Engineering Thermodynamic and Heat Transfer MSE 321

Project I: Sustainable Heating System for Residential Buildings

Assigned date: Oct. 2019 Due date: Nov. 29, 2019

Notes:
The project should be completed individually.

The report should be typed and be accompanied with a CD including your code. It should not exceed 11 pages, appendices extra, if needed.

Please redirect your questions to TAs

Total mark is 100, which is 10% of your final mark. Innovative ideas or engineering recommendations have 10 bonus marks.

Introduction

Recently significant attention has been paid to the development of Smart Energy Management Systems (SEMS) for buildings. SEMS typically include a Smart Heating System (SHS). The objective of SEMS is to reduce the energy consumption in buildings to such a level that Net Zero Energy conditions can be achieved by using renewable energies. Net Zero Energy Buildings are highly energy efficient buildings that use renewable energy to produce at least as much energy as they consume over the course of a year. The first step to achieve net zero energy is to implement a highly-insulated, well-sealed building envelope. Highly energy efficient heating and cooling systems, such as sophisticated heat pump systems, smart lighting and appliances are then incorporated, and through implementation of SEMS, create a net zero energy ready building with over 80% reduction in annual energy consumption compared to conventional buildings. The remaining energy required will be generated by renewable energies such as photovoltaic (PV) solar panel systems, or solar hot water/air systems. Net zero energy buildings are connected to the electrical grid with a metering arrangement, so that power can flow either to or from the building depending on its energy consumption and production levels.

Project

It is intended to heat a house during the cold season. The house is to be maintained at $20°C$ (can be considered as a high temperature thermal reservoir) at all times. The heat transfer rate (heat loss) through the walls and the roof of the house can be estimated from:

$$\dot{Q}_{Loss} = UA(T_{Inside} - T_{Outside}) \tag{1}$$

where, A is the walls and roof surface area and U can be interpreted as the overall effective heat conductance of the house. For the house in this project, let's consider UA as a constant and equal to 0.7 $[kW/K]$. For a typical 24-hour period, the outside temperature can be assumed to vary as shown in Table 1.

Table 1: Assumed daily ambient temperature variation in cold season

Time Period	12:00am-6:00am	6:00am-12:00pm	12:00pm-6:00pm	6:00pm-12:00am
$T_{Outside}$	-5°C	2°C	7°C	0°C

Three different scenarios are proposed for heating the house:

I- Conventional electrical heater,

II- Heat pump, and

III- Heat pump in combination with photovoltaic (PV) solar panels and thermal energy storage. This is an emerging method for Net Zero Energy Buildings.

Your task as a design engineer is to calculate primary energy consumption reduction, the capital and annual costs associated with each scenario, annual carbon dioxide (CO_2) emissions, and recommend the most appropriate or optimal design for this house. You should provide detailed calculations and technical argument to convince your client.

The impact of an energy technology on the climate can be characterized by its carbon emission intensity, a measure of the amount of CO_2 or CO_2 equivalent emitted per unit of energy generated. Existing fossil fuel technologies possess high carbon emission intensity through the combustion of carbon rich fuels, while renewable technologies such as PV produce little or no emissions during operation, but may incur emissions during manufacture. The carbon intensity of primary electrical energy varies greatly depending on fuel source and is summarized in Table 2.

Table 2: Estimates for carbon dioxide emissions from various sources used for electricity generation

Source	Carbon dioxide emissions [g of CO_2/kWh]
Coal	1,000
Hydro	50
Nuclear	30

Consider three different provinces in Canada and compare the annual CO_2 emissions for each scenario:

British Columbia: Hydro

Alberta: Coal

Ontario: Nuclear

Assume that heating is needed for *8 months* (*30 days* each) per year.

