = 0.00626kg/0.7177kJ/kg = \$0.0087/kJ$$

$$\text{Cost of water used} = \$0.0087/kJ*150kg/min*0.7177kJ/kg*144000min$$

Cost of water = **$134870.184/year**

The cost of furnace from the question is given to be 27000$ and assuming a interest rate of 8% and the life span of the boiler to be 15 years we get.

$Z_{furnace}$ = (Rate*1+interest)^n/n = $27000*(1.08)^{15}/15 = **$5709.9/year**

The cost of furnace from the question is given to be 1600$ and assuming a interest rate of 8% and the life span of the boiler to be 7.5 years we get.

Z_{pump} = (Rate*1+interest)^n/n = $1600*(1.08$^{7.5}$)/7.5 = **$379.9/year**

$$\text{Exergy cost of natural gas} = c_o = Cost_{ng}*(1-T_o/T_{input})$$

$$Cost_{ng} = \$0.52/kg$$

Burning 1kg of natural gas gives 55.55MJ of energy

$$Cost_{ng}/MJ = \$0.52/55.55MJ = \$0.0093/MJ$$

$$c_Q = \$0.0093/MJ*(1 – 298K/2230K)$$

c_Q = **$0.0081/MJ**

Maintenance cost/year for natural gas = $0.005/kWh

E_{in} = 18766.491kJ/min = 312.77kW

No. of operating hours = 400minutes/60 = 6.67hrs

Ein for 6.67hrs for 360 days per year = 751023.324kWh

Maintenance cost per year = 751023.324kWh*$0.005/kWh

Maintenance cost per year = **$3755.116/year**

c_w = $5709.9/year + $379.9/year + $134870.14/year + $3755.116/year + ($0.0081/10^3kJ*16528.681kJ/min*144000)/(150kg/min*2.687kJ/kgK*144000min/year)

