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Abstract:
The sun in Norway is a very important source of energy due to the large number of hours of sunshine there are in spring and summer months. For this reason this source of energy could replace the oil and part of the electricity consume in these months; in last years lot of sources of energy has been studied and solar energy is one of the cheapest, because the energy of the sun is free, and the cost of the system is lesser than another systems for capture energy, as photovoltaic energy.
This type of energy depends a lot of the weather conditions so different weather conditions will be simulated and analyzed.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

Table of contents

PREFACE	5
NOMENCLATURE	6
OVERVIEW OF TABLES AND FIGURES	12
1.2.1 Location and weather in Norway	17
1.2.2 Water requirements in Norwegian houses	19
1.2.3 Total radiation	20
2.1.1 Solar collector	23
2.1.2 Energy storage tank	25
2.1.3 Underfloor heating	26
2.1.4 Boundaries of the system	27
2.2.1 Solar collector	28
2.2.2 Energy storage tank	31
2.2.3 Underfloor heating	34
2.3.1 Assumptions in the solar collector	35
2.3.2 Assumptions in the energy storage tank	36
2.3.3 Assumptions in the underfloor heating (house)	37
2.3.4 Assumptions of the electricity system, the solar collector system, and the underfloor heating	38
2.4.1 Coefficients and areas of heat transmission in the solar collector	38
2.4.2 Coefficients and area of heat transmission in the energy storage tank	43
2.4.3 Coefficients and area of heat transmission in the house	45
3.1.1 Mass balance	50
3.1.2 Energy balance	52
3.2.1 Inputs in the solar collector	63
3.2.2 Inputs in the energy storage tank	63
3.2.3 Inputs in the underfloor heating	64
3.2.4 Outputs of the solar collector	64
3.2.5 Outputs of the energy storage tank	64
3.2.6 Outputs of the radiant floor	65
3.2.7 Initial conditions	65
4.1.1 Simulation on a clear day	67
4.1.2 Simulation in a partly cloudy day	72
4.1.3 Simulation in a completely cloudy day	77
REFERENCES	88
APPENDICES	92

The table of contents is generated automatically using the styles "Heading 1", "Heading 2", and "Heading 3". Update the table of contents by right click inside the table and select "Update field" and then "Update the whole table".

Preface

This thesis is about Thermal solar energy use in Norway; in last years this technology has been each time more used in this country and is a green alternative energy. Here in Norway, in spring and summer seasons, sun is a good alternative of energy due to the hours of sun this country has.

This Thesis is divided in three important and different parts, first part, the system description in which a detailed configuration of the system is given; a second part about model of the system with mathematics equations and third, the simulation carried out with Open Modelica computer program in which the model is running over time. Different results have been obtained depending on the weather established.

Knowledge about solar collectors have been studied and about engineering of the same.

Knowledge about heat transmission in this collectors has been studied and applied in the system modeled.

The simulation of this system is carried out with Open Modelica, so some knowledge about this program was studied.

I would like to thank the teacher Bernt Lie, Adjunct Professor at University of Agder, Professor at Telemark University College , and the teacher Cesar de Prada, Professor of Systems Engineering and Automation and Doctor in Physics (Electronics) for their assistance in the preparation of this Thesis.

I would like to thank to the Aventa Solar Company for some information of this Thesis.

Porsgrunn, 04/06/2013

Juan José Pérez Martín

Nomenclature

Symbol	Comment
A	Absorber pipe
A_c	Cross sectional area of the collector-coil pipe (m^2)
A_A	Annular area of the absorber pipe (m^2)
A_E	Annular area of the glass envelope (m^2)
A_{A-c}	Area of heat transmission in the collector pipe (m^2)
A_{c-t}	Area of heat transmission by forced convection in the coil (m^2)
A_{lost}	Area of heat transmission through the walls of the house (m^2)
A_I^r	Area of heat transmission by radiation from the sun (m^2)
A_r	Area of heat transmission in the underfloor heating (m^2)
A_t	Cross sectional area of the tank (m^2)
A_{wall}	Area of each wall of the house (m^2)
A_{roof}	Area of the roof (m^2)
A_{A-E}^r	Area of heat transmission by radiation from the absorber pipe to the glass envelope (m^2)
$A_{E-cloud}^r$	Area of heat transmission by radiation from the glass envelope to the cloud (m^2)
A_{E-air}	Area of heat transmission between the glass envelope and the air (m^2)
A_{t-a}	Area of heat transmission by natural convection from the tank to the ambient air (m^2)
c	Collector
C_{pw}	Heat capacity of the water (J/kg/K)
C_{pa}	Heat capacity of air (J/kg/K)
C_{pA}	Heat capacity of the absorber pipe (J/kg/K)
C_{pE}	Heat capacity of the glass envelope (J/kg/K)
D_c	Diameter of the collector or coil (m)
D_t	Diameter of the tank (m)
dm	Variation of mass (kg)
dm_{wt}	Variation of the mass water of the tank (kg)

dt	Increase of time (s)
dx	Length of each control volume in the collector pipe (m)
dy	Length of each control volume in the coil pipe (m)
dz	Length of each control volume in the underfloor pipe (m)
dE	Energy change (J)
dH_c	Enthalpy change in the collector (J)
dH_t	Enthalpy change in the tank (J)
E	Glass envelope
e_A	Thickness of the absorber pipe (m)
e_E	Thickness of the glass envelope (m)
\dot{E}_I	Energy input of the system (J)
\dot{E}_O	Energy output of the system (J)
ε_A	Emissivity of the absorber pipe (-)
ε_E	Emissivity of the glass envelope (-)
σ	Stefan Boltzmann constant (J/m^2K^4)
h_{wt}	Height of water inside the tank (m)
H_t	Total height of the tank (m)
\dot{H}	Flow enthalpy (W)
\hat{H}	Mass enthalpy (J/kg)
\dot{H}_{ci}	Inlet enthalpy to the collector (W)
\dot{H}_{co}	Outlet enthalpy from the collector (W)
\dot{H}_{ti}	Enthalpy of the incoming water flow to the tank (W)
\dot{H}_{to}	Enthalpy of the output water flow from the tank (W)
h_c	Individual coefficient of heat transmission by forced convection inside the collector and coil pipe ($W/m^2/K$)
h_{cn}	Individual coefficient of heat transmission by natural convection from the wall of the house to the ambient air ($W/m^2/K$)
h_E	Individual coefficient of heat transmission by natural convection between the glass envelope and the ambient air ($W/m^2/K$)
h_{cnt}	Individual coefficient of natural convection from the tank to the air of the