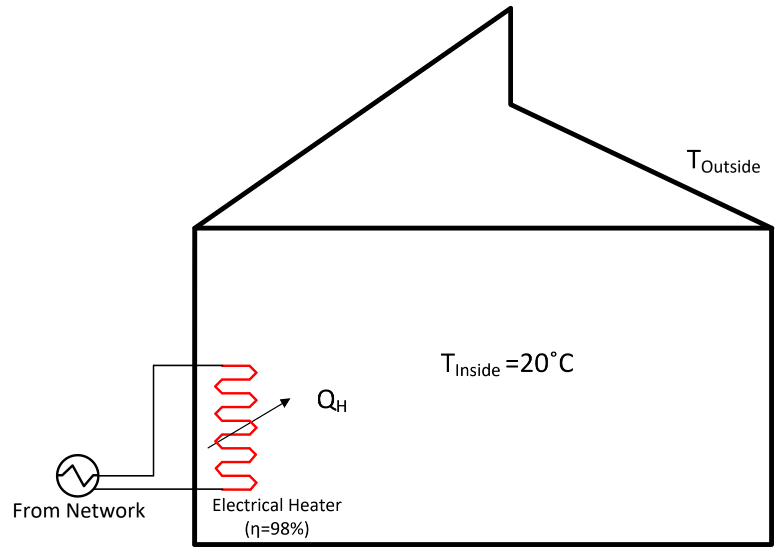

Figure 1: Schematic of scenario I

Scenario I: Electrical Heater

Electrical heater will be used and the required power will be purchased from the electric grid network, see Fig. 1. Note the required heat, to keep the inside temperature at *20˚C,* is equal to the heat loss from the house, which should be calculated using the ambient temperature profile given in Table 1, and Eq. (1). Consider the electrical efficiency of the heaters 98%.

Suggestions for calculations:

a) Prepare a table and a plot to show the energy consumption,

b) Use $\$0.08/kWh$, for electricity cost to estimate the annual cost for heating, and

c) Electrical heater capital cost: $\$150/kW$.

Scenario II: Heat Pump

A heat pump can be used to heat up the house; the electrical power needed for the compressor will be purchased from the network, see Fig. 2.

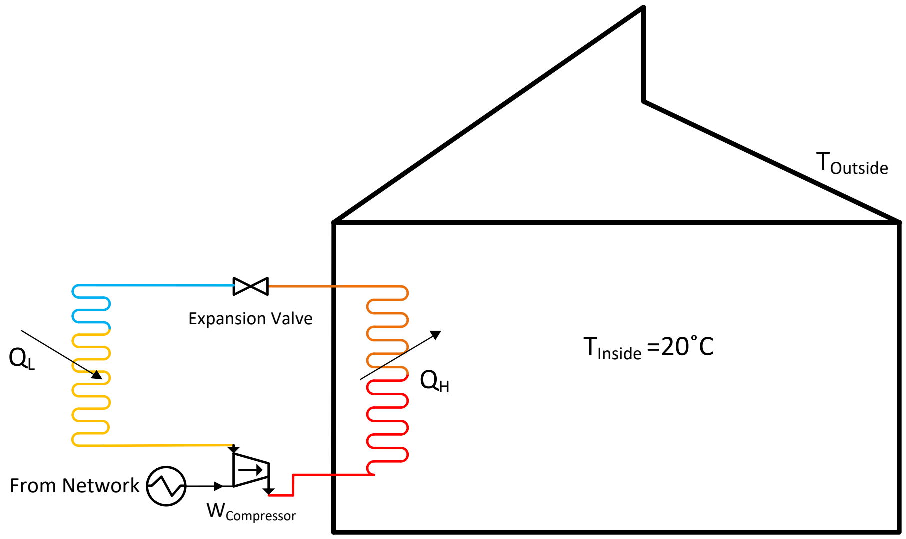

Figure 2: Schematic of scenario II, using a heat pump

The efficiency of a heat pump is expressed in terms of the coefficient of performance (COP), and it is assumed to be 70% of its maximum possible value, i.e. the COP of a Carnot cycle working between the two thermal reservoirs ($\eta_{HP} = 0.7\eta_{Carnot}$).

Suggestions for calculations:

a) Prepare a table and a plot to show the energy consumption,

b) Use $\$0.08/kWh$, for electricity cost to estimate the annual cost for heating, and

c) Estimate the capital costs of a heat pump installation for the house. Assume a heat pump system cost approximately $\$2{,}000/kW$.

Scenario III: Solar Panel, Heat Pump and Thermal Energy Storage System (SHS)

The proposed system includes PV solar panels to generate electricity and waste heat, thermal energy storage (TES) tank, and heat pump. The electricity generated by the PV will be fed into the heat pump when the system works. The excess generation will be sold to the network; electricity will be purchased from the network when the generation is less than consumption. The PV system can only convert up to 17% of the incoming solar energy to electricity and the rest will be converted to low-grade thermal energy or waste heat (and stored at TES at T~10 °C). In order to maintain a desirable and steady-state operating temperature, the PV panels should be cooled down. This waste-heat is significant (almost 80% of the total incoming solar energy). The proposed SHS takes advantage of this energy by storing it in a TES that is filled with a phase change material (PCM), which is used as low-temperature thermal reservoir of the heat pump, see Fig. 3.

