The Bartlett School of Environment, Energy and Resources

MSc SBDE Title Page

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Coursework Title: Performance Analysis of Building Systems Components

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I certify that all additional assistance which I have received is indicated and referenced in the report.

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In the case of coursework that is submitted late and is also over length, then the greater of the two penalties shall apply. This includes research projects, dissertations and final reports.

Contents

Project 1 – Analysis of a vapour compression system

Introduction

Background

A frozen food processing factory located in Barcelona, Spain currently employs a single stage vapour compression system with outdated R12 refrigerant to keep the food in cold environment.

Aim

The aim of this task is to analyse possible upgrade scenarios, calculate COP's for refrigeration cycles and evaluate: single stage compression system and cascade compression system with two more environmentally friendly refrigerants (R404A, R134a) to answer appointed questions from the client.

Approach

Novel tools can accelerate design process and reduce the burden of repetitive tasks. Even if tools were validated it is important to check the results as these tools are not always entirely resistant to human errors. Mixed methodology of standard engineering approach with the use of self-build script is presented.

Methodology

Assumptions

- Ambient temperature, $T_{ambient} = 35°C$
- Cold room temperature, $T_{cold\ room} = -15°C$
- Evaporation temperature, $T_e = -25°C$
- Condensation temperature, $T_c = 50°C$
- Peak capacity, $Q_{41} = 20$ kW
- Phase change in heat exchanger happens at about the same temperature, $T_{c\_low} \approx T_{e\_high}$

Methodology is composed of 5 parts:

1. Understanding circuits and thermodynamic processes.

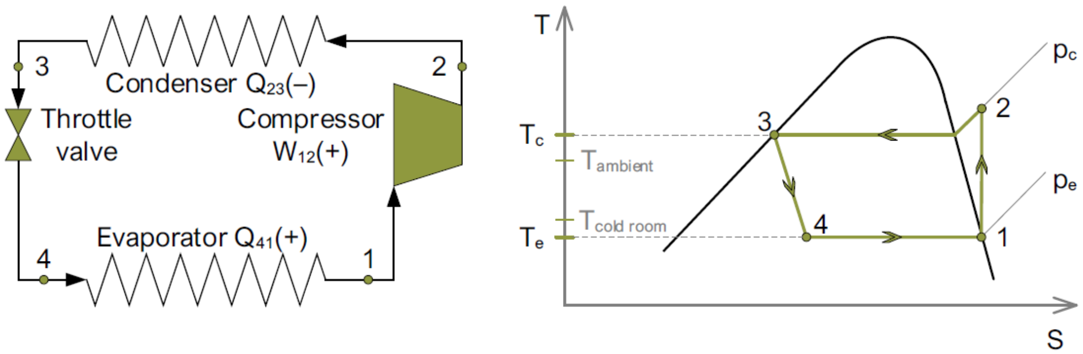


Figure 1 - Single stage vapour compression system [Brief]

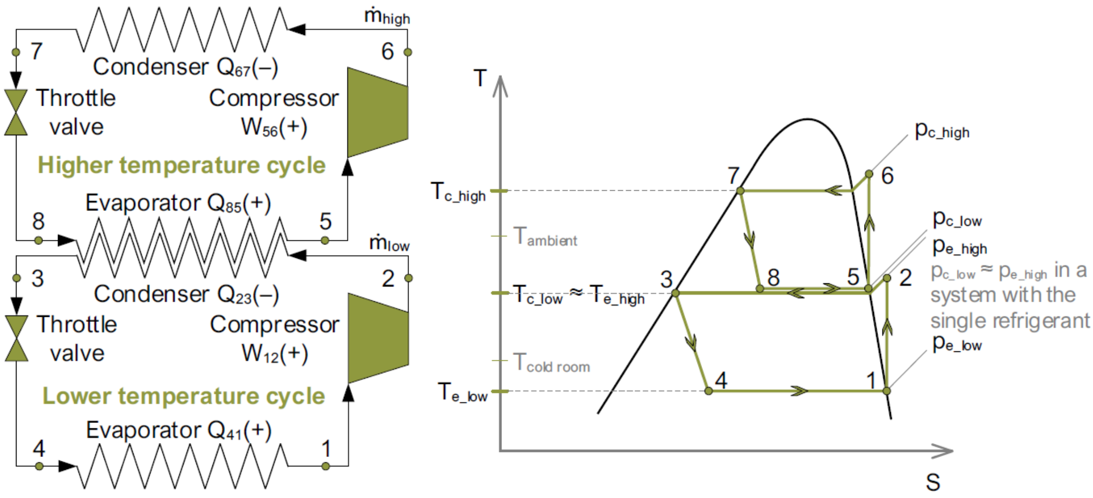


Figure 2 - Cascade vapour compression system [Brief]

2. Drawing single stage process on R404A P-h diagram for future value validation [appendix 1]
3. Creation of a python definitions developed with the use of Google Colaboratory [5] for faster prototyping and script development. As a source of fluid properties CoolProp library [6] was used.
    a. Single stage definition outputs COP with fluid type as an input

```
def COP(fluid):
  #definition for single stage cycle
  #fluid used in the cycle
  ...
  return q41/w12 #COP
```

    b. Cascade system definition outputs COP for lower temperature fluid, higher temperature fluid and intermediate temperature for heat exchanger between loops as an input.

```
def COP2(fluid1,fluid2,tint):
  #definition for cascade system
  #fluid1 lower temperature cycle
  #fluid2 higher temperature cycle
  #tint intermediate temperature
  ...
  return Q41/(W12+W56) #COP
```

CoolProp PropsSI function can output many properties based on this simple exemplar formula.

```
enthalpy = PropsSI('H', 'T', 298.15, 'P', 101325, 'R404A')
```

Figure 3 - Equation example from CoolProp

4. Fluid properties from CoolProp for validation on the cascade system with the values from the R404A P-h diagram,

5. Calculation of COP in the single stage system for refrigerants:
    a. R12
    b. R404A
    c. R134a
6. Calculation of COP in the cascade system for combinations:
    a. R404A in both lower and higher cycle
    b. R134a in both lower and higher cycle
    c. R404A in lower and R134a in higher cycle
    d. R134a in lower and R404A in higher cycle

Validation and Results

Validation

Validation of fluid properties from CoolProp on cascade system with the values from the R404A P-h diagram with intermediate temperature t_{int} equal 0°C. There are no major mistakes, values are similar to a certain degree, CoolProp is validated.

Point on the process	Enthalpy read manually from the P-h diagram [kJ/kg]	Enthalpy from CoolProp [kJ/kg]
1	352.3	353
2	369.9	370
3	200.0	200
5	365.8	365
6	391.8	393
7	277.6	281

Table 1 - Enthalpy values from two sources

Results - Figures for single stage system and cascade systems.

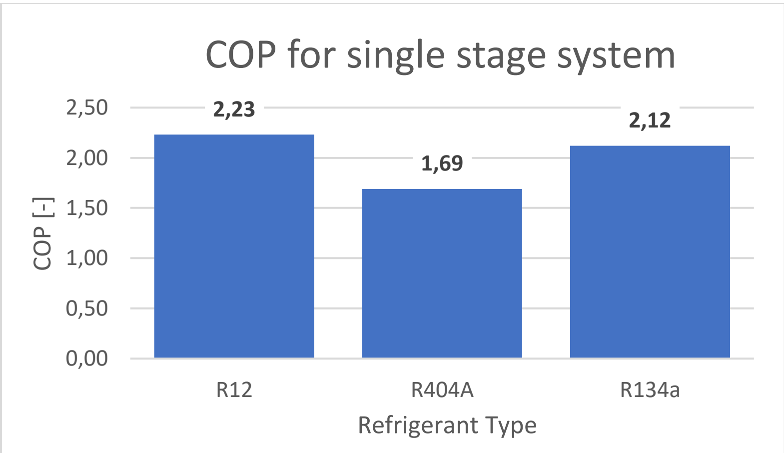


Figure 4 - Coefficient of performance for single stage systems with different refrigerants

