EQUA

Using simulation to study energy flexibility

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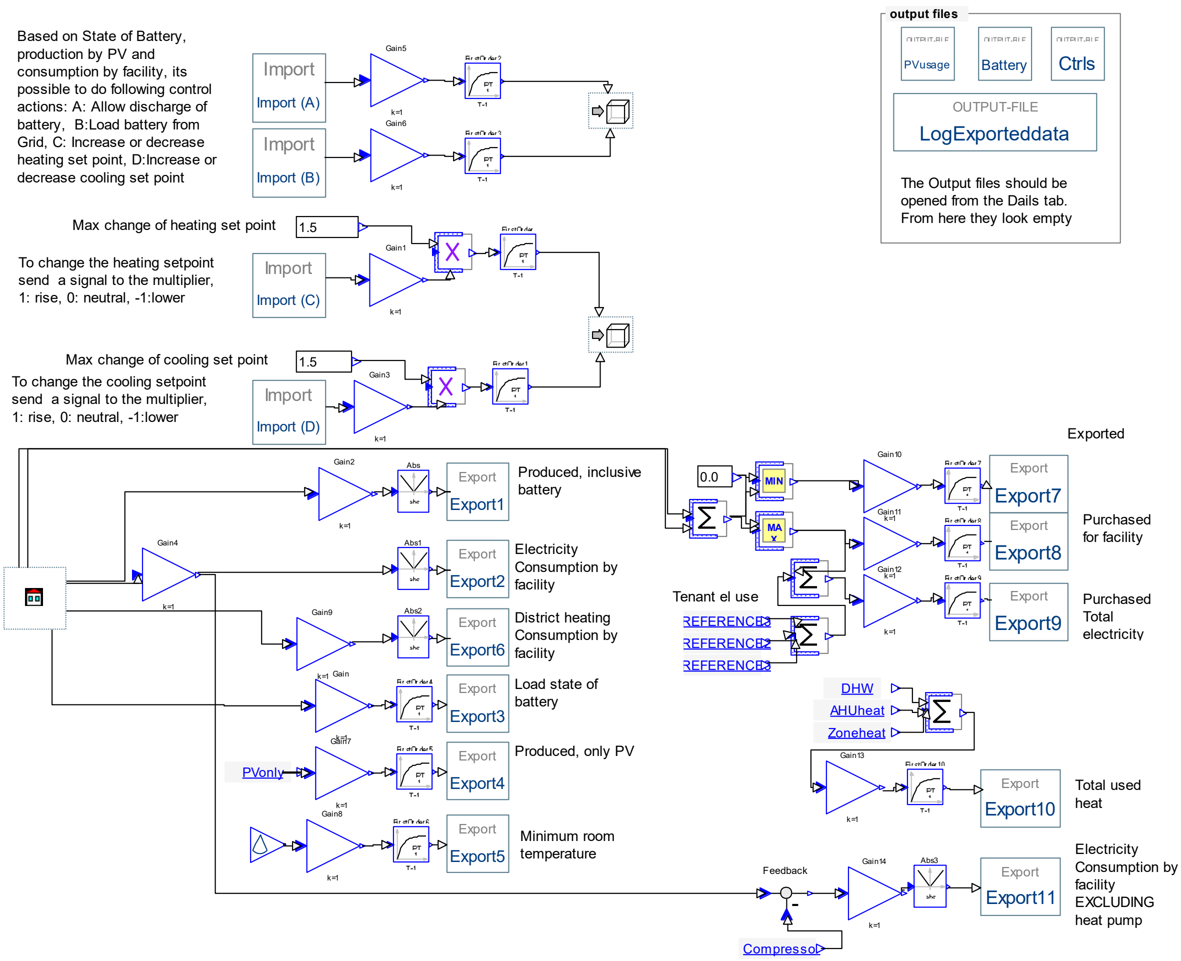
Testbench for external optimization routines to study PV and battery storage in connection with building operation

To study the possibility to optimize the use of batteries and heat pumps using forecasting a testbench was developed to be used by Uppsala University. The test bench consists of a building modeled and simulated in IDA ICE with a connection to python as an external control. This enables Python to be used to control battery charging/discharging, use of the heat pump and changing the room temperature set points.

Supervisory control and connection to Python.

Below is shown, the supervisory control used in IDA ICE to connect to Python. Four signals are imported from the python optimization algorithm to control the building and 11 signals are exported to be used in the python optimization algorithm.

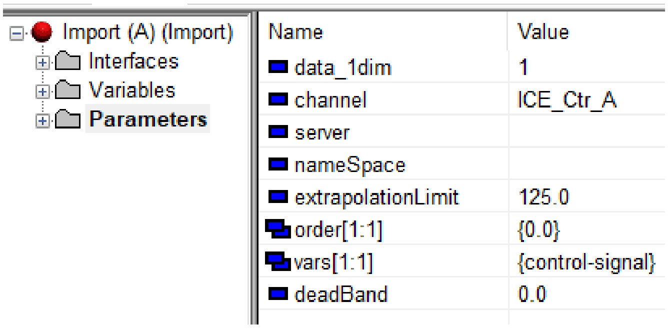


In the table below the import and export signals are specified

Export	Measured signals
1	Produced, PV and battery
2	Electricity Consumption by facility
3	Load state of battery
4	Produced by PV only
5	Minimum temperature of all room in the building
6	District heating Consumption by facility
7	Exported electricity
8	Purchase electricity for facility
9	Purchased Total electricity
10	Total used heat
11	Electricity Consumption by facility EXCLUDING compressor
Import	Control action
A	Allow discharge of battery,
B	Allow to load battery from Grid
C	Increase or decrease heating set point
D	Increase or decrease cooling set point

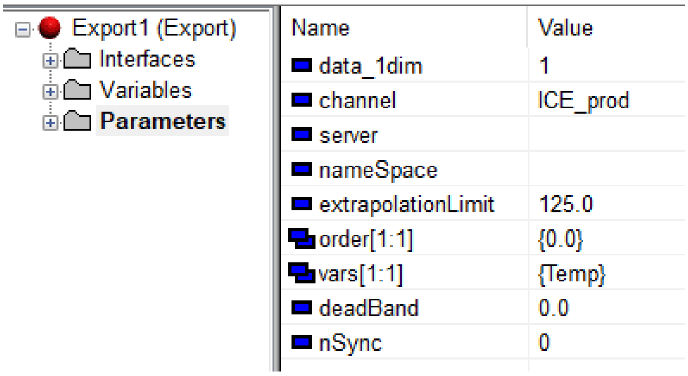
Example of import signal description

Set the **channel** to "ICE_Ctr_A". This is the name of this channel and should have the same name in MATLAB or Python. The **extrapolationLIMIT** here is set to 125 sec. In general, it should be equal to 2x Maximal timestep + ε. In this case our MATLAB or Python code will deliver a control signal every 60 seconds (timestep). Continue by changing the **order** to 0, the variable name in **vars** to "control-signal" and the **deadBand** to 0.



Example of export signal description

Set the **channel** to "ICE_prod". This is the name of this channel and should have the same name on the Python side later. The **extrapolationLimit** can be set to 125 sec just for stability reasons, the **order** should be set to 0, the variable name in **vars** can be set to Temp, the **deadBand** should be set to 0 and the **nSync** to 0, as well.



Example of Python code to import and export a signal from IDA ICE

Setting up the Python model

Two files are needed to set up and running a co-simulation between IDA ICE and Python, Idalibn.dll and libzmq-mt-4_3_1.dll. They can be obtained from EQUA Solution AB.

Below is the basic code needed in python to run a co-simulation described.

Make sure that you have.

1. First import the `ctypes` library.

   ```
   import ctypes
   ```

   and load the library which contains the communication routines we shall use.

   ```
   mydll=ctypes.CDLL('.\idalibN.dll')
   ```

   Define function prototypes for the arguments and return values of the functions.

   ```
   mydll.CreateStorage.restype = ctypes.c_longlong
   mydll.CreateStorage.argtypes = [ctypes.c_char_p,
   ctypes.c_longlong, ctypes.c_longlong, ctypes.c_longlong,
   ctypes.c_void_p, ctypes.c_longlong]

   mydll.RetrieveStoredData.restype = ctypes.c_longlong
   mydll.RetrieveStoredData.argtypes =[ctypes.c_longlong,
   ctypes.c_double, ctypes.c_void_p]

   mydll.StoreData.restype = ctypes.c_longlong
   mydll.StoreData.argtypes =[ctypes.c_longlong,
   ctypes.c_double,ctypes.c_void_p,    ctypes.c_longlong]

   mydll.CloseStorage.restype = ctypes.c_longlong
   mydll.CloseStorage.argtypes =[ctypes.c_longlong]
   ```

2. Creating and opening the import and export channels.

   Creating the channel is done using the function **CreateStorage** which requires 6 arguments: pointer to channel name, number of variables passed on the channel, number of clients linked to the same variable, extrapolation time, whether to interpolate the variables or not, and whether there is an opc server or not. I what follows an example is shown for the channel that will be reading the data from the "Export" in ICE, which should be matched with the import channel here. We must use the same `c_types` as in the function prototype.

```
Channel_name   = b'ICE_prod';
Channel_ptr    = ctypes.c_char_p(Channel_name);
nVar           = ctypes.c_longlong(1);
nSync          = ctypes.c_longlong(1);
dTExtrap       = ctypes.c_longlong(0);
VarInterp      = ctypes.c_double(0);
opc            = ctypes.c_longlong(0);
import_Channel = ctypes.c_longlong;

import_Channel=mydll.CreateStorage(Channel_ptr,nVar,nSync,dTE
xtrap,ctypes.byref(VarInterp),opc);
```

The second channel that will communicate with the "Import" in ICE and thus is an export channel here, can be created and opened in the same way, but takes the following parameters:

```
Channel2_name   = b'ICE_Ctr_A';
Channel2_ptr    = ctypes.c_char_p(Channel2_name);
nVar            = ctypes.c_longlong(1);
nSync           = ctypes.c_longlong(1);
dTExtrap        = ctypes.c_longlong(75);
VarInterp       = ctypes.c_double(0);
opc             = ctypes.c_longlong(0);
export_Channel  = ctypes.c_longlong;

export_Channel=mydll.CreateStorage(Channel2_ptr,nVar,nSync,dT
Extrap,ctypes.byref(VarInterp),opc);
```

In the above function calls the variable `VarInterp` is called by reference using the `ctypes.byref` Function.