Heat pump COP will increase significantly when the temperature difference between low temperature and high temperature thermal reservoirs is minimized. With this in mind, we need to select a proper phase change material, and an optimum size (amount) for the TES system to improve the COP of the proposed SHS. For the design purpose, let's assume an efficiency of $\eta_{PV} = 17\%$ for the PV panels. We can also assume that 30% of the heat produced by the solar panels is lost to the ambient as it is transferred from the PV panels to the TES tank. The solar gain for the house can be assumed constant and at a rate of $0.5\ kw/m^2$. In Fig. 3, you can neglect the work needed by the pump, compared to the compressor work.

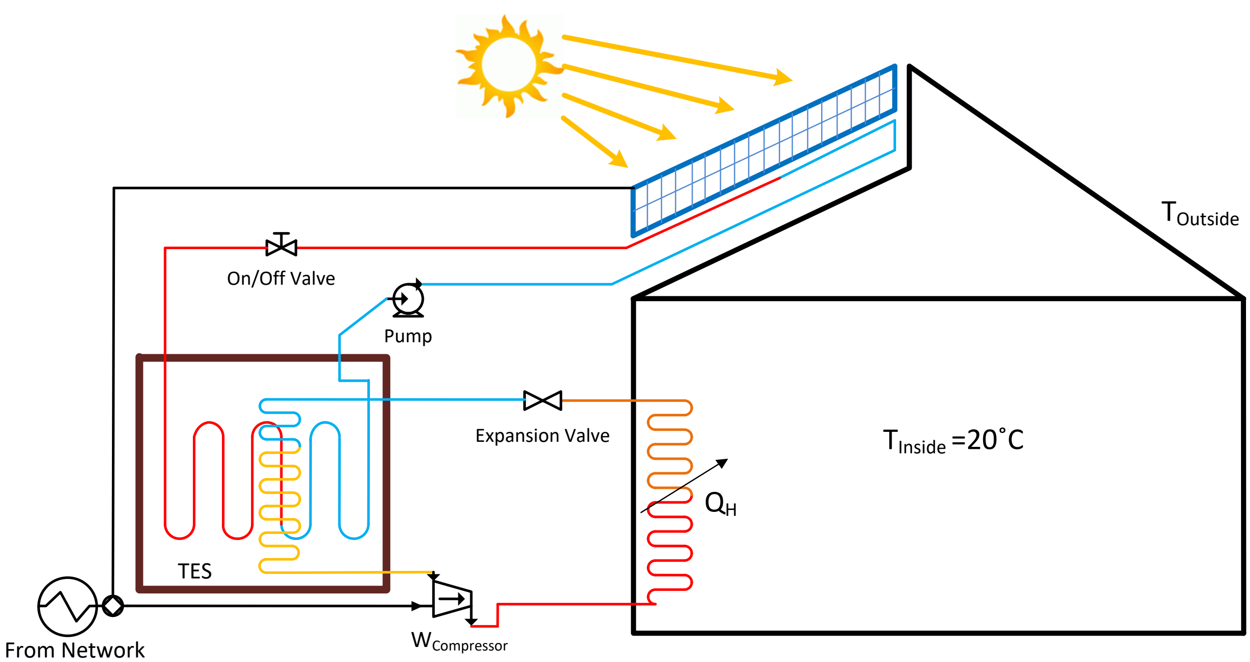

Figure 3: Schematic of scenario III, Solar Panel, Heat Pump and Thermal Energy Storage System

PlusICE, an industrial PCM, with physical and thermal properties shown in Table 3 should be used in the TES calculations and optimization.

Table 3: physical properties of PlusICE PCM

PCM type	Melting point (T_m)	Latent heat capacity (h_{sl})	Density (ρ)
Hydrated Salt S10	10 [°*C*]	155 [*kJ/kg*]	1,470 [kg/m^3]

To find the optimum design, you should compute the TES tank size, electricity consumption, capital cost, and operating (electricity) costs for SHS with PV panels with area ranging from $20m^2$ to $120\ m^2$, with a $10m^2$increment.