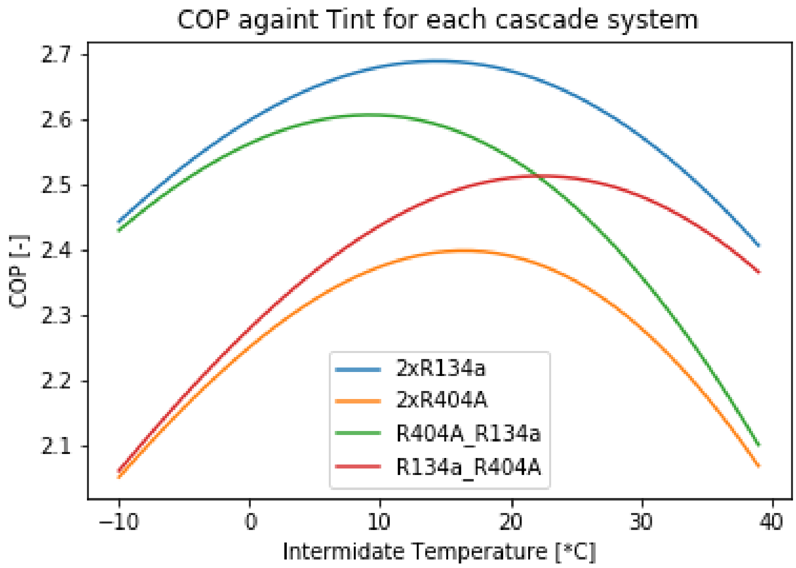


Figure 5 - Coefficient of performance for cascade systems against intermediate temperature for each refrigerant

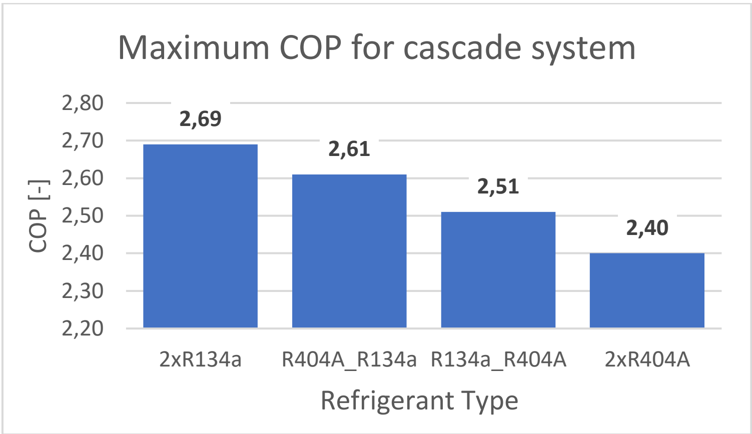


Figure 6 - Maximum coefficient of performance for cascade systems with different refrigerants

Analysis and Discussion

Results were validated by comparing them to the P-h diagram. R134a in a single stage cycle gives higher COP than for R404A. Cascade system made from two loops with better performing refrigerant is better than the mix of both refrigerants or two loops with worse performing refrigerant. Cascade system with two loops filled with R12 would have even higher COP 2.74.

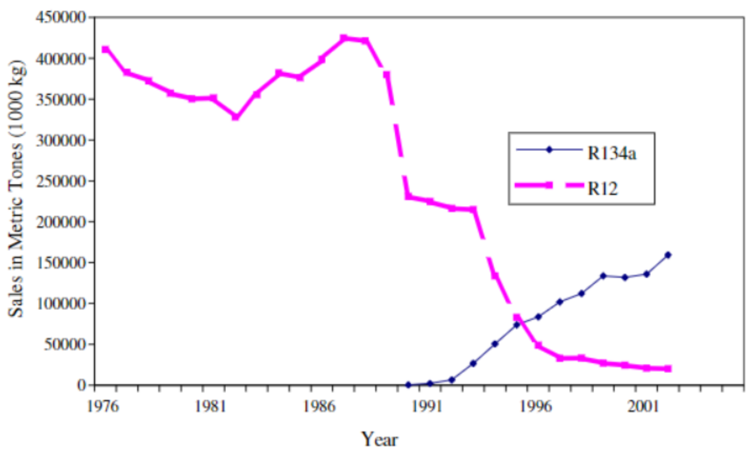


Figure 7 - Comparison of R134a sales with R12 [4]

Unfortunately, R12 refrigerant is in the family of chlorofluorocarbons which have the highest ozone depletion potential and was banned by the Montreal Protocol which created an opportunity for R134a refrigerant. Once script is developed it can be reused for other refrigerants and the results can be created in a second.

Project 2 – Air conditioning facility

Introduction

Initial design characteristics

1. Air-cooled liquid chiller with R134a refrigerant and the nominal capacity of 743.7 kW
2. Chilled water pump with constant mass flow rate of 32 kg/s
3. Air fan with constant mass flow rate of 16 kg/s
4. The chilled water temperature leaving chiller is set to 7°C

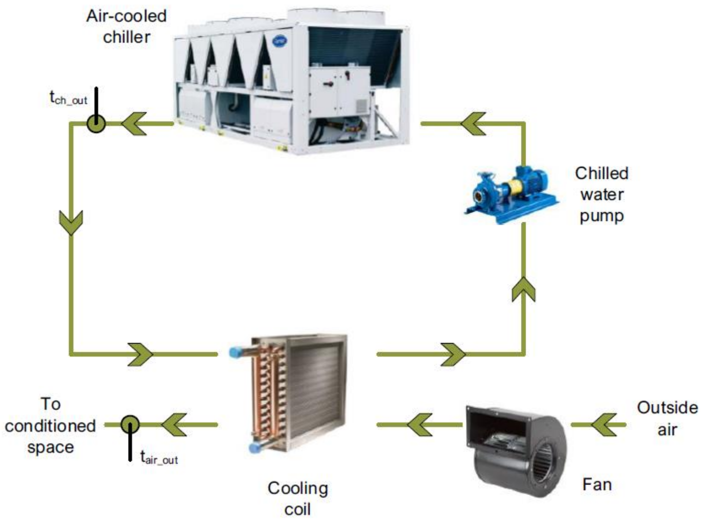


Figure 8 - Air-conditioned system (initial design) [brief]

Background

An air-conditioning facility installed in Barcelona, Spain is operated with a variable temperature of air delivered to the conditioned space, which fluctuates between 8°C and 10°C during most of the warm season period.

Aim

The aim is to modify the original system [Model A] to operate with the fixed air temperature T_{air_out} = 13°C. Two quantitative control type measures are proposed to keep the air temperature constant:

1. Bypass chilled water loop with the three-port valve to modulate flow rate through the cooling coil. Second initial characteristic changes from constant to variable water flow rate. [Model B]

2. Modulate the air flow via installing variable speed drive which controls the fan motor speed. Third initial characteristic changes from constant to variable air flow rate. [Model C]

Methodology

To simulate and analyse air-conditioning systems three models were provided:

- Model A – Task2a.mo
- Model B – Task2b.mo
- Model C – Task2c.mo
- with weather file (ESP_Barcelona.081810_SWEC.mos).

Each model was a circuit composed of object such as chiller, pump, fan, water to air cooling coil with or without controls depending on the model. All models were provided by Anneka Kang and simulated in Modelica language in Dymola 2020 environment.

These models use Buildings.Fluid.Chillers.ElectricEIR model first introduced by Brandon Hencey and later included in the Buildings library by Michael Wetter [1] After initial run model C was changed by implementing cooling coil that condensates water and takes latent heat into account. All imput parameters were exactly the same as in the brief except for water mass flow rate in task C which was changed from 32 kg/s to 16 kg/s.

Results, Analysis and Discussion

Results are presented for 34th week (warm summer) for three models A, B and C.

Model C changes after preliminary results

Initial fan power demand from model C was very high, model had to be revised and validated. Fan had to create pressure of up to 60kPa to move 140 kg/s of air through cooling coil through which normally was flowing 16kg/s. This resulted in big power demand from fan. The brief specified that the water loop should stay intact however water cycle was changed without additional control, water flow was changed from 32kg/s to 16kg/s.

Supply air temperature and enthalpy was out of the psychometric range which would mean that the air is supersaturated (air 100% moist plus additional water droplets) which meant that water did not condensate on the cooling coil.

Cooling coil in task C was modeled as Buildings.Fluid.HeatExchangers.BaseClasses.HADryCoil where in task A and B it was modelled as Buildings.Fluid.HeatExchangers.WetCoilCounterFlow. "HADryCoil model ignores condensation and should be used with care in climate where the dew point temperature of the air frequently drops below the coil surface temperature." [2] Cooling coil in model C was changed to WetCoilCounterFlow to incorporate condensation.