	house ($\text{W/m}^2/\text{K}$)
h_r	Individual coefficient of heat transmission by natural convection between the wood floor and air of the house ($\text{W/m}^2/\text{K}$)
i	Position at the pipe (-)
N	Final position at the pipe (-)
I	Intensity (A)
I_c	Direct solar irradiance incident on the collector surface (W/m^2)
L_c	Length of the collector (m)
L_{coil}	Length of the coil (m)
L_r	Length of the underfloor pipe (m)
L	Length of heat transmission (m)
m_{ah}	Mass of air inside the house (kg)
m_c	Mass of water inside the collector (kg)
m_{coil}	Mass of water inside the coil (kg)
\dot{m}_c	Mass flow inside the collector (kg/s)
m_A	Mass of the absorber pipe (kg)
m_E	Mass of the glass envelope (kg)
\dot{m}_i	Mass flow inlet (kg/s)
\dot{m}_o	Mass flow outlet (kg/s)
\dot{m}_g	Mass flow generated (kg/s)
\dot{m}_{ti}	Inlet mass flow to the energy storage tank (kg/s)
\dot{m}_{to}	Outlet mass flow from the energy storage tank(kg/s)
m_{wt}	Mass of water inside the tank (kg/s)
p	Pressure (bar)
P_c	Perimeter of the collector pipe (m)
P_{Ai}	Inner perimeter of the absorber pipe (m)
P_{Ao}	Outer perimeter of the absorber pipe (m)
P_{Ei}	Inner perimeter of the glass envelope (m)
P_{Eo}	Outer perimeter of the glass envelope (m)
P_r	Perimeter of the underfloor heating pipe (m)

P_t	Perimeter of the tank (m)
\dot{Q}	Heat transferred to the system (W)
Q'	Heat transferred to the collector (W)
Q''	Heat transferred to the tank (W)
Q'''	Heat transferred in the house (W)
\dot{Q}_I^r	Heat transferred by radiation of the sun to the absorber pipe (W)
\dot{Q}_{A-E}^r	Heat transferred by radiation from the absorber pipe to the glass envelope (W)
\dot{Q}_{A-c}	Heat transferred from the absorber pipe to the water inside the collector pipe (W)
$\dot{Q}_{E-cloud}^r$	Heat transferred by radiation from the glass envelope to the clouds (W)
\dot{Q}_{E-air}	Heat transferred by natural convection from the glass envelope to the air (W)
\dot{Q}_{el}	Heat transferred to the tank by the electricity system (W)
\dot{Q}_{c-t}	Heat transferred to the tank by the coil (W)
\dot{Q}_{t-a}	Heat transferred from the tank to the air of the house (W)
\dot{Q}_r	Heat transferred from the underfloor heating to the air of the house (W)
\dot{Q}_{lost}	Heat transferred from the walls of the house to the ambient air (W)
r_c	Radius of the collector or the coil (m)
r_{Ai}	Inner radius of the absorber pipe (m)
r_{Ao}	Outer radius of the absorber pipe (m)
r_{Ei}	Inner radius of the glass envelope (m)
r_{Eo}	Outer radius of the glass envelope (m)
r_t	Radius of the tank (m)
r_r	Radius of the underfloor pipe (m)
T_{air}	Temperature of ambient air (K)
T_A	Temperature of the absorber pipe (K)
T_E	Temperature of the glass envelope (K)
T_c	Temperature of the water that flows inside the collector pipe (K)
T_{cloud}	Temperature of the clouds (K)
T_{ci}	Inlet temperature of the collector pipe (K)

T_{co}	Outlet temperature of the collector pipe (K)
T_h	Temperature inside the house (K)
T_t	Temperature of the water inside the tank (K)
T_w	Temperature of the water that enters to the tank (K)
T_{wall}	Temperature of the wall of the house (K)
T_r	Temperature of the underfloor pipe (K)
\bar{T}	Average temperature between input and output of the collector or coil or underfloor pipe (K)
U_{A-c}	Overall coefficient of heat transmission of the collector pipe ($W/m^2/K$)
U_{E-air}	Overall coefficient of heat transmission between the glass envelope and the air ($W/m^2/K$)
U_{lost}	Overall coefficient of heat transmission through wall of the house ($W/m^2/K$)
U_{t-a}	Overall coefficient of heat transmission between the tank and the air of the house ($W/m^2/K$)
U_{c-t}	Overall coefficient of heat transmission between the coil and the tank ($W/m^2/K$)
U_r	Overall coefficient of heat transmission in radiant floor ($W/m^2/K$)
V	Voltage (V)
V_c	Volume of the water inside the collector (m^3)
V_{coil}	Volume of the water inside the coil (m^3)
V_a	Volume of air in the house (m^3)
V_t	Volume of the tank (m^3)
V_{wt}	Volume of the water inside the tank (m^3)
v_{wt}	Velocity of water inside the tank (m/s)
v_{wc}	Velocity of water that flows inside the collector (m/s)
v_{wr}	Velocity of water that flows inside the underfloor pipe (m/s)
\dot{W}	Work transferred to the system (W)
\dot{W}'	Work transferred to the collector (W)
\dot{W}''	Work transferred to the tank (W)
\dot{W}'''	Work transferred in the house (W)

x	Axial position in the collector pipe (m)
η_{coll}	Efficiency of the solar collector (-)
ΔT	Temperature increase between surfaces of heat transmission(K)
Δx	Increment in the axial position
δ	Infinitesimal increment
ρ_w	Density of water (kg/m^3)
ρ_A	Density of the absorber pipe (kg/m^3)
ρ_E	Density of the glass envelope (kg/m^3)
ρ_{air}	Density of the air (kg/m^3)

Overview of tables and figures

List of Figures:

1.1.	Location of Porsgrunn.....	17
1.2.	Average temperature per month for Porsgrunn.....	18
1.3.	Average number of rain and snow days.....	19
1.4.	Temperature in a normal spring day in Porsgrunn.....	19
1.5.	Changes in annual mean global irradiance measured within the Polar Circles.....	21
2.1.	Simplified system description of the solar collector.....	23
2.2.	Components of the solar collector	24
2.3.	Scheme of the solar collector.....	24
2.4.	Collector configuration.....	24
2.5.	Scheme of the energy storage tank configuration.....	25
2.6.	Coil configuration.....	26
2.7.	Scheme of the underfloor heating.....	27
2.8.	Underfloor heating configuration.....	27
2.9.	Different colors of solar collectors	28
2.10.	Scheme of the solar collector pipe.....	29
2.11.	Scheme of the solar collector and the tank.....	32
2.12.	Underfloor heating scheme.....	34
2.13.	Heat transferred between different parts of the collector.....	39
2.14.	Area of the solar irradiance.....	40
2.15.	Heat transferred from the coil to the tank and lost in the tank.....	43
2.16.	Heat transferred in the house.....	46
2.17.	Heat transmission of underfloor heating.....	46
2.18.	Heat transmission by natural convection through the wall of the house.....	48
3.1.	Draw of the solar collector controller.....	51
3.2.	Cross sectional area of the energy storage tank.....	52
3.3.	Complete model of the solar collector.....	53
3.4.	A side view of the collector pipe assembly illustrating discretization for numerical simulation.....	56
3.5.	A side view of the coil pipe assembly illustrating discretization for numerical simulation.....	61
4.1.	Inputs in a sunny day: T_w , T_{air} , T_{cloud} (K).....	68

4.2. Inputs in a sunny day: Q_{elec} (W), I_c (W/m^2).....	68
4.3. Inputs in a sunny day: m_{ti} , m_{to} (kg/s).....	69
4.4. Inputs in a sunny day: v_{wc} , v_{wr} (m/s).....	69
4.5. Outputs in a sunny day: hw_t (m).....	69
4.6. Outputs in a sunny day: T_A , T_E (K).....	70
4.7. Outputs in a sunny day: T_t , T_{hou} , T_r (K).....	70
4.8. Outputs in a sunny day: Q_{c-t} , Q_r , Q_{lost} (W).....	71
4.9. Outputs in a sunny day: T_{c1} , T_{c2} (K).....	72
4.10. Inputs in a partly cloudy day: Q_{elec} (W), I_c (W/m^2).....	73
4.11. Inputs in a partly cloudy day: m_{ti} , m_{to} (kg/s).....	73
4.12. Inputs in a partly cloudy day: v_{wc} , v_{wr} (m/s).....	73
4.13. Outputs in a partly cloudy day: hw_t (m).....	74
4.14. Outputs in a partly cloudy day: T_A , T_E (K).....	74
4.15. Outputs in a partly cloudy day: T_t , T_{hou} , T_r (K).....	75
4.16. Outputs in a partly cloudy day: Q_{c-t} , Q_r , Q_{lost} (W).....	76
4.17. Outputs in a partly cloudy day: T_{c1} , T_{c2} (K).....	76
4.18. Inputs in a completely cloudy day: Q_{elec} (W), I_c (W/m^2).....	77
4.19. Inputs in a completely cloudy day: m_{ti} , m_{to} (kg/s).....	77
4.20. Inputs in a completely cloudy day: v_{wc} , v_{wr} (m/s).....	78
4.21. Outputs in a completely cloudy day: hw_t (m).....	78
4.22. Outputs in a completely cloudy day: T_A , T_E (K).....	78
4.23. Outputs in a completely cloudy day: T_t , T_{hou} , T_r (K).....	79
4.24. Outputs in a completely cloudy day: Q_{c-t} , Q_r , Q_{lost} (W).....	79
4.25. Outputs in a completely cloudy day: T_{c1} , T_{c2} (K).....	80
4.26. Outputs in a partly cloudy day: T_t , T_{hou} at $v_{wr} = 2.0$	Appendix 4
4.27. Outputs in a partly cloudy day: T_t , T_{hou} at $v_{wr} = 0.005$	Appendix 4
4.28. Outputs in a partly cloudy day: $T_r[1]$, $T_r[10]$ at $v_{wr} = 2.0$	Appendix 4
4.29. Outputs in a partly cloudy day: $T_r[1]$, $T_r[10]$ at $v_{wr} = 0.005$	Appendix 4

List of Tables:

1.1. Tabular view for temperature and wind per month.....	18
1.2. Consume of water for different activities.....	20
2.1. Properties of the solar collector.....	29
2.2. Parameters of the solar collector.....	30
2.3. Different sizes of the storage energy tanks.....	31
2.4. Properties of the energy storage tank.....	32
2.5: Parameters of the energy storage tank.....	33
2.6. Underfloor heating properties.....	34
2.7. Parameters of the underfloor heating and the house.....	35
2.8. Coefficients and areas of the collector water	39
2.9. Forced convection coefficient inside the collector pipe.....	40
2.10. Heat transferred in the absorber pipe.....	41
2.11. Area of heat transmission in the absorber pipe.....	41
2.12. Heat transferred in the glass envelope.....	42
2.13. Areas of heat transmission in the glass envelope.....	42
2.14. Coefficient of the glass envelope.....	42
2.15. Natural convection coefficient between the glass envelope and the air.....	43
2.16. Coefficients and areas in the energy storage tank.....	44
2.17. Forced convection coefficient inside the coil pipe.....	44
2.18. Heat transferred from the coil.....	45
2.19. Natural convection coefficient between the tank and the air.....	45
2.20. Coefficients of the underfloor heating.....	46
2.21. Natural convection coefficient between underfloor pipe and air of the house.....	47
2.22. Loss coefficient in the house.....	48
2.23. Natural convection coefficient between wall and air.....	48
3.1. Mass balance.....	50
3.2. Mass balance to the energy storage tank.....	51
3.3. Energy balance.....	52
3.4. Energy balance to the collector.....	53
3.5. Energy balance to the water that flows inside the collector.....	55
3.6. Energy balance to the glass envelope.....	57
3.7. Energy balance to the energy storage tank.....	58
3.8. Heat transferred into the tank.....	59

3.9. Enthalpy balance.....	59
3.10. Energy balance to the water that flows inside the coil.....	61
3.11. Inputs in the solar collector.....	63
3.12. Inputs in the energy storage tank.....	63
3.13. Inputs in the underfloor heating.....	64
3.14. Outputs in the solar collector.....	64
3.15. Outputs in the energy storage tank.....	64
3.16. Outputs in the underfloor heating.....	65
3.17. Initial conditions of state paremeters.....	65

1 Introduction

Many times in our life people have heard about the end of oil, but at the moment, the world has enough oil for continue spending and consuming. In some years this problem will be real and governments should find alternatives to this not renewable energy.