c_{SH} =$0.00281/kJ

Exergy needed per wash E = 150kg/min*2.686kJ/kg*10min

E = 403.05kJ

Cost of one wash = C_w*E

= $0.002709/kJ*403.05kJ

Cost of one wash = **$1.13/wash**

For Solar thermal Collector

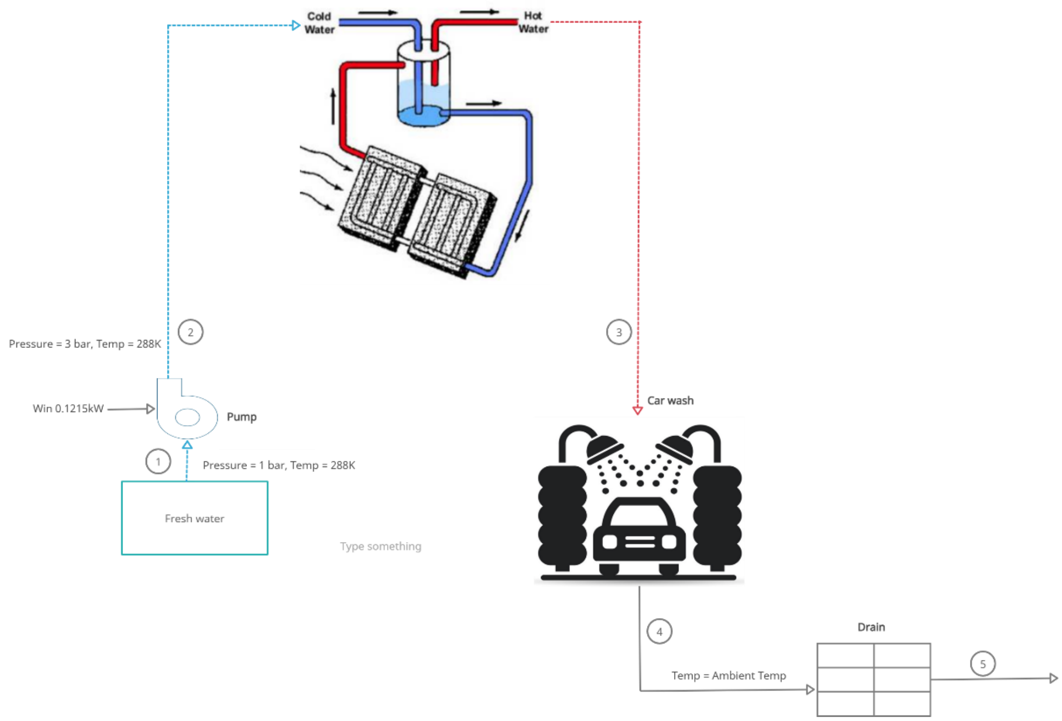


Fig 3. Alternate Solution

$$I_{sol} = 543W/m^2$$

$$\Delta t_{sol} = 10hrs$$

$$Efficiency = 13\%$$

$$Q_{sh} = Q_{coll} = Efficiency * Q_{sol} = Efficiency * A_{coll} * Q_{sol}$$

$$A_{coll} = Qsh/Efficiency * Q_{coll}$$

$$A_{coll} = 312.77kW/(0.13*0.543kW/m^2)$$

$$A_{coll} = 4430m^2$$

Instead of matching demand with incident solar energy, we will consider solar energy saved throughout the day.

$$\int Qshdt = A_{coll} \int_0^{\Delta tsol} Efficiency * Isoldt$$

$$Q_{sh} = Efficiency * I_{sol} * A_{coll} * \Delta t_{sol}$$

$$A_{coll} = Q_{sh}/Efficiency*I_{sol}*\Delta t_{sol}$$

$$= (187.664MJ*(1kWh/3.6MJ)/0.13*0.543kW/m^2*10hr/day)*40washes$$

$$A_{coll} = \mathbf{2953.89m^2}$$

The above area of collector is multiplied with 40 because as considering earlier 187.664MJ is the energy needed for 10 lanes to wash 10 cars and hence 40 times this is repeated and hence multiplying with 40 to get the total area needed for the entire operation.

Exergy destruction

$$\text{Exergy destroyed} = W_{in} + m_3*(e_2 - e_3)$$

$$W_{in} = I_{sol}*Area$$

$$= 0.543kW/m^2*(2953.89m^2)$$

$$W_{in} = 1603.96kW = 96237.6kJ/min$$

$$\text{Exergy destroyed} = 96237.6kJ/min + 150kg/min*(0.9098 - 2.887)kJ/kg$$

Exergy destroyed = 35941.02kJ/min

Exergy destroyed for 10 minutes

Exergy destroyed = 359410.2 or 359.410MJ

Exergetic efficiency

$$\text{Exergy efficiency} = (m_3*(e_3 - e_2))/(W_{in}))$$

$$= (150kg/min*(2.887 - 0.9098)kJ/kg)/96237.6kJ/min$$

$$\text{Exergy efficiency} = 0.3\%$$

Thermoeconomic cost

While doing thermo economic cost I am not considering the land cost needed as it would not be a fair comparison as it would off set the price of the solar connector by a lot. The first thermoeconomic cost is without the land area.

Assuming that there is a maximum allowable temperature drop of 2K in the tank $\Delta T = 2K$

Energy balance for storage tank during wash is given by

$$\Delta E_{ST} = E_{start} - E_{stop} = \sum Qin - \sum Qout + \sum Win - \sum Wout$$

$$\Delta U_{ST} = \sum Qin - \sum Qout = (\int Qcoll - Qw)dt$$

$$\Delta U_{ST} = (Q_{coll} - Q_w)*\Delta t_w$$

$$\Delta U_{ST} = m_{ST}*c_{ST}*(-\Delta T_{ST}) \text{ [-ve sign as temperature is decreasing]}$$

$$m_{ST} = (Q_w - Q_{coll})\ \Delta t_w/c_{ST}\Delta T$$

$$Q_{coll} = \text{Efficiency}*A_{coll}*I_{sol}$$

$$= 0.13*2953.89m^2*0.543kW/m^2$$

$$Q_{coll} = 208.51kW$$

$$m_{ST} = (312.77kW - 208.51kW)*10min*60s/4.182kJ/kgK*5K$$

$$m_{ST} = 7479.19kg$$

$$V_{ST} = m_{ST}*v_{ST}$$

$$= 7479.19kg*1.005L/kg$$

$$m_{ST} = 7516.59L \text{ or } 4627.23 \text{ gallons}$$

$$c_{gw} = \text{Cost of water}/e_1 = 0.00624/0.7177 = \$0.0087/kg$$

Cost of water used = \$0.0087/kg*15kg*0.7177*144000min

Cost of water = \$134870.184/year

Cost of 4700-gallon tank = 4946\$ [1]