3. The data that will be communicated need to be initialized with the right c_types.

```
dData = ctypes.c_double(0);
dData_sim = ctypes.c_double(0);
extrap = ctypes.c_longlong(0);
```

4. The data that will be communicated need to be initialized with the right c_types.

```
dData = ctypes.c_double(0);
dData_sim = ctypes.c_double(0);
extrap = ctypes.c_longlong(0);
```

5. To retrieve and send data now, all that needs to be done is to use the functions **StoreData** and **RetrieveStoredData:**
   a. StoreData takes as arguments the name of the storage, the time of stored slice, a pointer to the data to store/send and whether to extrapolate or not. The pointer to the data is easiest created by using the `ctypes.byref` function. The data to store/send needs to be cast to the right type before used in the function.

```
dData = ctypes.c_double(PID_sig);
```

```
mydll.StoreData(export_Channel,tt,ctypes.byref(dData),extrap)
;
```

b. RetrieveStoredData takes as arguments the name of the storage, the time of the retrieved slice and a pointer to the retrieved data.

```
mydll.RetrieveStoredData(import_Channel,tt,ctypes.byref(dData
_sim));
```

The retrieved data needs to be cast to the right type before used.

```
FeedBack[counter+1] = dData_sim.value;
```

6. At the end of the Python script the storages should be closed using the function **CloseStorage**.

```
mydll.CloseStorage(import_channel);
mydll.CloseStorage(export_channel);
```

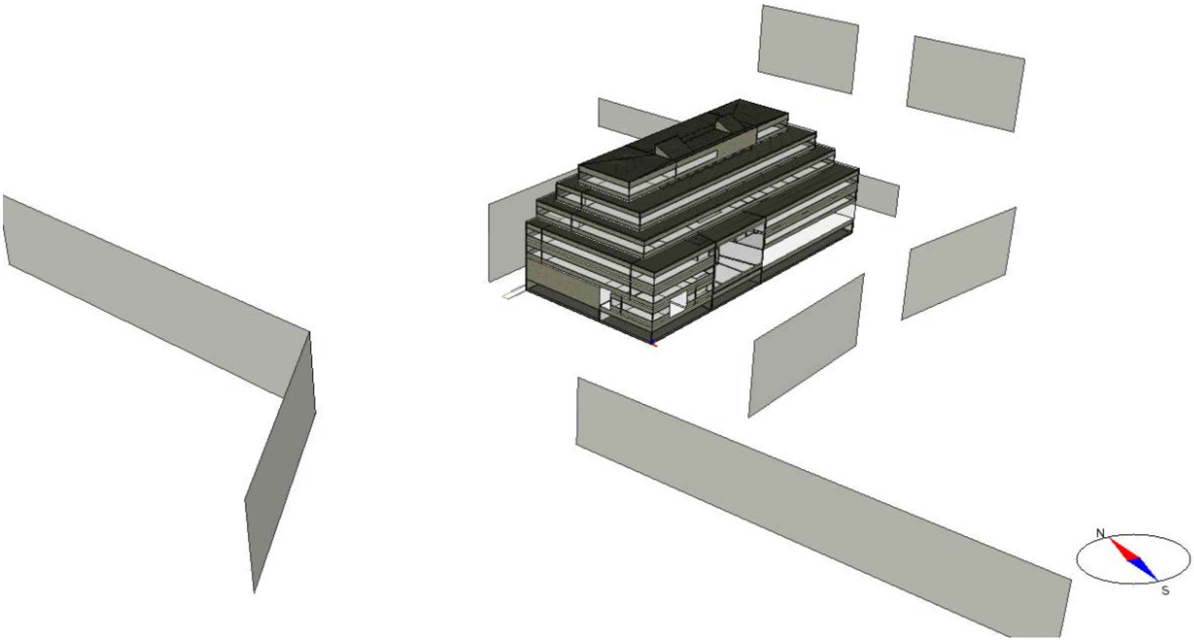
Running the simulations

To start the co-simulation, the total time should be setup in ICE under the Simulation tab in the Custom Simulation and should be of the same length as that used in the Python script. The startup period should be set to 0 in ICE or you can use a periodic simulation with only one period.

The Python script must be started first, it will write out the output of the first step and then wait for the IDA ICE model. The IDA ICE model can be started in the ordinary way by clicking the custom run button.

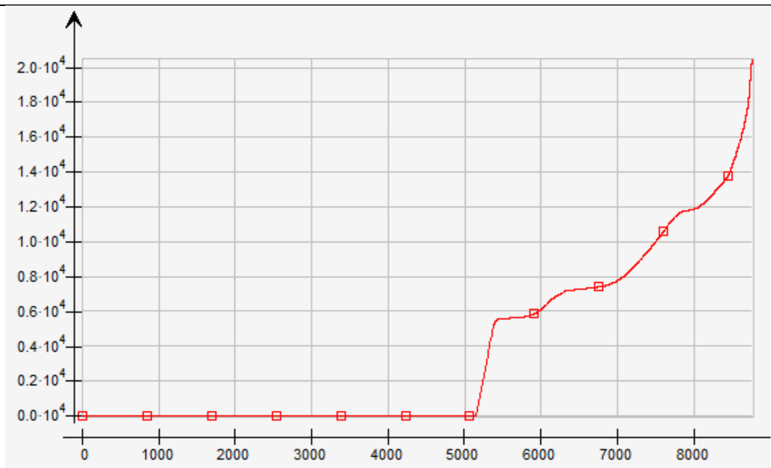
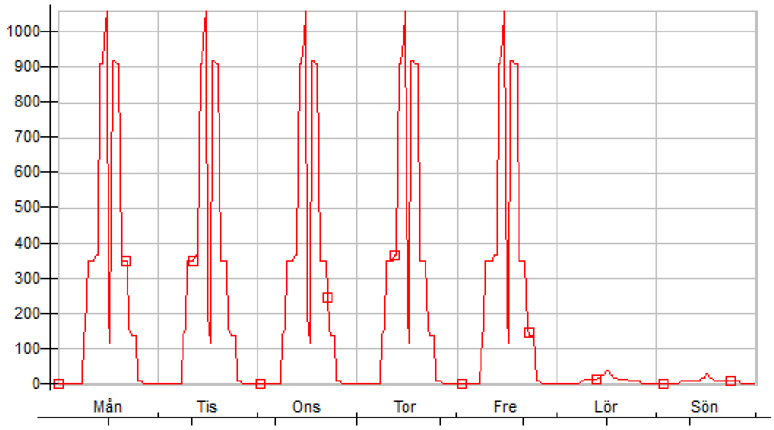
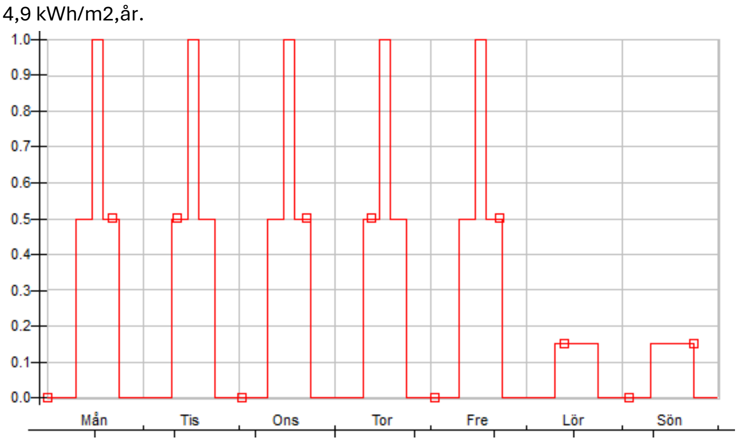
Office building

The office building used in the test bench, located in Gothenburg is shaded as shown in the picture below. The building is equipped with PV and a plant using a ground source heat pump as base heating and district heating as top-heating. The model of the building itself is a design model received from the consultant AFRY. The plant and PV are fictious and added to facilitate the use of the building to study energy flexibility.