Suggestions for calculations:

a) Electricity price: $\$0.08/kWh$; the extra electricity will be sold to the network at the same rate.

b) PV panels initial cost: $\$100/m^2$

c) The PCM price: $\$4/kg$

d) The manufacturing/installation costs of TES tank and heat exchanger: $\$450/m^3$

e) Heat pump system capital costs: $\$2{,}000/kW$

Your report should include both tabular and graphical results. Provide at least 4 different graphs, as shown in Fig. 4, in your report. Choose one or two highest ranked scenario(s), based on your engineering judgment and justify your selection(s). Provide detail engineering recommendations.

Useful Equations

To calculate the thermal energy required to maintain the inside temperature:

$$\dot{Q}_H = \dot{Q}_{Loss} = UA(T_{Inside} - T_{Outside}) \tag{1}$$

For the power needed to heat the house:

$$\dot{W}_e = \frac{\dot{Q}_H}{\eta_{Electrical}} \quad [kW] \tag{2}$$

Heat pump COP:

$$COP_{Heat\ Pump} = \frac{\dot{Q}_H}{\dot{W}_{Comp.}} = 0.7\left(\frac{1}{1-\left(\frac{T_L}{T_H}\right)}\right) \tag{3}$$

Annual CO_2 emissions (kg/year) =
CO_2 emissions for technology (kg/kWh) × Annual electricity consumption (kWh/year) (4)

Annual electricity consumption (kWh/year) =
Supplied electricity power (kW) × Annual operational hours (h/year) (5)

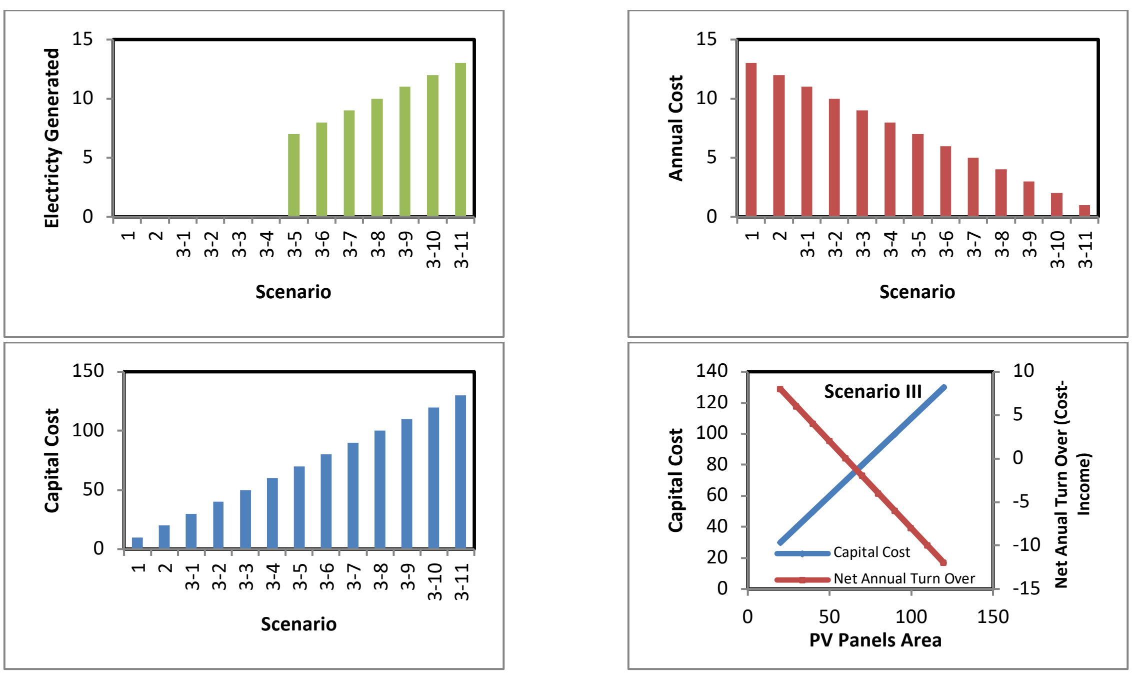

Figure 4: Example graphs needed to be included in final report (The values and trends are not real)

Hints:

a) The capacity that you choose for the heating system should be equal to or greater than the highest load, when a safety factor is considered.

b) The solar energy is available for 12 hours per day (6 am to 6 pm), and the given specific solar energy is an average value over the entire cold season.