$$Z_{ST} = (\text{Rate}*(1+\text{interest}))^n/n = \$4946*1.08^{15}/15$$

Z_{ST} = \$1045/year

Collector cost for 1.88m^2 = \$4500

No. of collectors = 2953.89m^2/1.88m^2 = 1571 collectors

Z_{coll} = (Rate*1+interest)^n/n = 1571*4500*1.08$^{`15}$/15 = \$1,495,043/year

Z_{pump} = (Rate*1+interest)^n/n = \$1600*(1.08$^{7.5}$)/7.5 = **\$379.9/year**

C_w = \$1045/year+\$1,495,043/year + \$134870.184/year + \$379.9/year/(150kg/min*2.687KJ/min*144000min)

C_w = \$0.028/kJ

Energy needed per wash = 150kg/min*2.686kJ/kg*10min

E = 403.05kJ

Cost of one wash = C_w*E

= \$0.028/kJ*403.05kJ

Cost of one wash = **\$11.23/wash**

Cost when including subsidy, there is a one-time tax credit of 15% which brings down the annual payment to the bank to be,

Z'_{coll} = (1571*4500 – 1571*4500*0.15)*1.08^{15}/15 = \$1,270,786/year

Cw = \$1045/year+\$1270786/year + \$134870.184/year + \$379.9/year/(150kg/min*2.687KJ/min*144000min)

C_w = \$0.024/kJ

Energy needed per wash = 150kg/min*2.687kJ/kg*10min

E = 403.05kJ

Cost of one wash = C_w*E

= \$0.024/kJ*403.05kJ

Cost of one wash = **$9.77/wash**

<u>Summary</u>

After calculations the values came out to be

System	Cost per wash	CO_2 Production
Natural gas	$1.13/wash	134870.184_{kgCO_2}/year
Solar collector (no subsidy)	$11.23/wash	Nil
Solar collector (with subsidy)	$9.77/wash	Nil

The cost per wash with natural gas is very less when compared with solar thermal even with subsidy as shown in the table above. The increase in cost is mainly attributed to the cost of the solar panel which as per question is $4500 for 1.88m^2. The number of collectors needed is 1571 and hence there is a need for an initial investment of $7 million. This is the main reason why the cost per wash by solar collector is way more than that of natural gas. On the other hand, the solar collector does have an advantage when you take the yearly CO_2 production. The natural gas produces 134870.184_{kgCO_2} whereas the solar collector apart from the Co_2 during its manufacturing process produces NIL CO_2.

When you look profit wise natural gas is way better but when you look environment wise the solar collector is the better option. I suggest the car wash can be made better with the adoption of a cogeneration system using both the natural gas and the solar collector to make profit as well be environment friendly at the same time. This is because even if the solar collector alternative where to be adopted by the car wash the amount of land area needed is to wash 400 cars per day is going to 2953.89m^2. This is a massive area of land and is going to need a huge investment especially in Boston, Massachusetts area. Hence it is not viable to select the solar collector alternative on its own. Hence the cogeneration system is a better alternative as of the present.

Land analysis

For an area of $2400m^2$

The cost comes up to be around $3,750,000 [2]

If there is land tax credit of $\$5/m^2$ and the interest is still 8% and when we also consider a one-time federal tax credit of 15% and a 15-year life time the cost per car wash comes out to be

$$\text{The cost of land} = (\$3,750,000 – 5*2400m^2) = \$3,738,000$$

$$Z_{land} = (3,738,000*1.08^{15})/15) = \$790,504/year$$

The cost per wash =

$$c_w = \$1045/year+\$1270786/year + \$134870.184/year + \$379.9/year + \$790,504/year/(150kg/min*2.687KJ/min*144000min)$$

$$c_w = \$15.26/wash$$

References

[1] Plasticmart.com [shopping site]

[2] Zillow.com [Online land area finder]