The table below shows a summary of the input to the simulation model.

Parameter	Desription
Location	Göteborg
Envelope	See separate table below
Thermal bridges	See separate table below
Infiltration	Wind driven infiltration 0.3 l/s,m2 at 50 Pa. Wind profile: Urban Semi sheltered Opening of entrances according to schedule
Windows	See separate table below Ground reflectance 20%
Sun screen	Integrated, g=0.2 down at 50 W/m2 on inside of windows
Shading buildings	See figure above
Room heating	Water radiators controlled to maintain +21°C
Plant, heating	Ground source heat pumps with district heating as top heat.
Room cooling	VAV using sub coold air controlled to maintain 25 °C
Plant, cooling	Frikyla/kyla från bergvärme
Ventilation	Temperature and CO2 controlled VAV: Max flow 20.4 m^3/s
AHUs	Always on SFPv=2,06 $kW/m^3/s$ at 34 m^3/s, air flow limited to 20,4 m3/s Heat recovery, 85%, Minimum return temperature -7° C. Duration of air flows i l/s

	
Occupants	Max 927 people Occupancy: enligt schema Metabolism: 1,2 Met Clothing =0.85±0.25 CLO (varying to receive comfort if possible). 
Lighting and equipment	Lighting power, kW — Schedule — Energy 44 — Weekdays 06-19 — 142 MWh 6.3 — Meating rooms — 6.26 MWh Equipment 39.7 — (60%) offices — 57 MWh 2.9 — (100%) offices — 6.7 MWh 4.3 — Dining room — 2 MWh 1.9 — Meeting rooms — 1.9 MWh
Additional facility	Elevators etc 1 kW with yearly usage 2.7 MWh
Service hot water	4,9 kWh/m2,år. 
Losses	50% of losses to zones

	Cooling system: 5% of delivered cooling Heating system: 5% of delivered heat Hot water circulation: 0,5 W/m2,
Climate file	Goteborg_Goteborg_102201_2021_svb.prn (real data for 2021)
Areor etc	
Floor area	11171.1 m²
Volume	37584.2 m³
Wall area	8446.9 m²
Window fraction	21.4 %
Mean U-value	0.3031 W/(m² K)

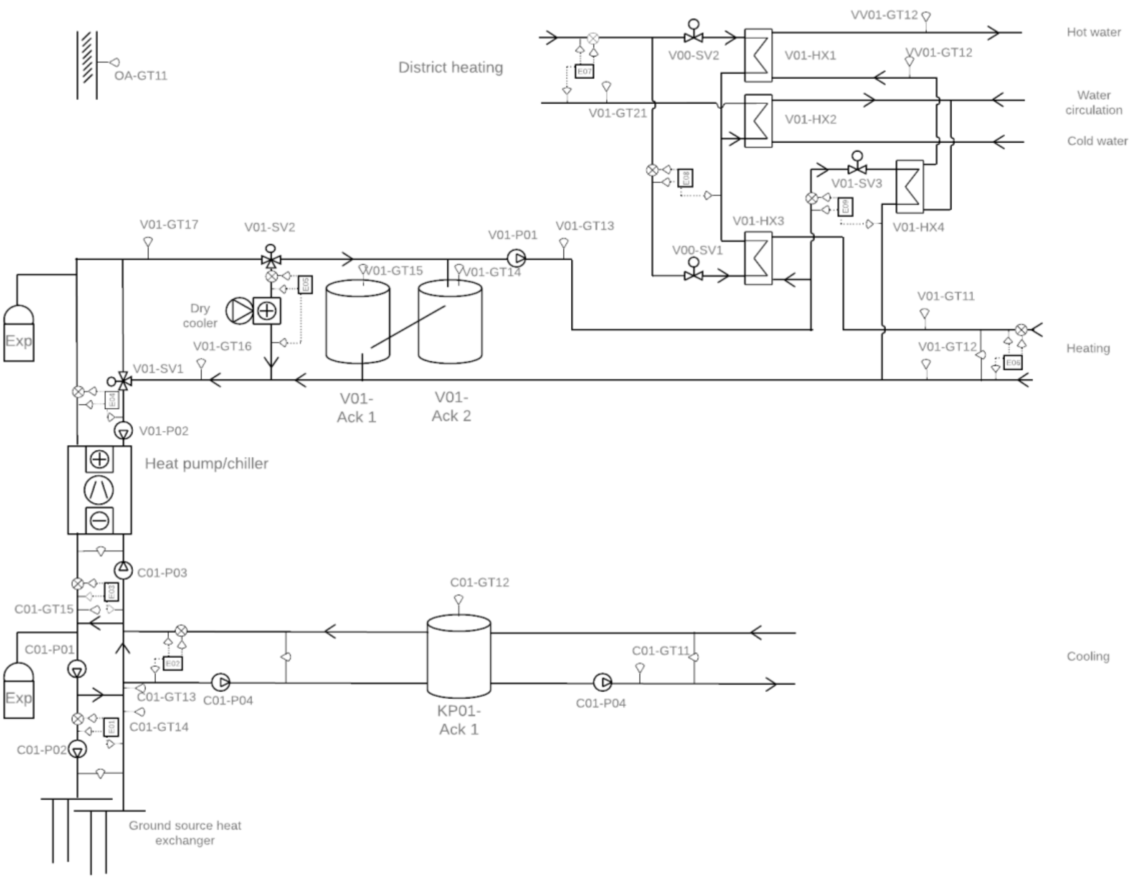
Building envelope	Area [m²]	U [W/(m² K)]	U*A [W/K]	% of total
Walls above ground	2073.00	0.30	621.90	24.29
Walls below ground	610.28	0.21	128.04	5.00
Roof	1970.79	0.08	158.27	6.18
Floor towards ground	1987.20	0.19	387.29	15.13
Floor towards amb. air	0.00	0.00	0.00	0.00
Windows	1805.59	0.39	708.51	27.67
Doors	0.00	0.00	0.00	0.00
Thermal bridges			556.44	21.73
Total	8446.86	0.30	2560.46	100.00

Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External wall / internal slab	1534.82 m	0.112 W/(m K)	171.899
External wall / internal wall	596.55 m	0.076 W/(m K)	45.457
External wall / external wall	133.10 m	0.320 W/(m K)	42.592
External windows perimeter	2523.09 m	0.049 W/(m K)	124.136
External doors perimeter	0.00 m	0.000 W/(K m)	0.000
Roof / external walls	634.07 m	0.086 W/(m K)	54.530
External slab / external walls	342.07 m	0.287 W/(m K)	98.242
Balcony floor / external walls	0.00 m	0.000 W/(K m)	0.000
External floor towards amb. air/internal wall	0.00 m	0.000 W/(K m)	0.000
Roof / Internal walls	236.01 m	0.083 W/(m K)	19.589
External walls, inner corner	25.70 m	0.000 W/(m K)	0.000
Roof / external walls, inner corner	426.37 m	0.000 W/(m K)	0.000
External slab / external walls, inner corner	139.82 m	0.000 W/(m K)	0.000
Total envelope (incl. roof and ground)	8446.86 m²	0.000 W/(m² K)	0.000
Extra losses	-	-	-0.001
Sum	-	-	**556.444**

Windows	Area [m²]	U Glass [W/(m² K)]	U Frame [W/(m² K)]	U Total [W/(m² K)]	U*A [W/K]	Shading factor g
ENE	288.23	0.30	0.30	0.30	86.47	0.50
SSE	698.09	0.52	0.52	0.52	365.47	0.43
WSW	266.28	0.30	0.30	0.30	79.88	0.50
NNW	552.98	0.32	0.32	0.32	176.69	0.50
Total	1805.59	0.39	0.39	0.39	708.51	0.47

Plant

The plant used in the office test bench model is shown below. Heat is by default generated by two ground source heat pumps that run against two buffer tanks. If the heat doesn't reach the set point, district heating is used as top heating. Hot water is prepared mainly by the district heating system, however if the capacity of the heat pumps is enough, the hot water is pre heated by the heat pump circuit. The cooling is first taken as free cooling from the cold side of the heat pumps. During summer when the free cooling is not enough the heat pumps work in chiller mode. If the heat can't be used for hot water preparation, it's rejected by the dry cooler.



The main equipment is listed below:

- ✓ Heat pumps, 2 x IVT geo 238, capacity 39 kW each with COP 4.5 at 0/35.
- ✓ Bore holes, 20 x 190 m depth with bore hole resistance, Rb=0.11 m,K/W
- ✓ Buffer tanks at hot side, 2 x 1m^3.
- ✓ District heating sub station.

Control of plant

Below is the control described in detail.

Hot side

H1: The supply temperature to the heating system (HSP) is a curve set as a function of outdoor temperature, OA-GT11.

H2: In heating mode, the Heat pump is controlled to maintain the temperature of V01-GT15 as HSP + an additional temperature, DT1.

H3: The Valve V01 SV1 is controlled to maintain the temperature of V01-GT15 as H1.val + an additional temperature, DT2.

H4: The valve V00-SV1 is controlled to maintain the temperature of V01-GT11 as H1.val.