Each year the consume of oil is increased because society need more energy for life, for example new and more powerful forms of transportation, new materials that need more energy to be built, and more new aspects of life which promote more consume of oil.

An alternative to oil are green energies; last years, the governments have investigated and developed new kinds of green energies to reduce contamination in air and water, because ecology aspects are each day more important in our lives.

The society has each time these ecology aspects more implemented in their lives, and is aware of the change that should be done; one example of this change is Kyoto's protocol to reduce emission of some gases to the atmosphere, laws of waste of water and laws about recycle or treatment of solids.

Summing up, each year, society is more aware of the important of the residues and its treatment, and we know that the search of new alternatives of energy is necessary.

1.1 Problem background

One of these alternatives to reduce contamination is solar collectors to produce hot water without using petroleum products.

Thanks to this alternatives like solar collectors, photovoltaic panels, wind energy, geothermal energy, consume of oil is decreased with the time, but at this moment society depends a lot of the oil.

Some years ago we knew that solar energy could be used, but they did not know how; some of this forms is photovoltaic panels, but the cost of build it is too expensive; so new types of energy should be find.

One of the simplest types of green energy are solar collectors, they are not expensive, and have very simple function, only heating the water that flow inside a pipe, thanks to the sun. The sun concentrate the energy in a special pipe with high conductivity, and this pipe conduce the heat through it to a fluid that flow inside it.

Each year this kind of energy is most important due to the simple function and the low cost.

1.2 Previous work

In this chapter is analyzed the location, weather, total radiation in the south of Norway (Porsgrunn), and the water requirements in a normal Norwegian house.

The normal house in Norway are built with wooden panels and slate roofs due to Norway is a producer of slate; it is typical to be painted with colors such as red, blue, but white is the most popular color.

Normally, in Norway a house has little rooms, to keep in heat, and steep roofs to help the snow slide off. Windows are small, because glass lets out the heat, and there is always a fire place or wood oven in the centre of the house to warm up the rooms during the cold winters, due to in Norway there are lots of forests.

The orientation of the house is normally south- west because is the best due to they have sun in the morning and in the afternoon.

It is common in Norwegian houses to have a patio or balcony on the sun side with chairs and hanging pots on the railing.

Norwegians love being at home, and they make a lot of effort to make it sweet.[1]

The temperature inside of any house should be between 292 and 294 K, so in this Thesis will try to get these temperatures inside the house.

1.2.1 Location and weather in Norway

The dates of this Master's Thesis are chosen for Southern Norway, exactly for Porsgrunn, that a small coast village located at 151 km at south–west of Oslo, capital of Norway.

Porsgrunn is located at 59° 8' 17" N of latitude and 9° 39' 9" E of longitude, and the elevation above the sea level is 5 m, depends on the exactly place in which it has been measured.

In the figure below can be seen the location of Porsgrunn (letter A of the map):

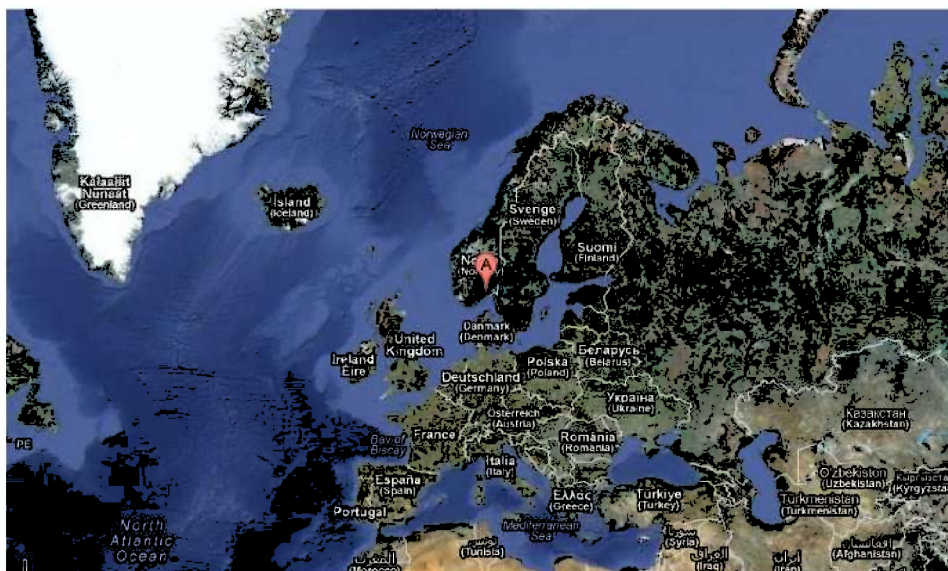


Figure 1.1 Location of Porsgrunn(A).

The climate in Porsgrunn in spring can be very variable; there may be days when it is cold enough to snow and days when it is warm enough to sit outside in the sunshine. These months can be very windy.