Chiller COP

`Chiller.Electric.EIR` model uses three functions to predict capacity and power consumption:

- A biquadratic function is used to predict cooling capacity as a function of condenser entering and evaporator leaving fluid temperature.
- A quadratic function is used to predict power input to cooling capacity ratio with respect to the part load ratio.
- A biquadratic function is used to predict power input to cooling capacity ratio as a function of condenser entering and evaporator leaving fluid temperature.

Condenser entering temperature is outside air dry-bulb temperature, variable but the same for each analysed case. Evaporator leaving fluid temperature is water supply temperature set constant to 7°C. These two variables are the same for the warm summer week in each model. Last variable - part load changes in time and differs for each model. ChillerData for Carrier_30XA220 has performance curve expressed as a quadratic function with coefficients (0,1,0) which means that it does not influence the chillers efficiency. Unfortunately, I couldn't find Chiller Data for that specific model as it was probably extended from generic model. However, chillers with similar values are available. [3]

System B with water flow rate control use less energy than original A system as it lowers water mass flow rate. System C uses more energy both for fan as it increases air flow rate and for chiller as more air must be cooled to meet 13°C setpoint. Both B and C systems control supply air temperature setpoint precisely.

In that case if chillers part load is in range of minimum and maximum capacity than all the models have the same COP variable only to weather conditions as shown on figure 18.

The results have been presented in a client brief to not duplicate them here. Total accumulated electricity demand from model B will be used in task 3.

Building systems consist of many individual components create one integrated system. Each component often has variable efficacy dependent on many parameters. To understand overall building or system performance it is crucial to understand each component individually and in combinations to understand their interactions. More precise interactions exist in real life applications compared to any modelled example, but even with this simplified version of system it does pose a certain engineering challenge.

Project 3 – Offsetting electric energy demand using renewable energy source

Introduction

Background

As part of the previous project, there is a discussion about offsetting electricity requirements using renewable energy sources. [brief]

The aim of this task is to explore the opportunity of installing a solar photo-voltaic plant to support and partially offset electricity requirements of the facility. Simple concept circuit was simulated in Dymola environment to model energy generation for the same 34th week.

Barcelona is a hot and humid climate. When solar gains rise both cooling energy demand and PV generation rise. They both follow daily solar pattern. Offsetting cooling load with this renewable source may sound perfect. In 2007 Spain had second biggest PV farms in Europe. Economical aspects of PV cells are getting better, and more people are willing to invest without incentives [5]. But there is still another issue associated with PV panels. If energy demand and PV generation does not meet at the same time and they are offset by three or more hours this may cause grid instability. This issue can be possibly neglected with implementing batter storage.

Design process consists of finding tilt and azimuth for which PV panels generate most energy in analysed period. Calculating required battery capacity and calculating three area options for the client to give him flexible offering.

Methodology

In total 14 simulations were run in Dymola with tilt and azimuth 5° increments step by step optimisation to find best efficiency for the specific location based on supplied weather file. Followed by 3 simulations to find areas that meet targets:

- highest energy offset with minor crossing energy demand with generation,
- nearly zero energy building (NZEB) and meeting almost 100% of the electricity demand,
- generation that will focus on offsetting peak demand.

Advanced and NZEB packages have additional storage capacity for storing surplus energy for balancing energy demand.

At the end additional standard package was created to lower energy peaks with small PV array and tilt and azimuth optimized with meeting curve patterns to lower grid demand peaks without additional storage. Followed by additional 9 iterations for finding optimal tilt and azimuth.

Results, Analysis and Discussion

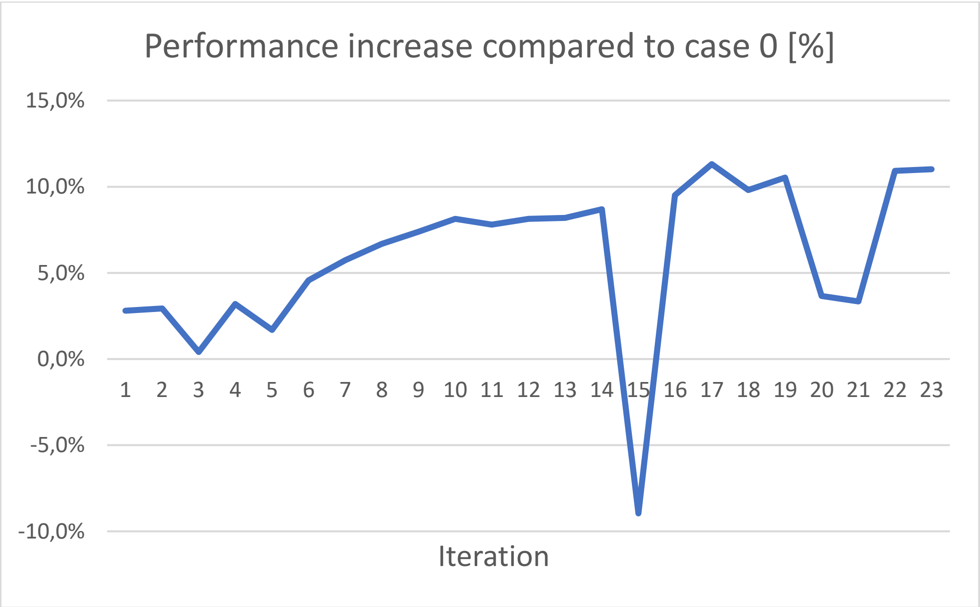
Finding best tilt and azimuth

Input parameters and generated energy for warm summer week for each iteration, with area = 100 m2. Simple iterative method did work and gave better results however did not yield optimal solution early. Running simulation one by one and comparing results with arithmetic mean signal operator in Dymola was faster than exporting results and comparing them in excel.

The use of built in Dymola functionality sweep parameters more solutions could be simulated and compare faster and possibly could result in more optimal tilt and azimuth. Due to lack of experience with the Modelica language I was unable to convert input parameters to the necessary form. Possibly that could be tested in the next project.

Case	Azimuth	Tilt	Generated [kWh]
0	10	30	513,7
1	10	20	528,1
2	10	10	528,8
3	10	0	515,9
4	10	15	530,2
5	0	15	522,4
6	20	15	537,2
7	30	15	543,3
8	40	15	548,1
9	50	15	551,7
10	70	15	555,6
11	90	15	553,8
12	80	15	555,6
13	75	15	555,8

1'	90	45	558,4
14	10	45	467,7
15	75	45	562,6
16	75	30	571,9
17	75	20	564,1
18	75	40	567,8
19	45	45	532,6
20	75	60	530,9
21	75	25	569,9
22	75	35	570,4



Proposed Offsetting

Three offsetting packages were analysed with different PV area and storage capacity.

Package	PV area [m^2]	Installed power [kWp]	Storage capacity [kWh]
Standard	600	75	0
Basic	1500	160	0
Advanced	2200	235	500
NZEB	3500	375	1500

Figure 9 - Package specification

First chart represents total electricity demand from first option from task 2 in blue, green line depicts electricity generated from PV array. Second chart shows grid energy demand.