H5: The Valve V01-SV3 is controlled to maintain a temperature of DHW at sensor VV01-GT11 of 55 deg. V01-GT13 must be dT higher than VV01-GT13

H6: The valve V00-SV2 is controlled to maintain a temperature of 55 degrees at sensor VV01-GT12

Cool side
C1: The supply temperature to the cooling system (CSP) is a curve set as a function of outdoor temperature, OA-GT11

C2: The pump C01-P01 is controlled to maintain a temperature at C01-GT15 of at minimum 2 degrees or A maximum temperature at C01-GT13 of C1.val - 4 degrees. The maximum value of the two control signals is used.

C3: The pump C01-P02 is controlled to maintain a maximum temperature of C1.val - 3 degrees at C01-GT13 (if the temperature at C01-GT14 is 1 degree lower than the temperature at C01-GT12) or or a minimum temperature at C01-GT15 of 1 degree. The maximum values of the two control signals is used.

C4:C01-P03 is running at full speed when Heat pump/chiller is running (HC1.val>0).

C5: In cooling mode the Chiller is controlled to maintain C1.val - 2 degrees at C01-GT13

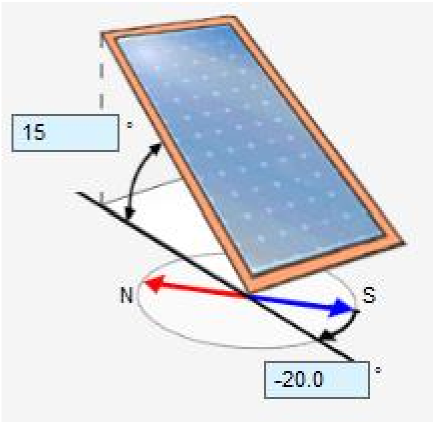
C6: C01-P04 is controlled to maintain C1.val at C01-GT11

C7: In cooling mode (H2.val=0)the valve V01-SV2 is controlled to maintain the temperature at V01-GT16 as H1.val. For V01-SV2 to be opened the valve V00-SV1 must be closed (H4=0).

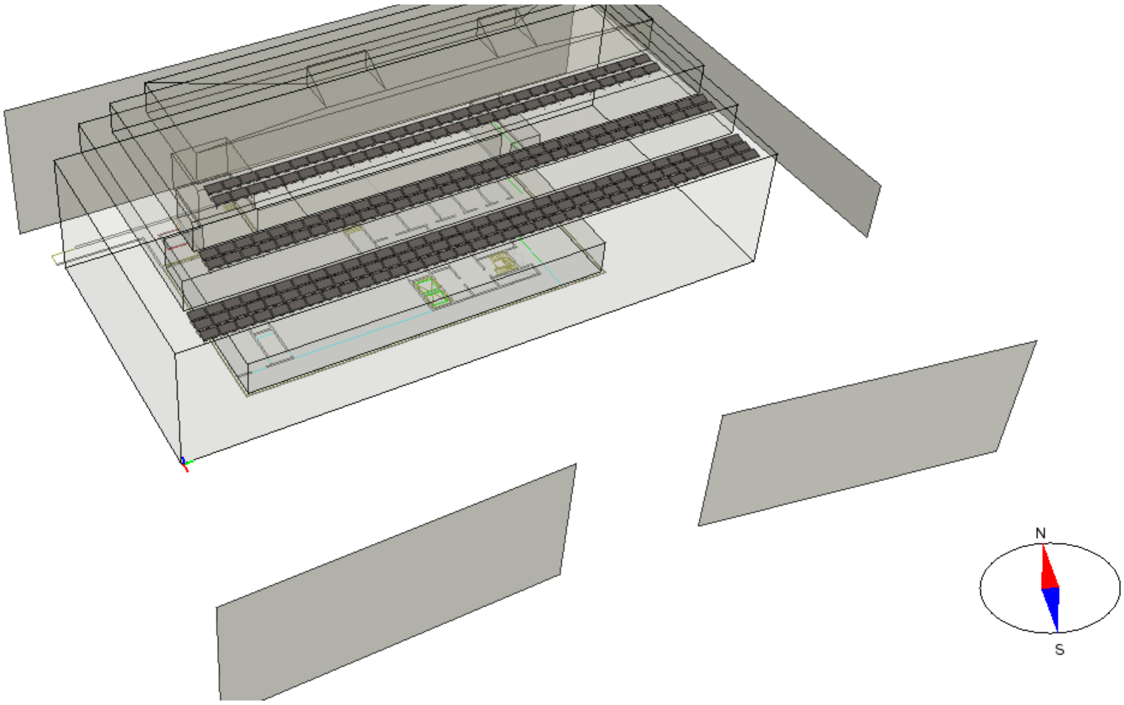
HC1: The heat pump chiller is run using the maximum of values from H2 and C5. If there is a signal sent from supervisory control, the use of the heat pump in heating mode will be prohibited. It will always work in cooling mode if needed as there is no other mean of producing chilled water.

Electrical system

The building is in this test bench equipped with 225 panels, 1.627 m^2/each shaded only by the building itself. This is not what is installed in the real building. Also, the electrical system is equipped with five Tesla_Powerwall of 268Ah.



310 W(STC) Mono-c-Si module, efficiency of 19% with estimated layout of 10 X 6 cells grouped in 3 sub-modules divided in width, Cells are square shaped in dimensions of 156 x 156 mm.



Generating PV and electricity data for a building at different locations in the world.

In another part of the project the testbench is run without external control in different locations, besides Gothenburg it is simulated located in Phoenix and Denver. Hourly data of the PV production, heat pump compressor usage, top-heating usage and the electricity used in the building was extracted from the model to be used in a separate analysis presented in the PhD thesis “Buildings’ Transition to Active Nodes: Assessing the Viability of DC Distribution, PV and Battery Storage”, Chapter 4, “AC vs DC Building Distribution: Effect from PV and Battery, and Supply–Demand Correlation.” by Patrik Ollas.

Climate files used:

Gothenburg (Goteborg_Goteborg_102201_2021_svb.prn)

	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudiness, %
January	-0.6	88.2	30.2	9.6	-0.8	0.2	79.2
February	-1.8	83.5	69.5	27.6	-1.1	0.3	66.9
March	3.5	80	88.4	43.7	1.4	1	71.2
April	6.1	58.3	220.2	73.1	1.6	-1.4	49.5
May	10.5	77.3	88.5	98.7	0.2	0.7	79
June	16.9	69.7	206.6	103.8	1.6	0.9	56.5
July	20	72.1	196.6	101.9	0.7	0.6	56
August	16.1	74.4	145.2	80.8	1	-0.3	63.3
September	13.8	78.8	90.8	56.4	-0.1	0.4	71.6
October	10.7	81.6	51.3	28.9	1.6	2.4	79.6
November	5.9	86.2	21.5	12.4	0.7	0.6	84.7
December	-0.3	87.2	30.7	7.7	-0.9	0.4	75.8
mean	**8.5**	**78.1**	**103.2**	**53.9**	**0.5**	**0.5**	**69.5**

Denver (USA_CO_Denver.Intl.AP.725650_TMY3_epw.prn)

	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudiness, %
January	0.8	46.7	201.1	30.7	0.7	1	42.9
February	-0.1	54.3	191.6	46.2	-0.1	0.3	52.6
March	6.1	40.6	246.8	57.3	0.8	0.7	49.8
April	5.8	61.4	185.8	84.1	-0.1	0.2	77.8
May	15.5	52.6	241.8	98.2	-0.6	0.8	59.3
June	23.1	42.3	305.4	87.5	-0.5	0.4	40
July	22.3	50.3	272.9	91.6	-0.1	0.5	43.8
August	22.6	44.9	254.7	82.2	0.9	1.1	53.7
September	19.2	40.9	256.6	67.4	0.2	1.2	47.9
October	10.1	60.9	215.6	46.7	0	1	49.9
November	2.9	52.2	164.3	40.5	0.9	1.3	51
December	1.4	48.8	169.4	28.9	0	0.5	42.6
mean	**10.9**	**49.6**	**225.8**	**63.5**	**0.2**	**0.7**	**50.9**

Phoenix (USA_AZ_Phoenix-Sky.Harbor.Intl.AP.722780_TMY3_epw.prn)

	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudiness, %
January	13	36.9	224.6	41.6	-0.6	0	27.3
February	15.7	51.6	233.2	53.4	-0.7	0.3	42.4
March	17.3	42	261.3	69	0.2	0.2	31.8
April	23.6	22.6	332.1	74.1	-0.2	0.6	26.3
May	27.3	24.8	347.3	83.2	-0.2	0.6	26
June	34	19.5	370.4	81.1	0.5	0	27.6
July	35.6	29.9	305.9	92	0.9	0.2	44.9

August	33.8	31.6	314.5	81.9	0.1	0.2	27
September	30.4	29.6	312.3	65.8	-0.9	0	30.4
October	24.8	34.7	271	52.9	-0.9	0.4	29
November	18	37.9	255.9	40.7	-0.5	0.1	26.8
December	11.7	50.5	227	36.4	-0.3	0.2	41.6
mean	**23.8**	**34.2**	**288.1**	**64.4**	**-0.2**	**0.2**	**31.7**