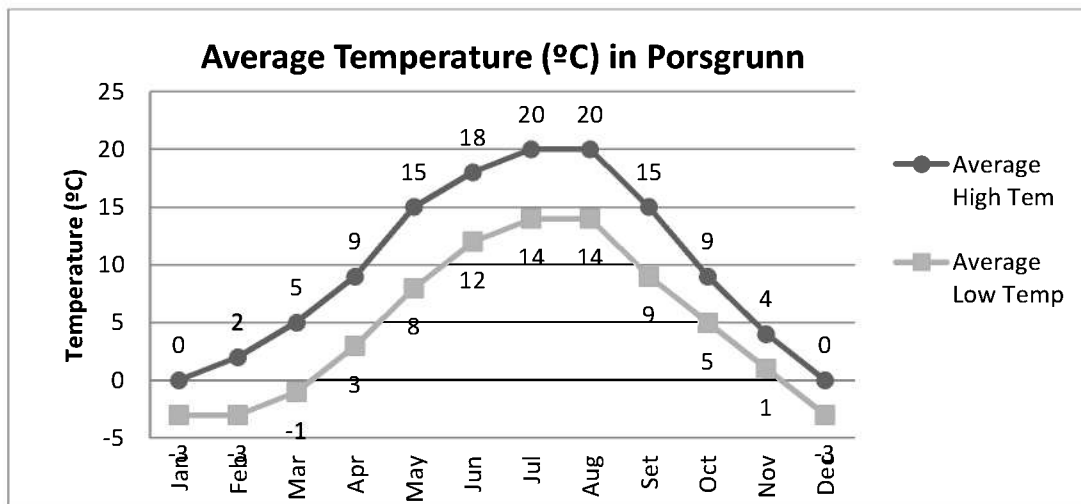


Figure 1.2 Average temperature per month for Porsgrunn.[2]

Here is attached a table with the hottest and coldest temperature per month, the average of this temperatures, and wind in Porsgrunn.

Table 1.1. Tabular view for temperature and wind per month. [3]

Months	Temperature(°C)			Wind(m/s)	
	Average	Warmest	Coldest	Average	Strongest wind
Mar 2013	-2.7	9.2 Mar 2	-14.7 Mar 14	3.1	11.8 ,Mar 2
Feb 2013	-3.5	9.3 Feb 28	-12.6 Feb 21	2.4	9.2 Feb 28
Jan 2013	-4.9	5.9 Jan 4	-16.1 Jan 23	2.5	10.5 Jan 31
Dec 2012	-4.9	5.2 Dec 30	-12.6 Dec 4	2.7	8.3 Dec 30
Nov 2012	2.9	9.0 Nov 20	-5.0 Nov 30	2.9	7.5 Nov 10
Oct 2012	5.1	15.2 Oct2	-3.5 Oct 30	2.9	9.5 Oct 3
Sep 2012	11.2	21.7 Sep3	2.4 Sep 21	3.3	9.6 Sep 4
Aug 2012	15.6	26.0 Aug 19	8.8 Aug 29	2.3	7.8 Aug 1
Jul 2012	15.7	25.5 Jul 25	9.3 Jul 17	2.6	8.6 Jul 23
Jun 2012	12.7	21.2 Jun 22	3.6 Jun 1	2.7	8.7 Jun 1
May 2012	11.8	29.7 May 25	-0.5 May 6	3.0	12.2 May 14
Apr 2012	4.6	14.6 Apr 29	-3.8 Apr 5	2.9	10.2 Apr 1

The chart below plots the average number of days in any month that you can expect to see rain or snow falling:

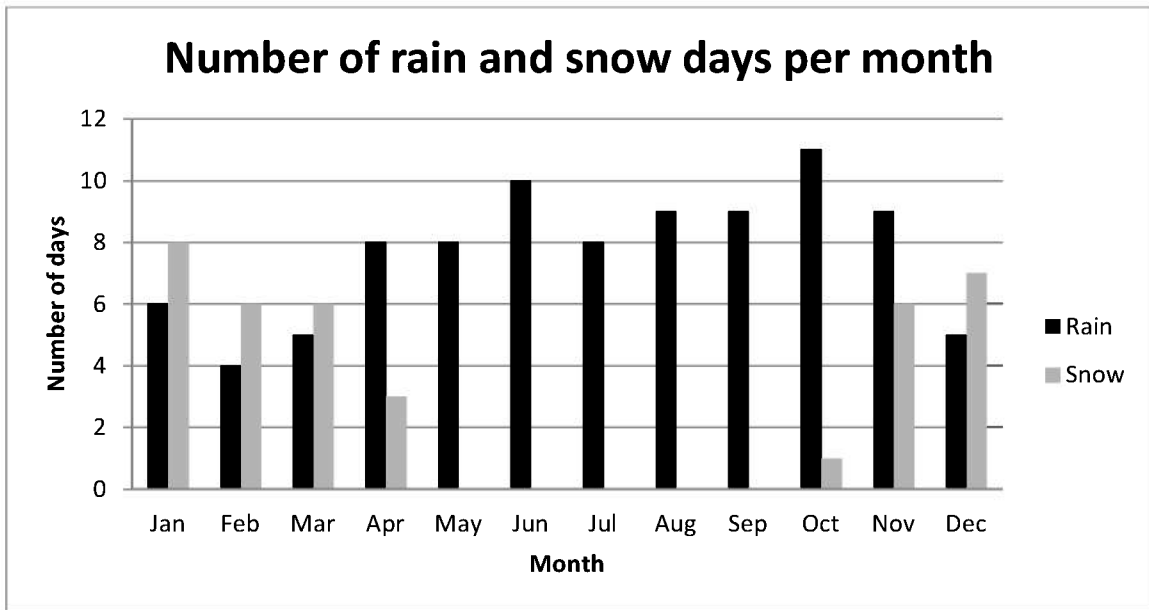


Figure 1.3 Average number of rain and snow days.[3]

Here is attached a picture of normal temperatures in a spring day:

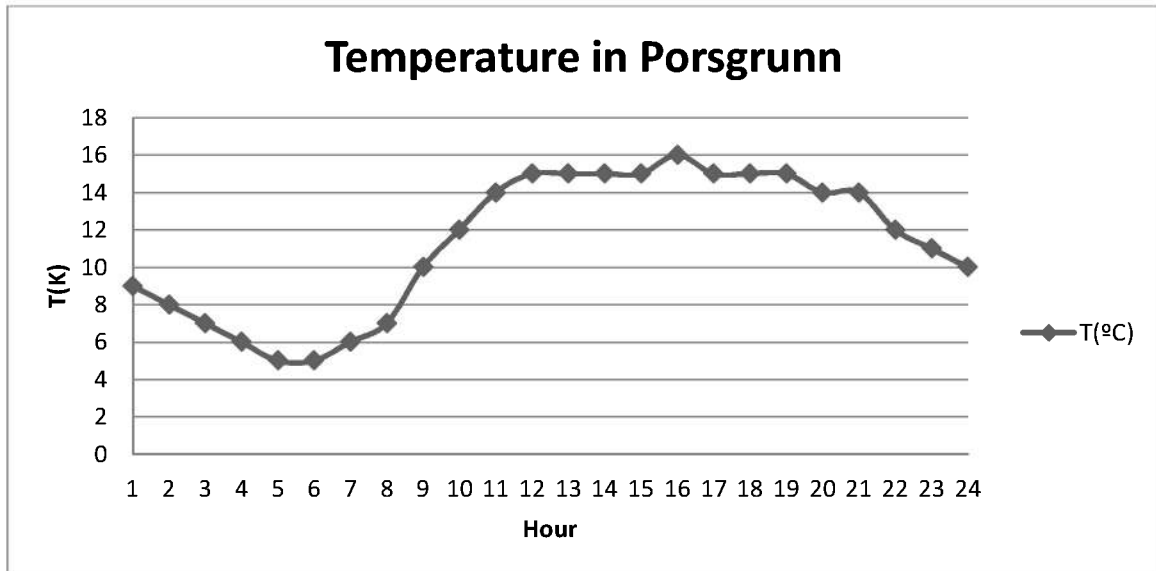


Figure 1.4 Temperatures in a normal spring day in Porsgrunn.[3]

1.2.2 Water requirements in Norwegian houses

Statistics Norway has based on reports from the municipal waterworks, estimated that an average Norwegian consumes 195 liters of water per day; if it is assumed that a house has four occupants, this consumption corresponds to an annual water consumption of 285 m³.

This consumption is divided into [4]:

Table 1.2. Consume of water for different activities. [5]

Activity	Consume(liters/day)
Shower/Bath	40
Cistern	24
Cleanliness	24
Cooking and drinking	2
Washer machine	26
Washing dishes	10
Cleaning	6
Irrigation	63
Total	195

It is assumed that in this consume do not enter the floor heating consume.

Not all of these water consumptions are hot water consumptions; in this project it is supposed that on average a person have a shower about 150 liters in 15 minutes per day (600 liter in a house of four people in an hour); this value is much higher than the average consume, and is carried out between 6 and 7 am.

Another consume of hot water in a normal house is the wash machine and wash dishes; they are supposed around 80 and 40 liters respectively, and they are carried out between 11 am and 13 pm.[6]

Other consumptions can be made with cold water.

It is assumed that in the house there are floor heating consume, that is around 127 liter per hour (0.025 liters/s); this consume can be variable depending on the temperature in the house.

It is needed to have in account that the supply water temperature is not constant throughout the day, and it has small variations.

1.2.3 Total radiation

Total radiation depends on the hour of the day, and depend on the day; there are days in which full time in sunny, there are another days in which not full time is sunny, they are partly cloudy and another days in which there are not sun, and the day is completely cloudy; despite of not having sun in these days there are radiation from the sun; it has not the same intensity, but exists.

There are kinds of radiation:

- ∞ Direct radiation: Comes directly from the sun without having undergone any change in its direction. It features cast a shadow set of opaque objects that intercepts. Normally

this type of radiation is radiation on sunny days, and depends on the latitude, declination, slope, surface azimuth angle, hour angle, angle of incidence, zenith angle, solar latitude altitude angle, and solar azimuth angle).

- ∞ Diffuse radiation: Part of the radiation through the atmosphere is reflected by clouds or absorbed by them. This radiation is diffused in all direction, due to the reflection and absorption of not only clouds, but atmospheric dust particles, mountains, etc. It is characterized by not produce any shadow over interposed opaque objects. Normally this type of radiation is radiation on cloudy days.
- ∞ Reflected solar radiation: Is the solar radiation reflected by the ground.

Total radiation is the sum of these types of radiation.[7]

In this Thesis is assumed that radiation in a total completely cloudy day is around 40% that radiation in a normal sunny day; and in a partly cloudy day is assumed that there are hours in which total radiation is maximum, and hours in which total radiation is around 40% of radiation in a sunny day.

In the last years radiation has decreased due to emissions of particles to the atmosphere; the degree to which scattering occurs is a function of the number of particles through which the radiation must pass and the size of these particles The decrease of the total amount of radiation from the sun to the earth [7], can be seen in next graph:

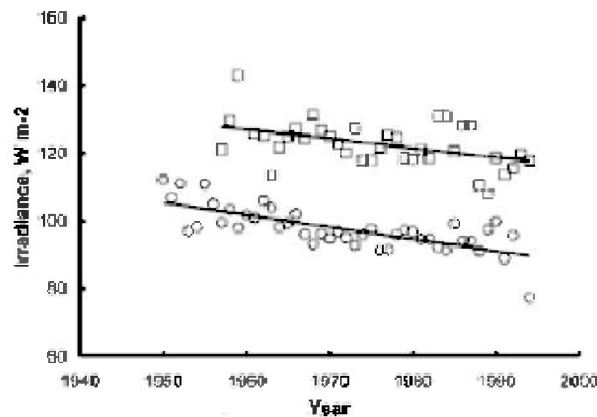


Fig 1.5: Changes in annual mean global irradiance measured within the Polar Circles. Upper line – the Antarctic; lower line – the Artic[8]

As can be seen the total radiation in Polar Circles are decreased around 2.3% per decade[9], so it should take into account the reduction of radiation over the years.

2 Problem description

2.1 System description

The system that is analyzed in this project is the model of heating of buildings in Norwegian homes, where the weather is freezing and it is necessary to provide the homes with a system of thermal solar energy for minimize the consumption of fuel or electricity at homes, because nowadays it is needed new forms of clean energy.

As it can be seen in the previous parts, homes have different needs of heat depend on the country, the location and the weather of each one.