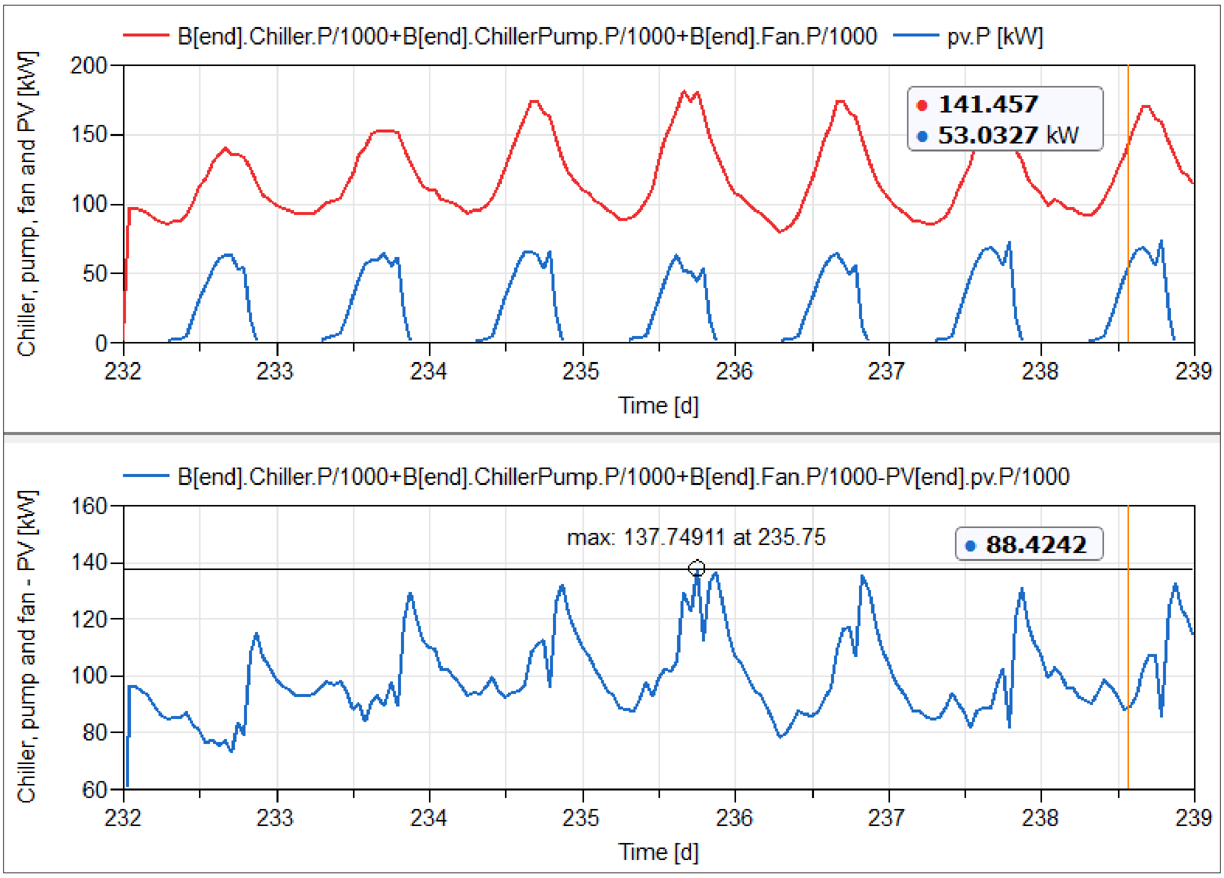


Figure 10 - Standard package

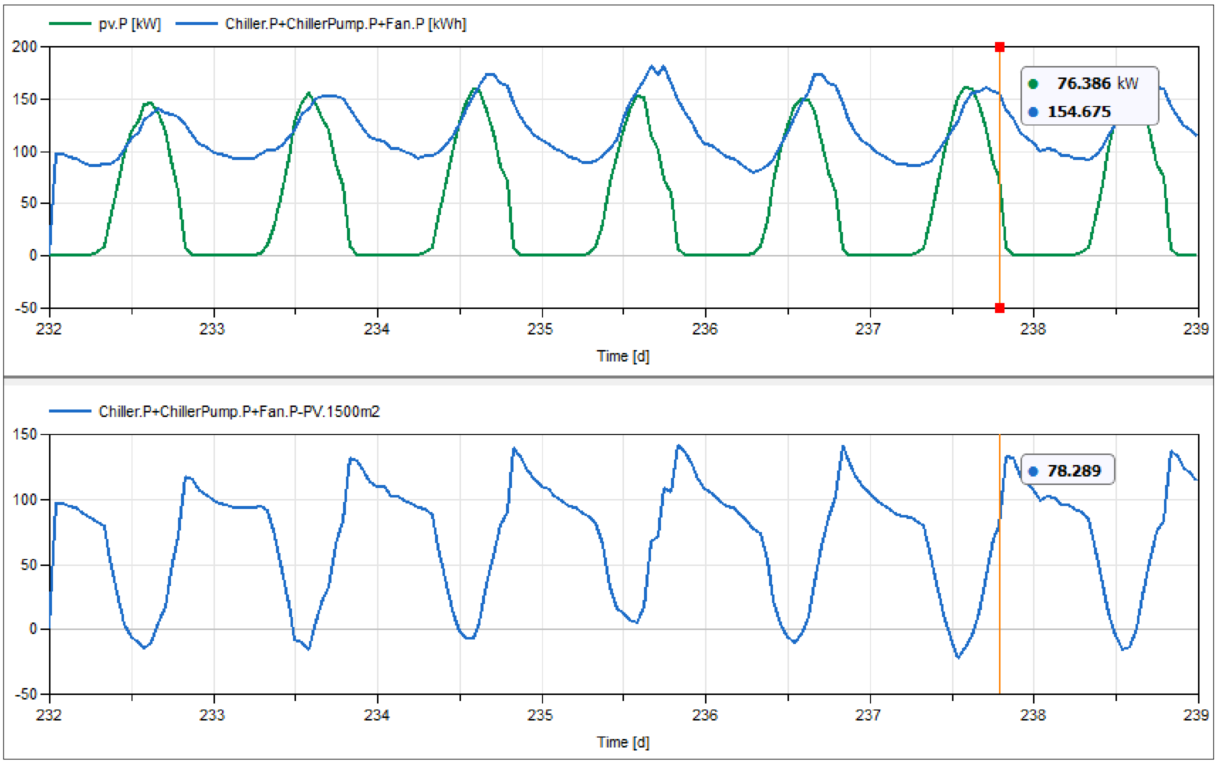


Figure 11 - Basic package

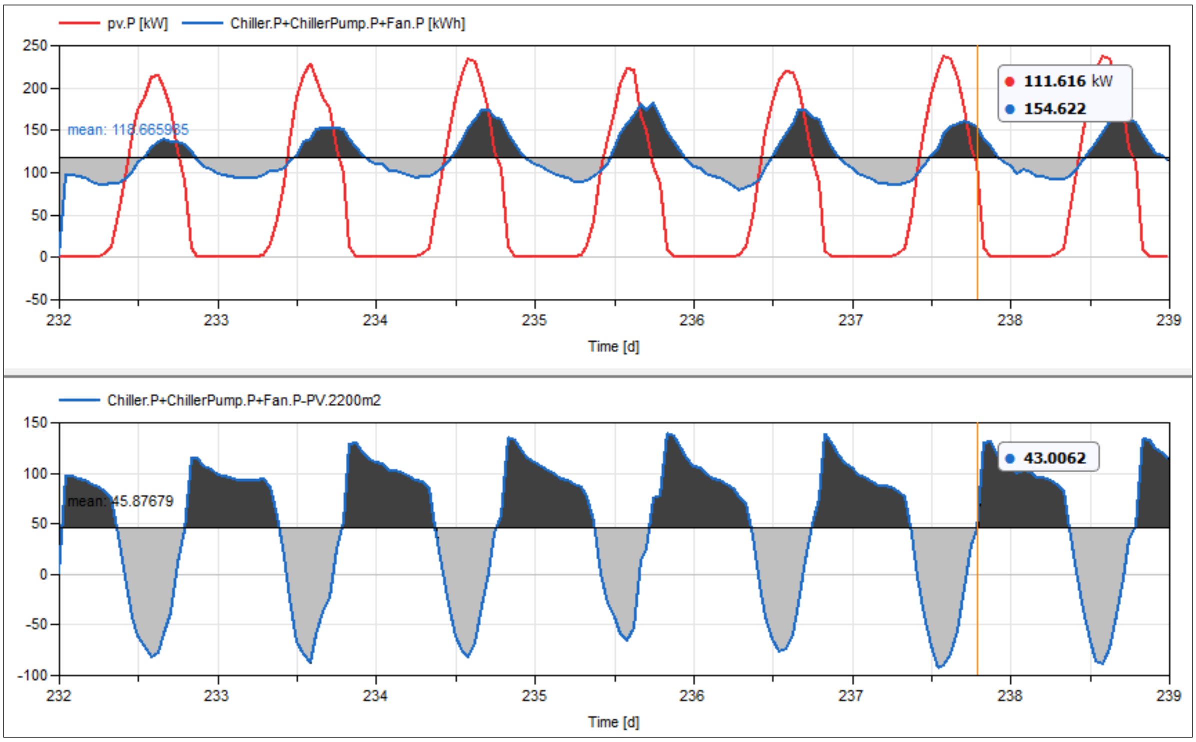


Figure 12 - Advanced package

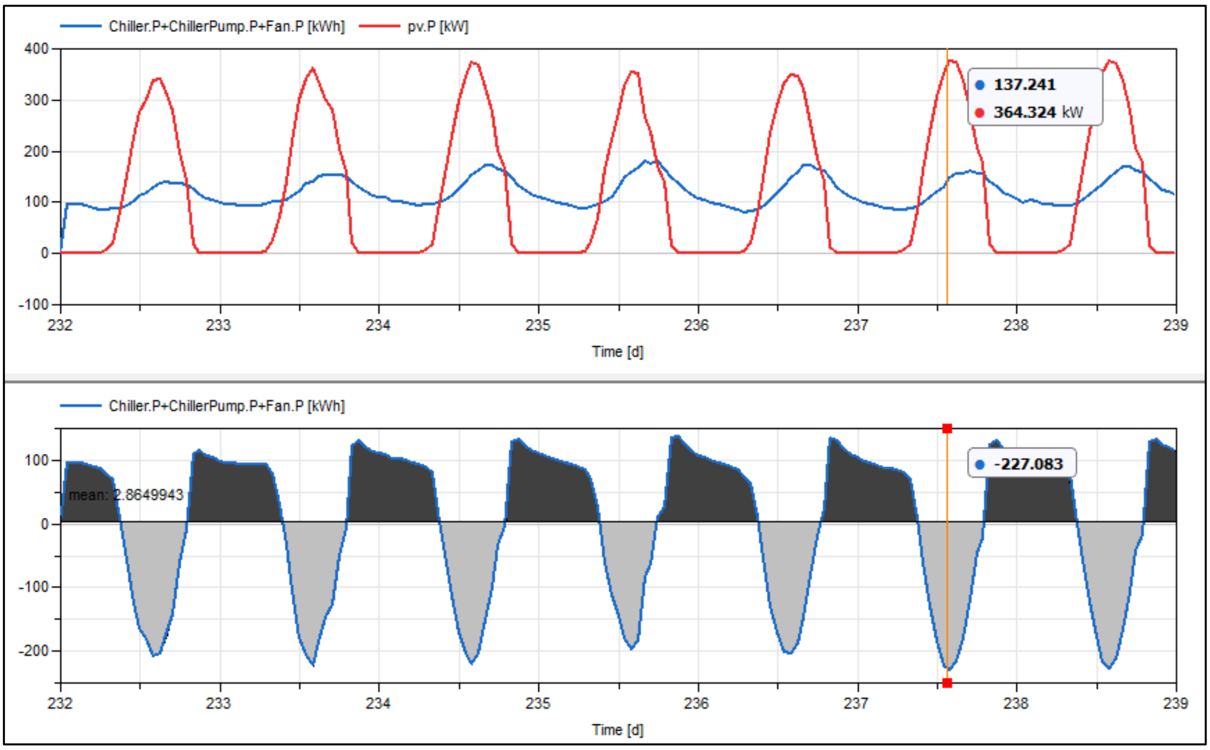


Figure 13 - NZEB package

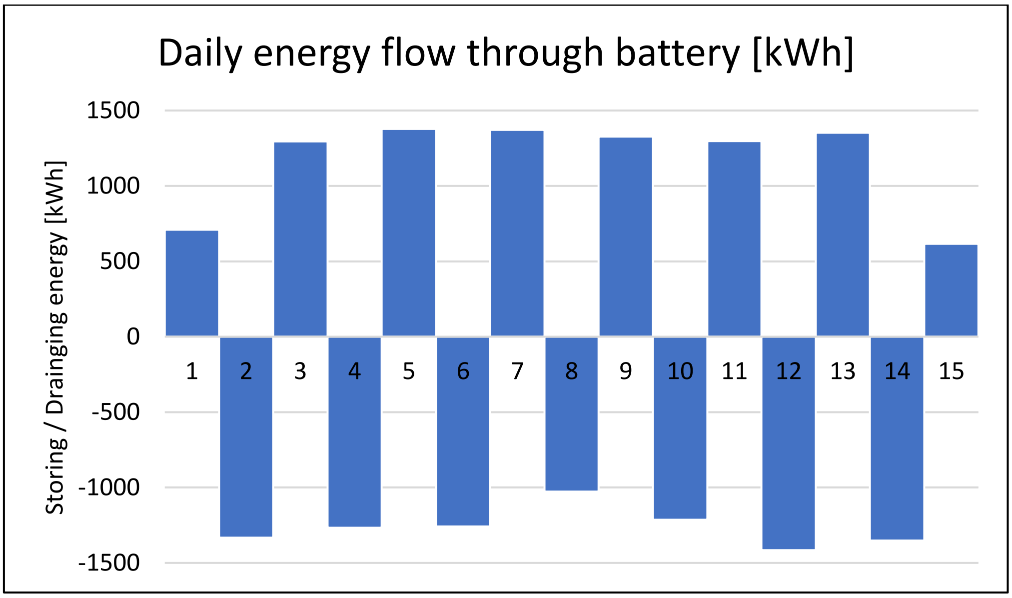


Figure 14 - Daily battery flow for NZEB solution

Basic package generates 42% of energy demand in that specific summer week. This solution may contribute to the grid instability as the grid energy demand varies even more after installing PV.

Advanced package generates 63% of energy demand, additional 500 kWh battery storage could align the demand and lower electricity peaks by 75.8% from as high as 181 kW to mean value of around 43,8 kW.