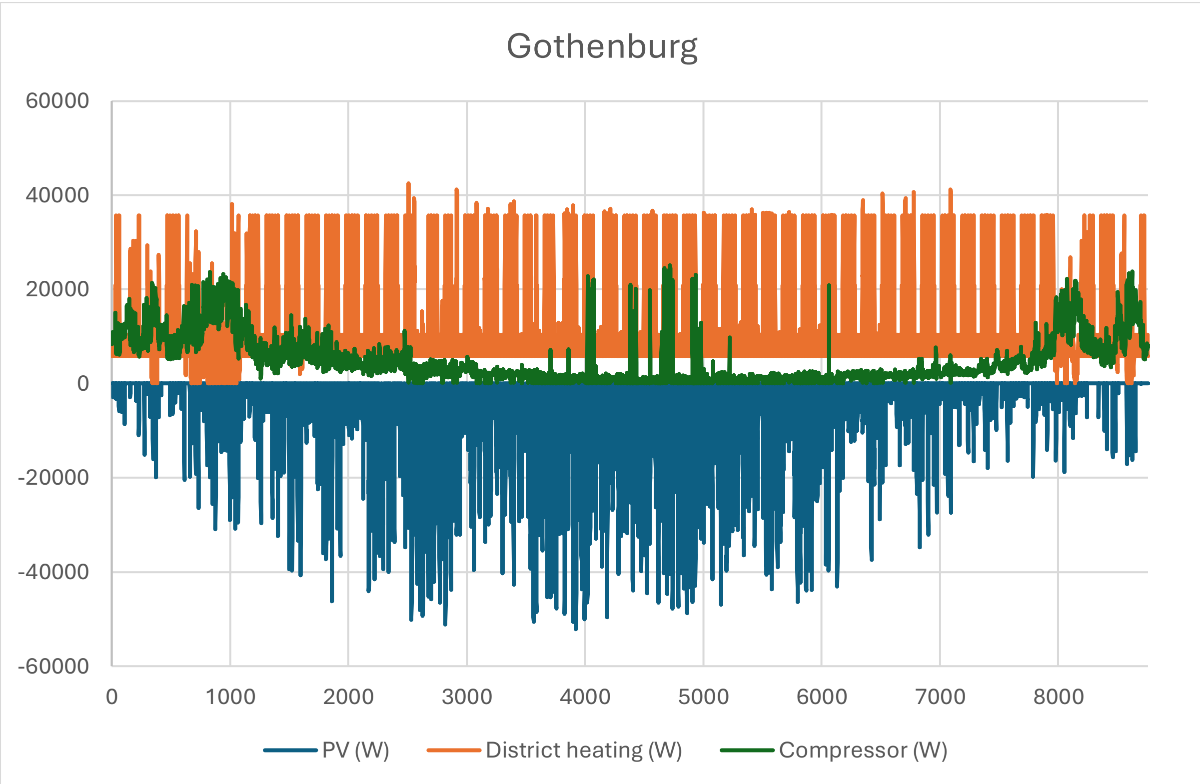
List of output

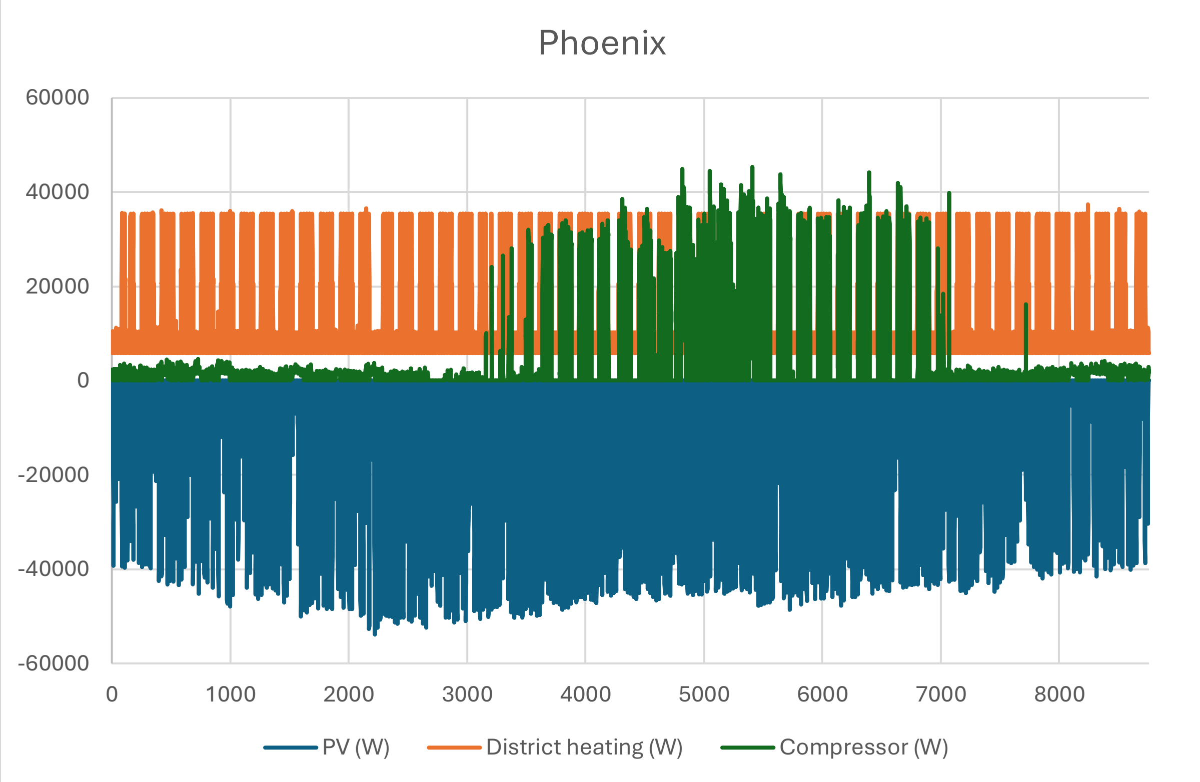
The following output was delivered for each location.

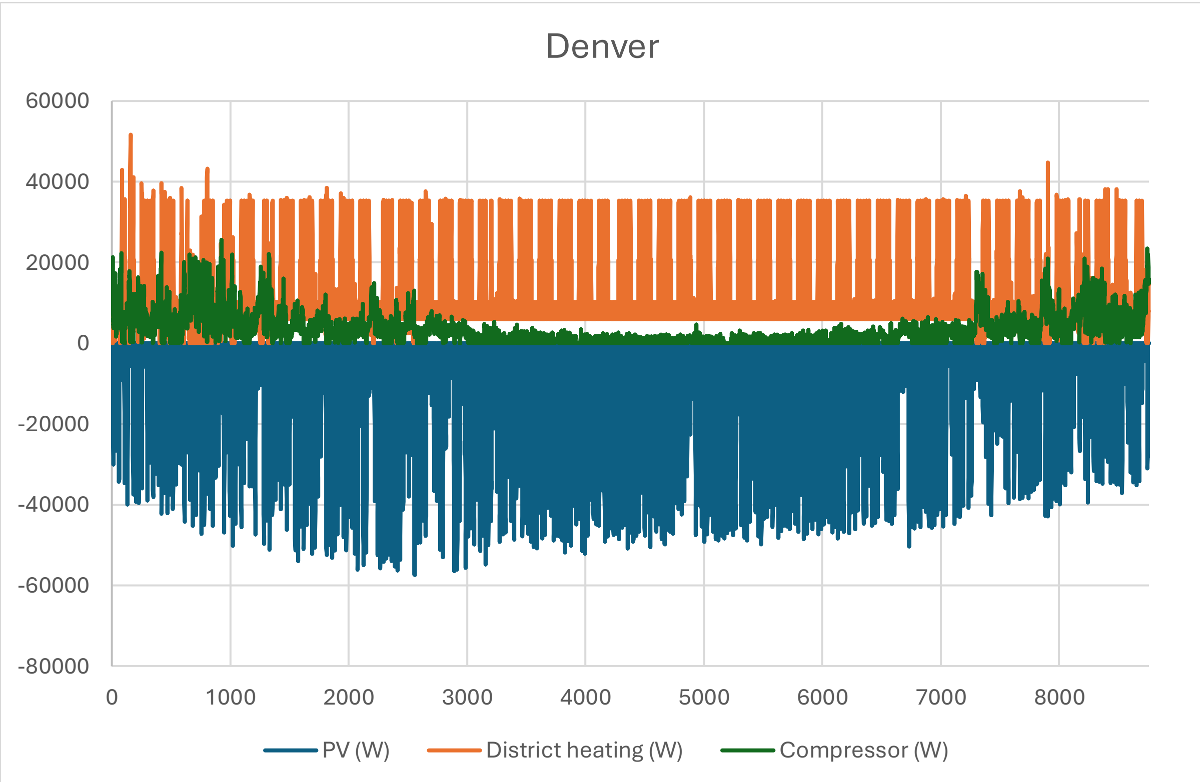
PV	Fans
District heating	Fans kitchen
Compressor	Equipment
Pumps cooling	Equipment, kitchen
Dry cooler	Lighting
Pumps, additional	Elevators

Diagrams of results

Below is shown some of the output is shown; PV, district heating and compressor electricity for the three locations.