Depend on the size of the building the components of the system must be greater or lesser.

This project is elaborated for a normal Norwegian house, with normal dimensions and normal consumptions.

The aim of this project is to provide energy to the home thanks to an energy storage tank, heating by an electricity system and a thermal solar energy system (collector) to maintain a constant temperature inside home at any time of the day thanks to a underfloor heating, and hot water supply at the house (this quantity of energy depends on the hour of the day, the date and the number of people inside the house).

The system that it is going to describe in this project is a system compound by three elements: the collector, the tank of water storage, and the underfloor heating.

The collector is the part of the system in which the solar energy is picked, but no storage, and the tank is the part of the system in which the energy is stored, and then distributed to the building for heating home or use water (bath consumption, shower consumptions). Heating of the house is thanks to an underfloor heating that provides of energy at home at any time of the day, mainly at night hours, when the heat losses are higher.

Each part of the system has a function; the collector captures energy, the tank stores energy, and then this energy is distributed at home thanks to underfloor pipes.

This parts of the system are connected by pipes, and thanks to this, the energy is transported from the collector to the storage tank, and then, of this tank to home, by pipes.

As it can be seen in the next figure, the collector has its own system of pipes and the water, that goes through it, have not contact with the rest of the system; this can prevent the growth of algae and microorganism soiling the building heating system.

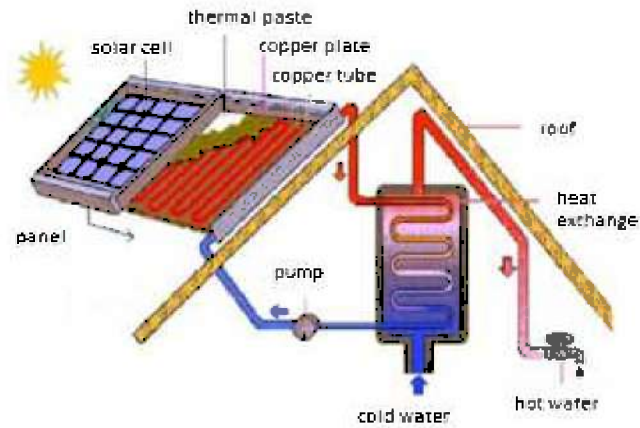


Figure 2.1: Simplified system description of the solar collector. Modification of figure at collector [10]

Apart from the collector piping system there is another piping system that is the system of pipes of building heating. This system departure of the storage heating tank and crosses the building to get the proper place of water need (shower or floor).

The system will be described by a dynamical model, where numerical values for parameters and typical operational date are chosen. This model will be verified through simulation.

2.1.1 Solar collector

The solar collector consists on a horizontal mirror, which focus the solar radiation into the absorber pipe. The absorber pipe runs along the area of the collector with an established diameter. It is enclosed in a glass envelope, which is mostly transparent to UV radiation, but opaque to IR radiation. The absorber pipe is designed to have high absorptivity and low emissivity, so that it absorbs high amounts of radiation, while minimizing radiative heat losses. This is typically done by applying a selective coating to the outer surface of the pipe. [11]

Normally the solar collector is located in the roof of the houses, but other configurations are possible, like in walls, depend on the orientation of the house, and the type of roof.

Solar collector is composed by a system of pipes that flow inside of a system of mirrors, to concentrate direct solar radiation, which permit to increase the temperature inside them below 373K, this is due to inside this system of pipes (absorber pipe), where circulate a heat transfer fluid, in this case, water, must not achieve more than 373K because at this temperature the water is steam, and it is not needed to transport steam; this system transport water.

As it can be seen in the next figures, the solar radiation crosses the mirrors (glass envelope) and it is concentrate in the absorber plate, increasing the temperature of the plate for heating the tubes of water that circulates inside the collector.

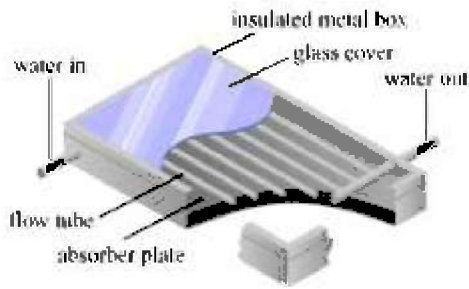


Figure 2.2: Components of the solar collector. [12]

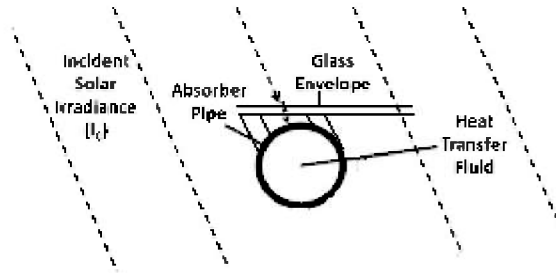


Figure 2.3: Scheme of the solar collector. Modified figure at [13]

These tubes of water go to the tank, where heat is transmitted to the water of the tank, thanks to a coil. Here, tubes of water of the collector losses temperature, and come back to the collector at low temperature, so the tank functions as a heat exchanger. This cycle is repeated at full time.

Only is considered the input of energy thanks to the sun radiation in the collector, and this quantity of energy depends on the area of the collector, the solar zenith angle, the incidence angle that depends on the location, the day of the year, the hour of the day and the optical efficiency of the collector.

In this model is considered the loss of heat through the walls of the collector to the ambient (h_E , coefficient of natural convection between the walls of the collector and the ambient).

The figure below shows the configuration of the collector on the roof:

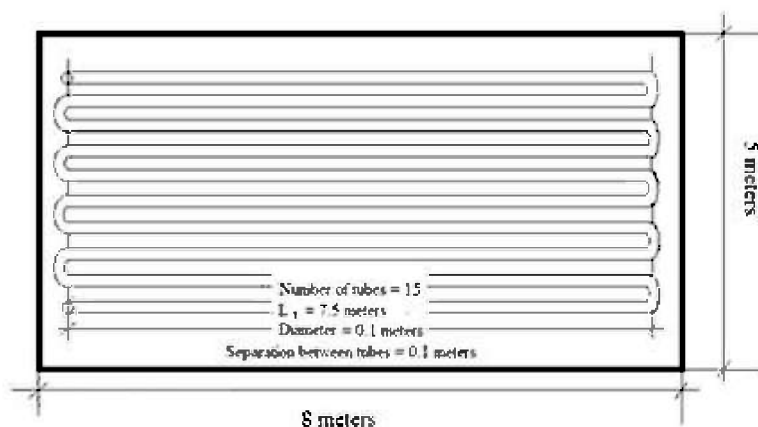


Figure 2.4: Collector configuration.