NZEB package generates 98% of energy demand and removes electricity demand from the grid almost entirely.

Client Brief

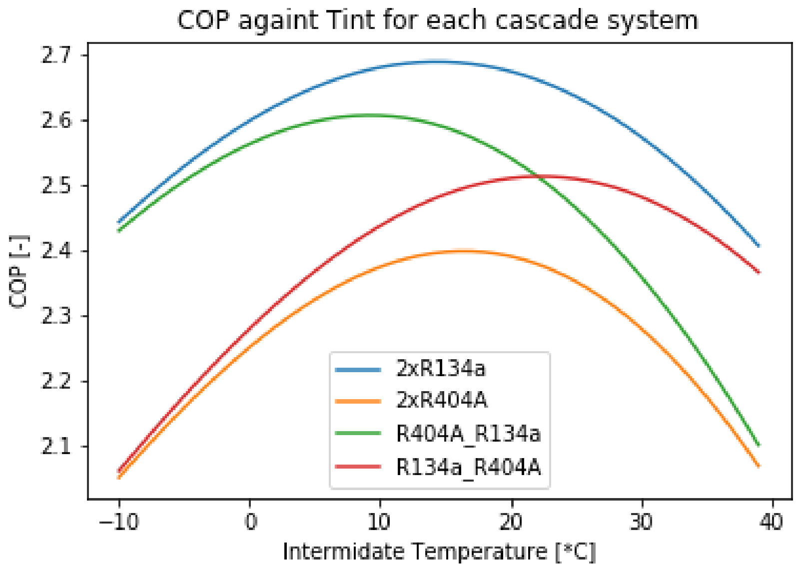
Task 1 - Questions and answers

1. Which solution from the first upgrade scenario would you propose based on the COP of the system at peak capacity? How does the proposed systems perform (in terms of COP) when compared to the original R12 system?

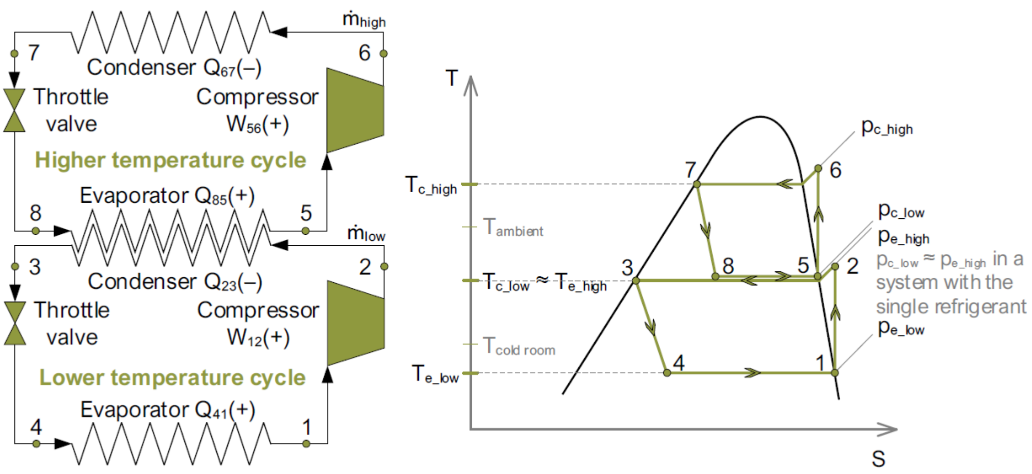
In single stage scenario R134a give highest COP and meets todays environmental regulations. Proposed system COP is 2.12 compared to the original single stage R12 system COP of 2.23.