Phoenix
60000
40000
20000
0
-20000
-40000
-60000
0
1000
2000
3000
4000
5000
6000
7000
8000
PV (W)
District heating (W)
Compressor (W)


Denver
60000
40000
20000
0
-20000
-40000
-60000
-80000
0
1000
2000
3000
4000
5000
6000
7000
8000
PV (W)
District heating (W)
Compressor (W)

Evaluating rule-based price control of heat production with heat pump and district heating

Previously apartment buildings and offices were designed to use as little energy as possible expressed in kWh/m^2 without any weight between district heating, electricity, or other sources. Sometimes this unweighted energy usage is still a requirement. However, minimum energy usage is not necessary the same as minimum cost neither for the building owner nor the society. Nowadays the Swedish building code has its requirement not in energy use but in weighted energy usage, primary energy number. The study below is intended to show how it looks like if a control algorithm is used to minimize the running cost. Will the lowest cost generate the lowest primary energy number? The study is performed on an office building and an apartment building.

Office building

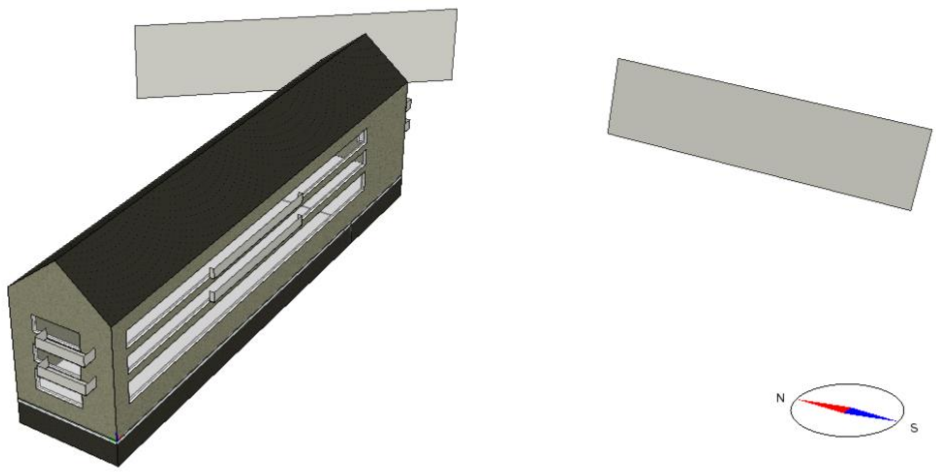
The office building used is the same as described in the testbench section above but with modified supervisory control.

Apartment building

Building

The apartment building simulated is of modern construction with an Um value of 0.38 W/K

The average ventilation air flow for the apartments is 0.6 l/s,m^2.



The table below shows a summary of the input to the simulation model.

Parameter	**Desription**
Location	Stockholm
Climate	SWE_Stockholm-Bromma_Stockholm_102613(SMHI-Bov)_1991-2020.prn
Envelope	See separate table below
Thermal bridges	See separate table below
Infiltration	Wind driven infiltration 0.3 l/s,m2 at 50 Pa. Wind profile: Suburban Semi sheltered
Windows	See separate table below Ground reflectance 20%

<table>
<tr><th>Parameter</th><th>Desription</th></tr>
<tr><td>Sun screen</td><td>None</td></tr>
<tr><td>Shading buildings</td><td>See figure above</td></tr>
<tr><td>Room heating</td><td>Water radiators controlled to maintain +21°C</td></tr>
<tr><td>Plant, heating</td><td>Ground source heat pumps with district heating as top heat.</td></tr>
<tr><td>Room cooling</td><td>None</td></tr>
<tr><td>Plant, cooling</td><td>None</td></tr>
<tr><td>Ventilation</td><td>Constant airflow 0.6 l/s,m²</td></tr>
<tr><td>AHUs</td><td>Always on
See list below.</td></tr>
<tr><td>Occupants</td><td>Max 112 people
Occupancy: 17-07 every day
Metabolism: 1,0 Met
Clothing =0.85±0.25 CLO (varying to receive comfort if possible).</td></tr>
<tr><td>Lighting and equipment</td><td><table>
<tr><td>Equipment</td><td>No units</td><td>Power,W</td><td>Schedule</td><td>Yearly total, kWh</td></tr>
<tr><td>Living area</td><td>224</td><td>75</td><td>17-07 every day</td><td>85837</td></tr>
<tr><td>Business area</td><td>18.67</td><td>75</td><td>Business</td><td>6135</td></tr>
<tr><td>Garage, light</td><td>6.14</td><td>100</td><td>Always on</td><td>5379</td></tr>
<tr><td>total</td><td></td><td></td><td></td><td>97351</td></tr>
</table></td></tr>
<tr><td>Additional facility</td><td><table>
<tr><td></td><td>kW</td><td>kWh</td></tr>
<tr><td>Elevators</td><td>0.276</td><td>2418</td></tr>
<tr><td>Pump, water</td><td>0.17</td><td>1489</td></tr>
<tr><td>Roof ice prevention</td><td>0.2</td><td>1752</td></tr>
<tr><td>Control</td><td>0.17</td><td>1489</td></tr>
<tr><td>External lighting</td><td>0.17</td><td>1489</td></tr>
</table></td></tr>
<tr><td>Domestic hot water</td><td>71810.4kWh/year</td></tr>
<tr><td>Losses</td><td>50% of losses to zones
Heating system: 10% of delivered heat
Hot water circulation: 0,685 W/m²,</td></tr>
<tr><td>Living area</td><td>3148.5 m²</td></tr>
<tr><td>Garage</td><td>614.0 m²</td></tr>
</table>

Building envelope	**Area [m²]**	**U [W/(m² K)]**	**U*A [W/K]**	**% of total**
Walls above ground	1303.68	0.10	133.63	8.73
Walls below ground	412.20	0.09	37.26	2.43
Roof	937.23	0.10	91.41	5.97
Floor towards ground	720.00	0.29	210.03	13.72
Floor towards amb. air	0.00	0.00	0.00	0.00
Windows	666.13	1.05	699.43	45.68
Doors	0.00	0.00	0.00	0.00
Thermal bridges			359.50	23.48
Total	**4039.23**	**0.38**	**1531.25**	**100.00**

Thermal bridges	**Area or Length**	**Avg. Heat conductivity**	**Total [W/K]**
External wall / internal slab	144.00 m	0.000 W/(m K)	0.000

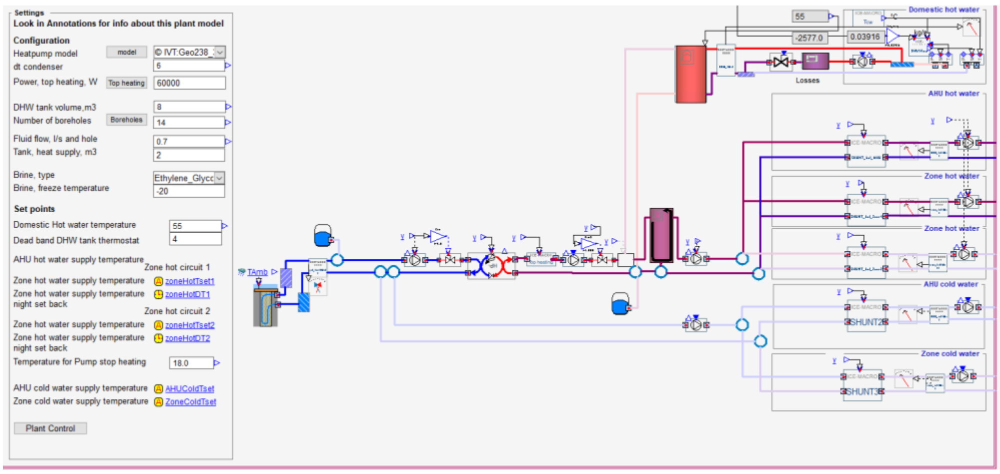
Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External wall / internal wall	0.00 m	0.000 W/(K m)	0.000
External wall / external wall	62.40 m	0.000 W/(m K)	0.000
External windows perimeter	668.70 m	0.000 W/(m K)	0.000
External doors perimeter	0.00 m	0.000 W/(K m)	0.000
Roof / external walls	151.28 m	0.000 W/(m K)	0.000
External slab / external walls	143.60 m	0.000 W/(m K)	0.000
Balcony floor / external walls	99.32 m	0.000 W/(m K)	0.000
External floor towards amb. air/internal wall	0.00 m	0.000 W/(K m)	0.000
Roof / Internal walls	0.00 m	0.000 W/(K m)	0.000
External walls, inner corner	0.00 m	0.000 W/(K m)	0.000
Roof / external walls, inner corner	0.00 m	0.000 W/(K m)	0.000
External slab / external walls, inner corner	0.00 m	0.000 W/(K m)	0.000
Total envelope (incl. roof and ground)	4039.23 m^2	0.089 W/(m^2 K)	359.491
Extra losses	-	-	0.005
Sum	-	-	**359.496**

Windows	Area [m^2]	U Glass [W/(m^2 K)]	U Frame [W/(m^2 K)]	U Total [W/(m^2 K)]	U*A [W/K]	Shading factor g
N	285.02	0.80	1.80	1.05	299.28	0.48
E	36.60	0.80	1.80	1.05	38.43	0.48
S	308.03	0.80	1.80	1.05	323.44	0.48
W	36.47	0.80	1.80	1.05	38.29	0.48
Total	666.13	0.80	1.80	1.05	699.43	0.48

Air handling unit	System SFP [kW/(m^3/s)]	Heat exchanger temp. ratio/min exhaust temp. [-/C]
Apartments	0.70/0.50	0.80/1.00
Business	0.80/0.60	0.80/1.00
Garage	1.00/0.67	0.80/-7.00
Other	0.70/0.50	0.80/-7.00

Plant

The heat is generated by a ground source heat pump with district heating as top-heating. In its basic configuration the plant either produces heat for the zones and air handling unit or domestic hot water. The switch between domestic hot water preparation or heating is made by a three-way valve that switches the flow direction. The top heating is located directly after the heat pump in series.