2. Which solution from the second upgrade scenario would you propose based on the optimal COP of the system at peak capacity? What is the optimal intermediate temperature in the proposed cascade system? Plot of the proposed cascade system performance (COP vs intermediate temperature). How does the proposed systems perform (in terms of COP) when compared to the original R12 system?

In cascade system two R134a cycles are proposed with the highest COP at the intermediate temperature at 13°C. Proposed cascade system COP is 2.69, compared to the original system 2.23.



3. Detailed description of a cascade vapour compression system.



This system is a combination of two separate single stage vapour compression systems. Single stage system is created from four components: compressor, two heat exchangers and throttle valve through which flows refrigerant. Compressor uses electricity and converts it to mechanical movement which compresses refrigerant vapour to higher pressure therefore temperature rises. Condenser exchanges heat with other medium that has lower temperature and condensates to the moment when it is 100% liquid. Refrigerant then in a liquid form flows through throttle valve where we have adiabatic process (constant enthalpy) and pressure drops rapidly therefore temperature is lower. Mixture of liquid and vapour flows to evaporator where it cools a chosen source and the rest of the liquid is converted to vapour. The whole cycle repeats.

Task 2 - Report

After a thorough analysis of each system - B is proposed as it operates with a desired setpoint of 13°C and uses less energy for that purposes compared to both A and C system. For C system to be implemented with this flow rate it would be necessary to resize the ducting which is not recommended solution. Many charts are presented below to show compliance with the requirements.

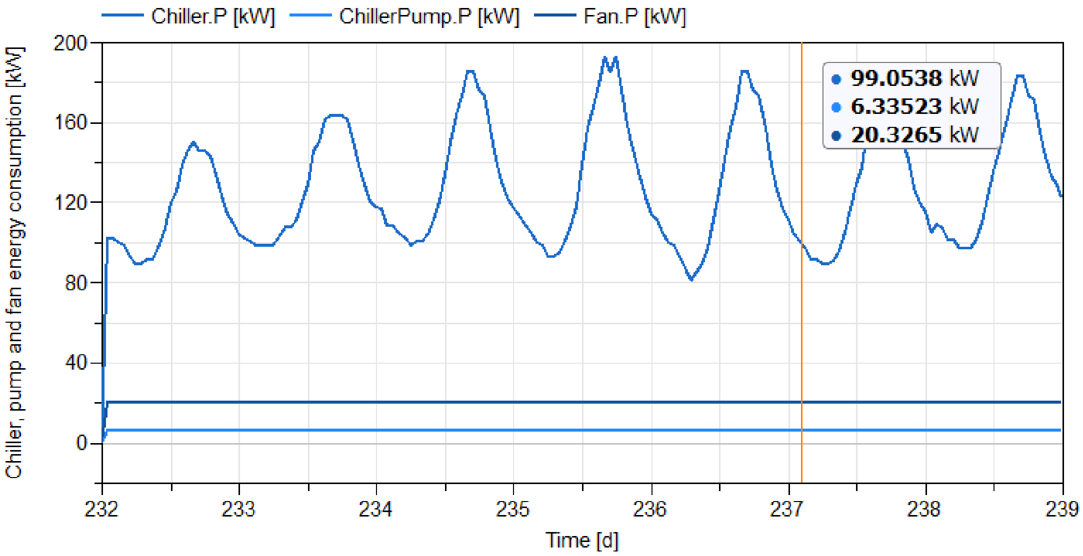


Figure 15 - A - Chiller, pump and fan energy consumption [kW]

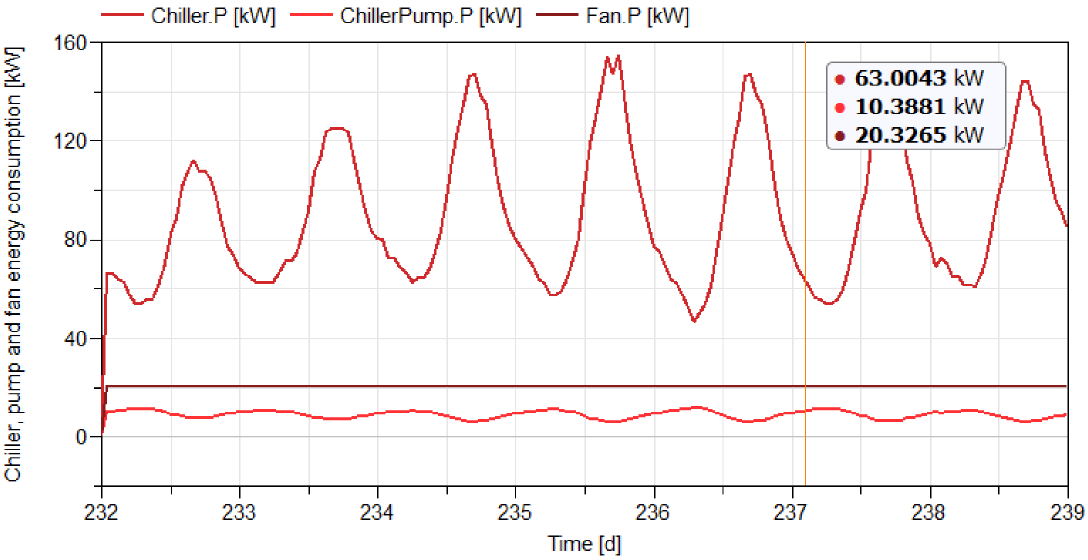


Figure 16 - B - Chiller, pump and fan energy consumption [kW]

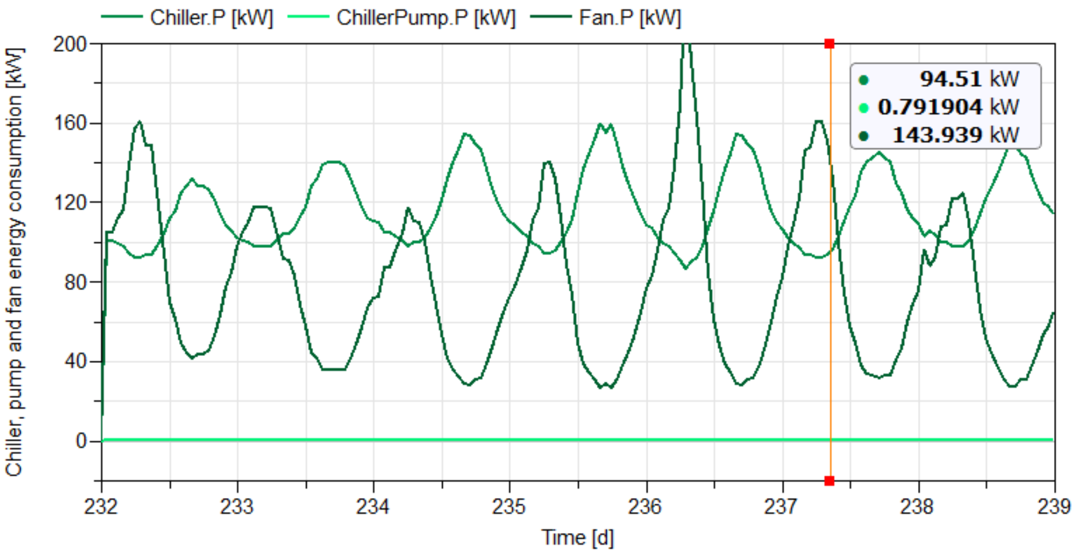


Figure 17 - C - Chiller, pump and fan energy consumption [kW]

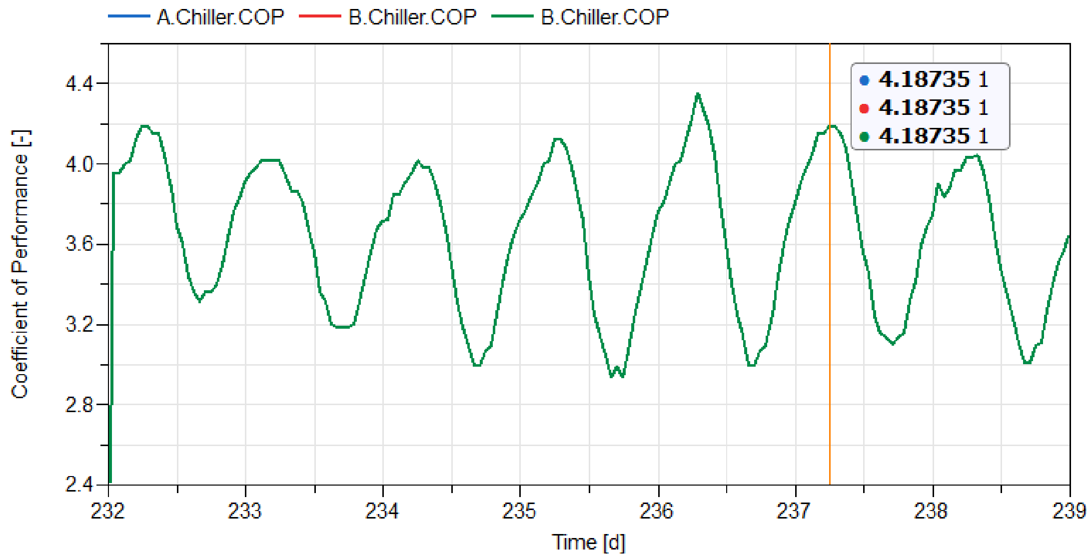


Figure 18 - Chiller COP for all systems

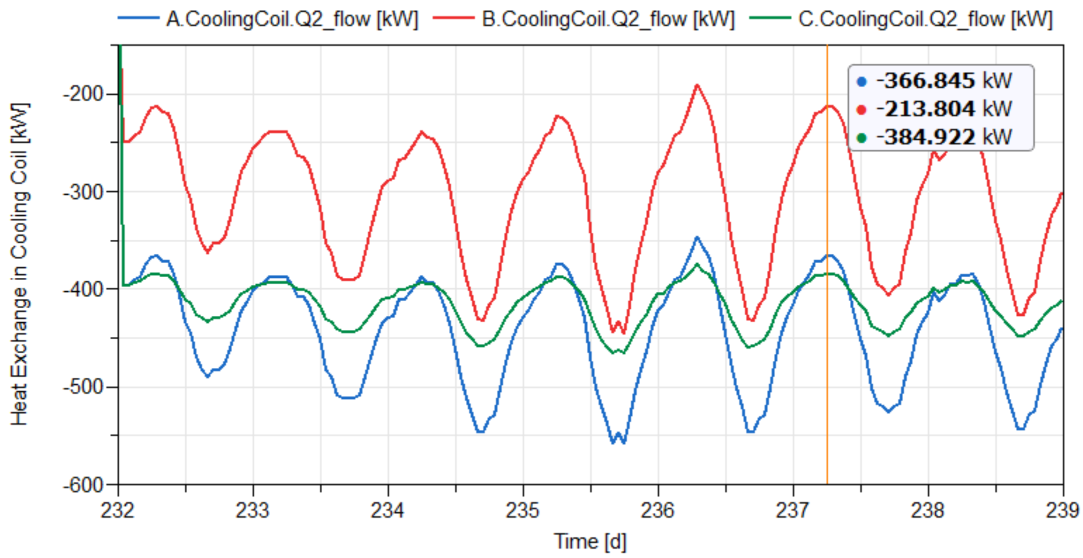


Figure 19 - Heat Exchange in Cooling Coil [kW]

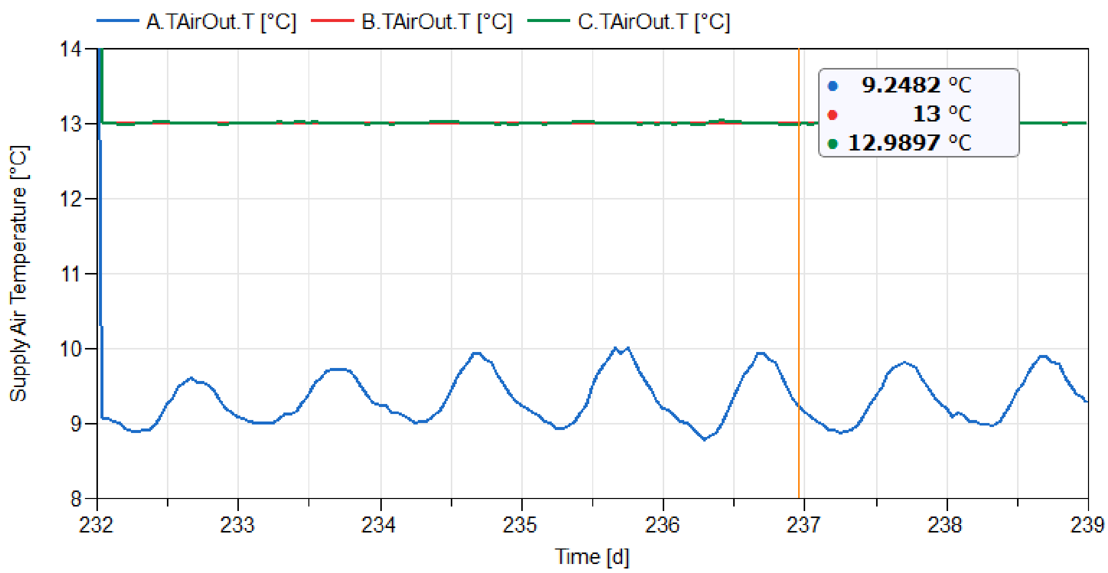


Figure 20 - Supply Air Temperature [°C]

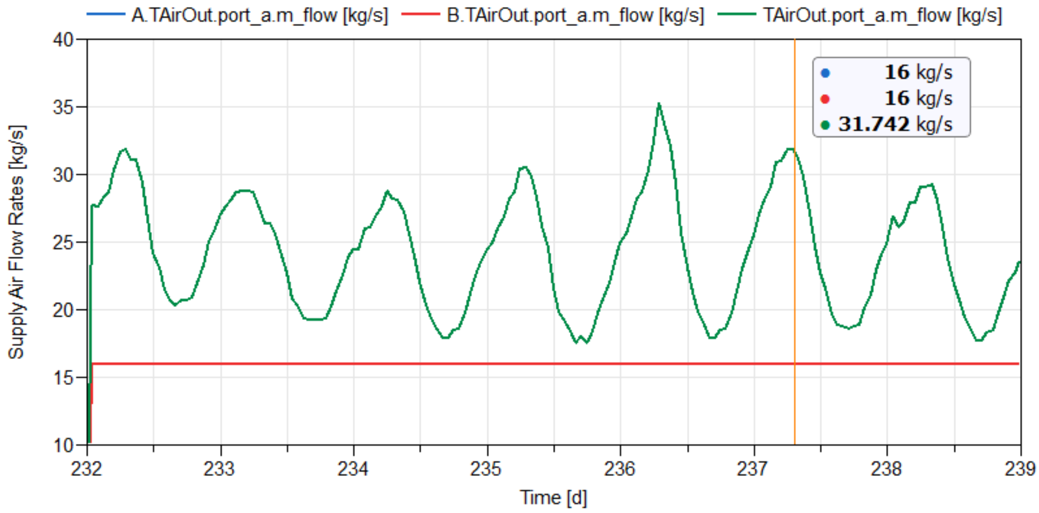


Figure 21 - Supply Air Flow Rates [kg/s]