In this particular case there are 14 boreholes, coupled to a heat pump of 58 kW heat and top up with 60 kW district heating.

The tank in the heating circuit has a volume of 2 m^3 and the tank for domestic hot water preparation, a volume of $8m^3$.

The heat pump works in two modes, heating mode or domestic hot water preparation mode. In heating mode, a PID controller is used to maintain the setpoint in the tank.

Supervisory control

The supervisory control overrides the control of the plant when use of the heat pump is not preferable due to the calculated cost. The algorithm is as follows, use district heating if the cost of district heating is less than electricity cost divided by the COP of the heat pump.

Different model for COP to be used in model-based control.

To select what energy source to use when multiple solutions are available using some kind of rule-based approach implies that some kind of model for heat generation is used. In the case of heat pumps with district heating there is a need for two models, one for district heating and one for the heat pump. The district heating can be modeled using constant efficiency as the efficiency is very high, close to 100%. In this study a constant value of 100% is used. The heat pump on other hand is complicated as the efficiency, COP depends on the temperature levels of the source and sink together with the speed of the compressor. When the heat pump is running, the COP can be measured and used directly in the control. However, when the heat pump has been turned off, there must be a model used in the control algorithm that enables it to be turned on again. If the control uses real measured COP to calculate when to turn off the heat pump, the model used to predict when to turn it on needs to be good enough not to cause an on-off oscillation. One way of limiting the risk for oscillations is to use the same model for the entire control and not to use the real COP at all. In this study two models have been tested, Constant COP, and a more complex model based on Carnot COP.

The constant COP used is in this study set to 3. However, in the case with alternative design below, the COP is 3 for heating and 2 for domestic hot water.

The Carnot based model below is calibrated against the normal IDA ICE model with following result with a deviation less than 5%.

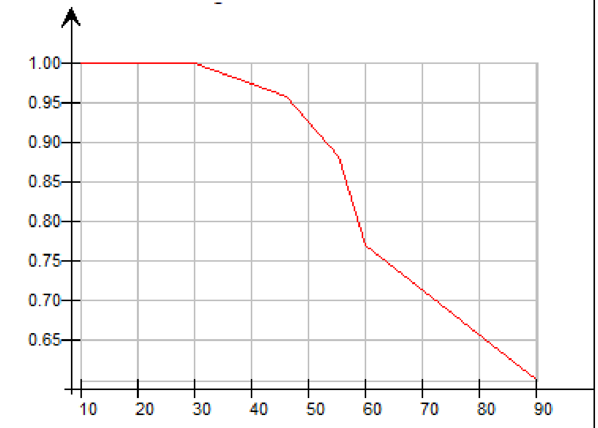
The model is based on following equation and there are two correction curves, one for supply temperature (corr1) from the condenser Tcond,out and one for the control signal to the heat pump, ctrl (corr2).

COP=COPc x eta x corr1x corr2

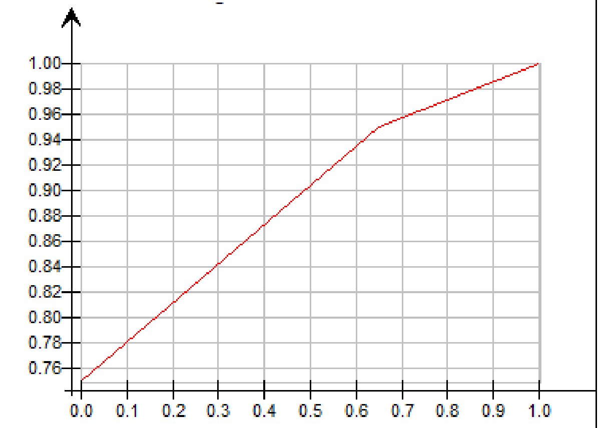
Where COPc=(273.15+Tcond,out)/(Tcond,out-Tevap,out).

With eta=0.6 and the following correction curves the calibration results is shown below.

Corr1, function of supply temperature from the condenser.

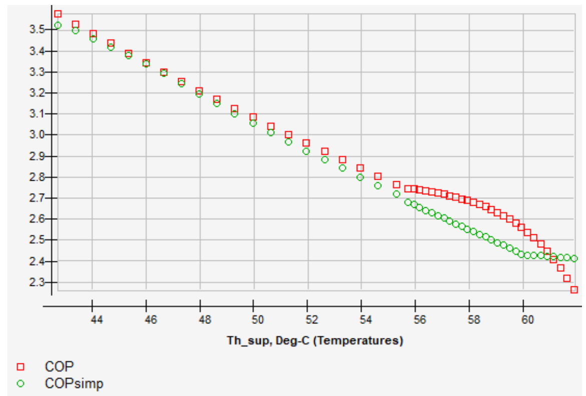


Corr2, function of the control signal to the heat pump.

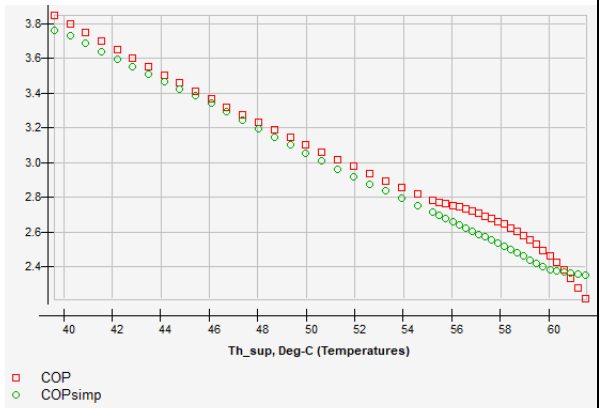


Calibration result of comresssor COP as function of leaving temperature from condenser for different control signals:

Ctrl=1



Ctrl=0.75



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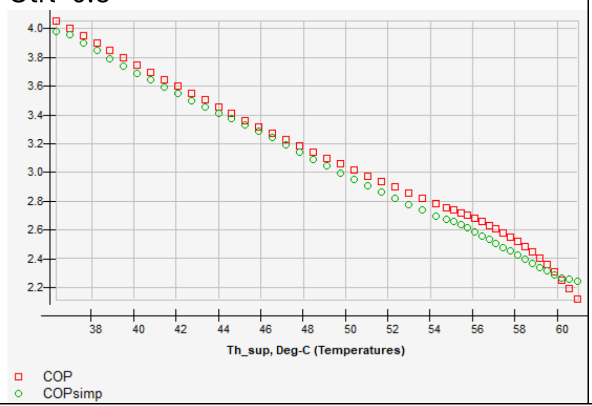
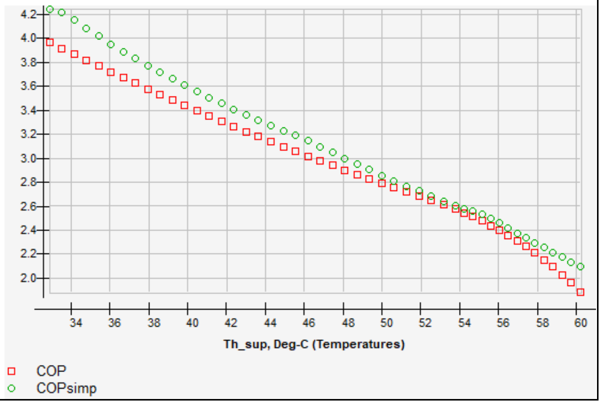


Ctrl=0.25

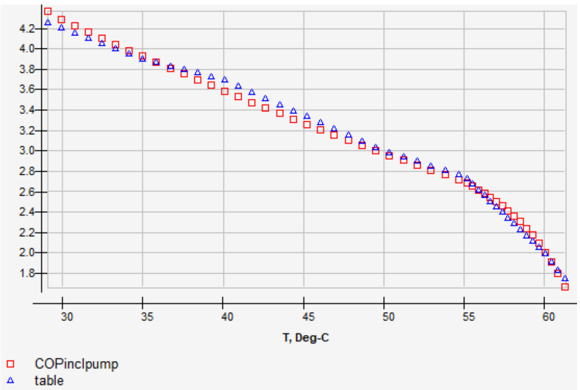


However, a ground source heat pump uses a large pump on the cold side, this pump uses a significant amount of electricity and needs to be part of the calculations. Then, it's more difficult to make a continuous mode. Instead, a table model is used based on the control signal and leaving temperature at the condenser side.