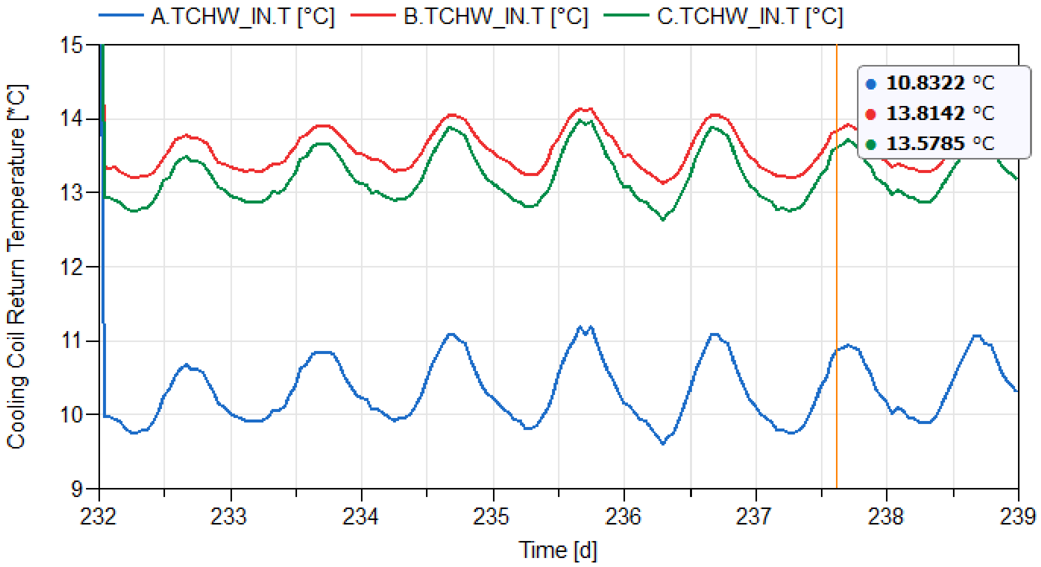
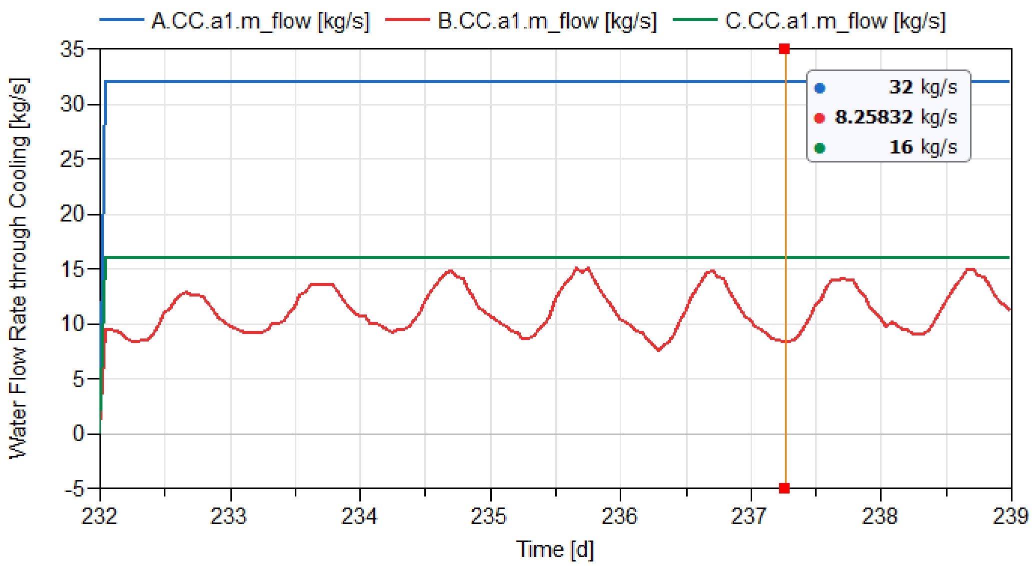


*Figure 22 - Cooling Coil Return Temperature [*C]*



Task 3 - Offsetting electricity demand

Assumptions: tilt: 30°, azimuth 75°, cell efficiency 12%, net area of panel 90%.

For flexibility of the offer three packages are proposed. First package does not need additional battery storage as it fits well with the electricity demand. If the requirement for offsetting would be dictated by meeting nearly zero energy building than NZEB PV package the one. Advanced package is somewhere in between.

	PV area [m2]	Storage capacity [kWh]
+ Standard PV	600	-
+ Advanced PV	2200	500
+ NZEB PV	3500	1500

	Energy use [kWh]	Energy offset [%]	Peak Demand [kW]	Peak Power offset [%]
System B	19935	-	181	-
+ Standard PV	16498	17,2	145	19,9
+ Advanced PV	7710	63,1	136	75,8
+ NZEB PV	480	100	136	100

References

1.www.simulationresearch.lbl.gov/modelica/releases/latest/help/Buildings_Fluid_Chillers.html#Buildings.Fluid.Chillers.ElectricEIR

2.Wetter Michael, Simulation model finned water-air-coil without condensation, LBNL-42355, Lawrence Berkeley National Laboratory, Berkeley, CA, 1999.

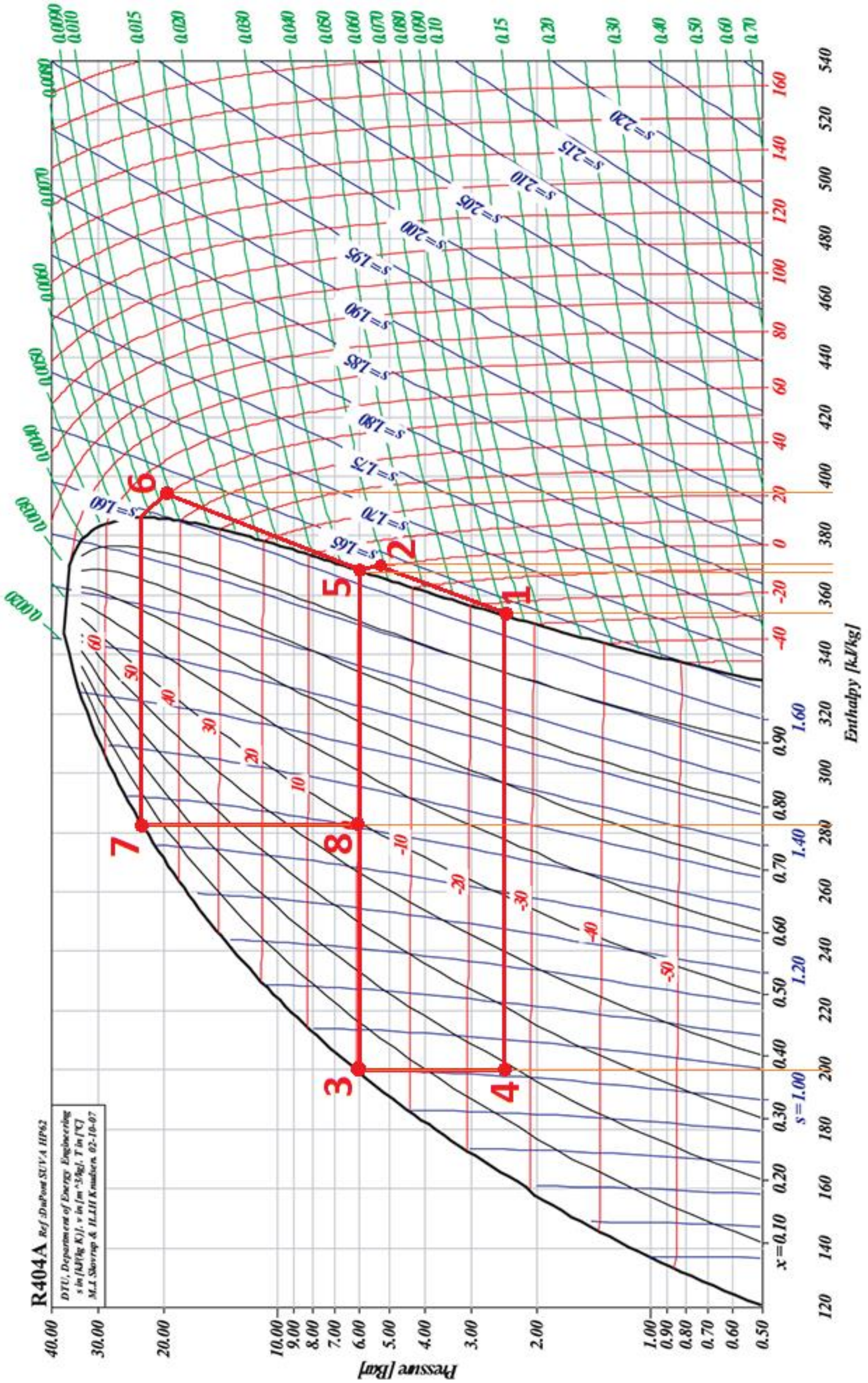
3.www.simulationresearch.lbl.gov/modelica/releases/latest/help/Buildings_Fluid_Chillers_Data_ElectricEIR.html#Buildings.Fluid.Chillers.Data.ElectricEIR

4. K. Senthil Kumar K. Rajagopal, Computational and experimental investigation of low ODP and low GWP HCFC-123 and HC-290 refrigerant mixture alternate to CFC-12

5. www.colab.research.google.com

6. www.coolprop.org

Appendix 1



R404A Ref :DuPont SUVA HP62
DTU, Department of Energy Engineering
s in [kJ/(kg K)]. v in [m^3/kg]. T in [ºC]
M.J. Skovrup & H.J.H Knudsen. 02-10-07
Pressure [Bar]
Enthalpy [kJ/kg]
1
2
3
4
5
6
7
8