Tcond,out / ctrl	30	35	40	50	55	60	65	70
0.25	2.3	2.2	2.1	1.86	1.7	0.8	0.5	0.5
0.5	3.4	3.16	2.95	2.5	2.3	1.47	0.7	0.7
0.75	3.9	3.7	3.4	2.8	2.6	1.85	0.8	0.8
1	4.2	3.9	3.7	3	2.75	2	1	1

Calibration result of COP with pumps included as function of leaving temperature from condenser for different control signals using the table model:

Ctrl=1



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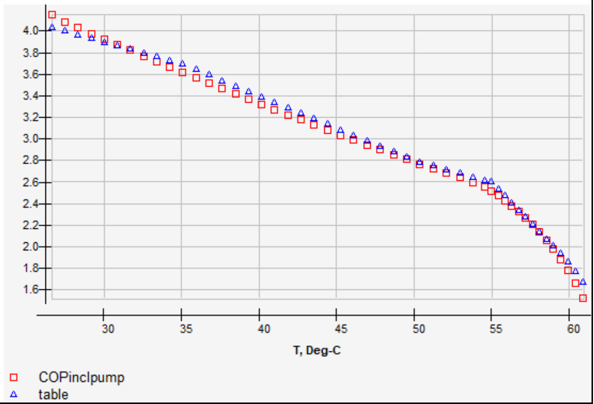

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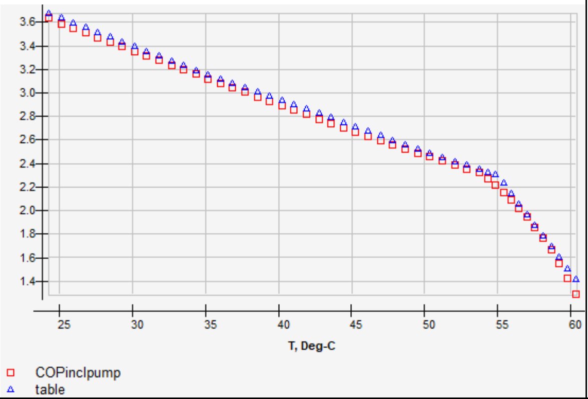

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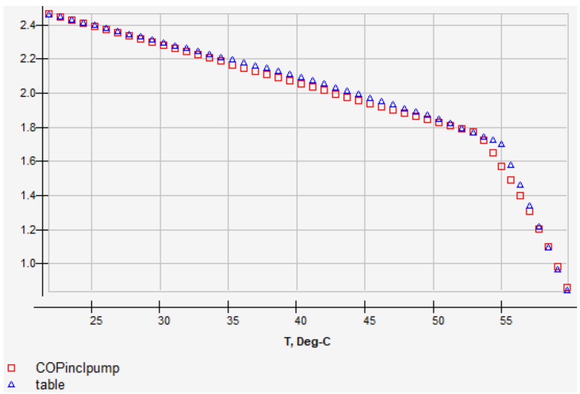
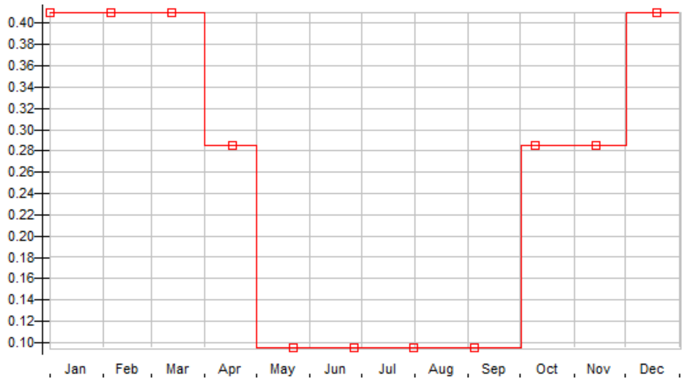


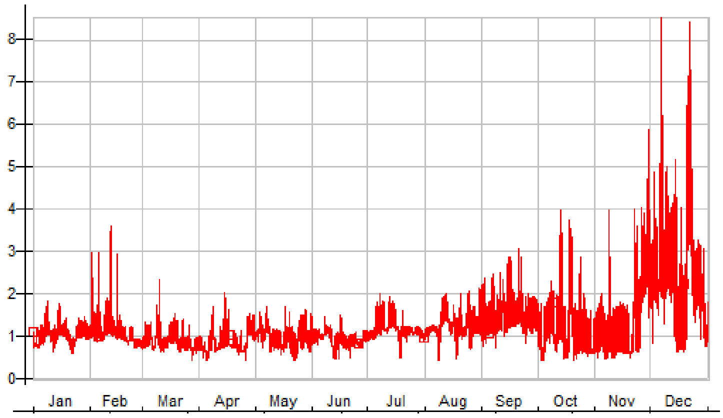
Cost

The cost of district heating is taken from Göteborg Energi 2023 and is a fixed price for certain months. Sek/kWh 0.41, 0.285 and 0.095, respectively, according to the graph below.

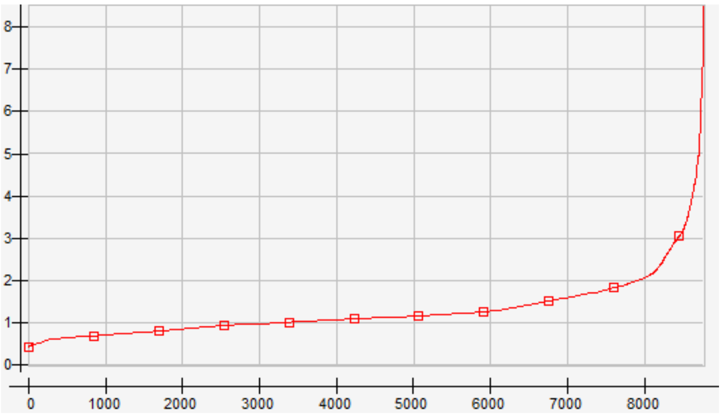


The hourly electricity price is taken from Nordpool for 2021. In addition to this there is cost for use of the net and electricity tax. The sum of tax and transfer cost are included in the price.

The electricity price over the year is indicated by the graph below. The average cost SEK/kWh 1.3, the minimum 0.4 and maximum 8.3.



The duration of the cost is as below.



Algorithm

The Algorithm for the override signal switching the heat pump on-off is straight forward.

If the total electricity price divided by COP including ground source pipe minus district heating price is greater than 0 then the heat pump is turned off. To avoid rapid on/off behavior there is a small hysteresis in the model +/- 0.025. The COP is calculated using the control signal from the plant control and the temperature setpoint for the heat pump. The setpoint is used instead of the actual value as the temperature of the condenser will be wrong when the heat pump is in off mode.

Alternative design for energy flexibility to minimize running costs.

An alternative design of the plant was tested, with the top-heating separated between domestic hot water and heating. This was motivated by the fact that the COP of the heat pump differs between hot water preparation and heating due to the differences in temperature levels.

Results from evaluation.

Results from simulation of multifamily house

Cost, SEK / Case	Electricity	District heat	Total	Saving, %
Heat pump first	53729	20030	73759	0
District heating	3500	46879	50379	32
Constant COP=3	17526	32324	49850	32
Table COP	14780	33522	48302	35
Alternative design Heat pump first	87476	5598	93074	-26
Alternative design Constant COP=3	18469	29602	48071	35
Alternative design Table COP	18610	29810	48420	34

Energy kWh / Case	Electricity	District heat	Total	kWh/m^2	Primary energy number (BBR)*
Heat pump first	36950	78167	115117	36.6	38.5
District heating	2730	158395	161125	51.2	36.8
Constant COP=3	18304	120970	139274	44.2	37.4
Table COP	14847	124622	139469	44.3	36.2
Alternative design Heat pump first	62874	14761	77635	24.7	39.2
Alternative design Constant COP	20345	112535	132880	42.2	36.7
Alternative design Table COP	18467	113391	131858	41.9	35.8

*Primary energy number for electricity 1.8 and for district heating 0.7.

Results from simulation of office

Cost, SEK / Case	Electricity	District heat	Total	Saving,%
Heat pump first	74980	42971	117951	0
District heating	17168	81293	98461	17
Constant COP=3	36000	58541	94541	20
Table COP	30531	60183	90714	23

Energy kWh / Case	Electricity	District heat	Total	kWh/m^2	Primary energy number (BBR)*
Heat pump first	54328	178729	233057	20.6	19.7
District heating	13323	284539	297862	26.3	19.7
Constant COP=3	34301	226282	260583	23.0	19.5
Table COP	29879	230041	259920	23	19.0

*Primary energy number for electricity 1.8 and for district heating 0.7.

Discussion

An interesting finding is that the case for the multifamily house with highest running cost have by far the lowest energy usage just looking at kWh. A few years ago, this would have been considered the best system and a lot of systems in use are designed and run with that in focus. Fortunately, changing the control can reduce the running cost to the level of the other systems.

In this study more complex rate plans are not studied. However, with the mix of heat pump and district heating it's possible to limit the fixed cost depending on installed power.

The COP with or without bore hole pump is totally different due to the increasing influence of the pump electricity on COP with decreasing delivered heat. This can however be optimized by changing the number of holes used depending on the extracted heat.