2.1.2 Energy storage tank

This tank provides water to the house, and then this water is used to heating floor, or, for example, to a shower in the house.

Depend on the hour the needs of water in the house are different, therefore the level inside the tank is continuously changed, thanks to a pump that continuously is providing of water (\dot{m}_{ti}) to the energy storage tank. This flow of water enters at a temperature (T_w).

The water tank is been heating thanks to a coil, and another type of energy, as electricity, because, lot of days in Norway are cloudy, and solar radiation cannot provide the necessary temperature to the tank; those days or hours of the day (as night), the system of electricity switch on and the necessary temperature of the tank is maintained; in Norway the 98% of the electricity is produced from hydropower [14].

In this figure it is possible to see the tank configuration.

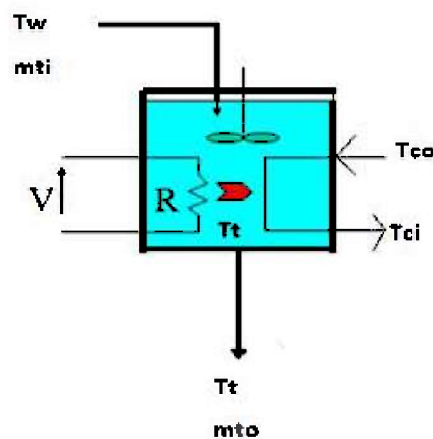


Figure 2.5: Scheme of energy storage tank configuration. Modification of figure in [15]

Inside the tank it is supposed that the temperature is constant (T_t) thanks to an agitator that maintain the tank completely mixed.

The capacity of the tank depends on the size of the house, and is usually located on the ground floor of the building, so heat losses will be minimal.

The tank functions as a heat exchanger where the water inside it, is heating, while tubes of the collector (coil) are cooled, and the tank is too heating thanks to the electricity system; the heat transmitted by the coil depends on the height of the water in the tank.

In the draw can be seen that there are two types of heating inside the tank, the electricity system, and the heat provided by the collector, here, the input is T_{co} (temperature at the outside of the collector) and the output T_{ci} (temperature at the inside of the collector).

In this model it is assumed that water from the collector (T_{co}) enter to the piping system of the tank (coil) at high temperature (below 373K) and leaves the tank at low temperature (this temperature depends on the circuit, heat transfer area, velocity of the water inside the pipe,

velocity of water inside tank); this heat transmission is controlled by a global coefficient of heat transmission (U_{c-t}).

In the model is considered the loss of heat in the tank, through the walls of the tank to the air of the house (because the tank is located in the house, not outside), this heat losses are controlled by coefficient of natural convection between the walls of the tank and the air of the house (U_{t-a}).

The stored energy in the tank is delivered to the building thanks to a system of pipes that lead the energy to each part of the house, where the heat is needed (bathrooms, kitchen or floor).

The figure below shows the coil configuration:

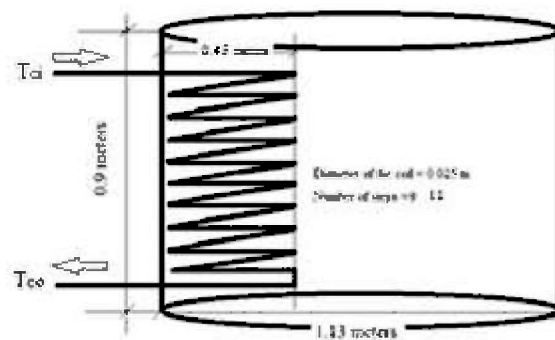


Figure 2.6: Coil configuration.

2.1.3 Underfloor heating

The underfloor heating takes the heat from the energy storage tank, and distributes this heat to the house; normally, in a house no full floor is heating, depends on the size of the house.

The house analyzed in this thesis has 8 meter long, 8 meter wide and 6 meter high.

Mainly two problems is considered when underfloor heating is installed: firstly, the maximum surface temperature of a radiant floor; because if the floor is operated above 303 K, the occupants are likely to complain of uncomfortably hot and sweaty feet; secondly, are limited by the amount of energy that can through floor coverings, such as certain carpeted and wood floors, because they have very low conductivity [16].

In this case, wood floor is used, and about 100% of the house if heat by underfloor heating.

The temperature inside the pipe of radiant floor is modeled thanks to dynamic equations controlled by a global coefficient of heat transmission with some simplifications; this simplifications neglected the individuals coefficients of heat transmission by conduction in plastic pipe and wood floor and only consider the individual coefficient of heat transmission by natural convection between the underfloor pipe and the air of the house, so, consider the temperature of the pipe as the temperature in the wood floor.

The underfloor pipe is full of water supplied by the energy storage tank, and at the end of the pipe this water is poured outside of the house, into sewer.

The hours in which this system is switched on in this Thesis is during all the day.

A picture of this radiant floor is seen below:

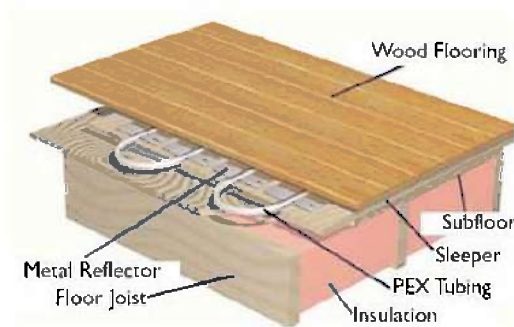


Figure 2.7: Scheme of underfloor heating. Modification of figure in[25].

Normally metal reflectors are used to improve the heat transmission from the tubes to the wood floor.

The figure below shows the floor configuration:

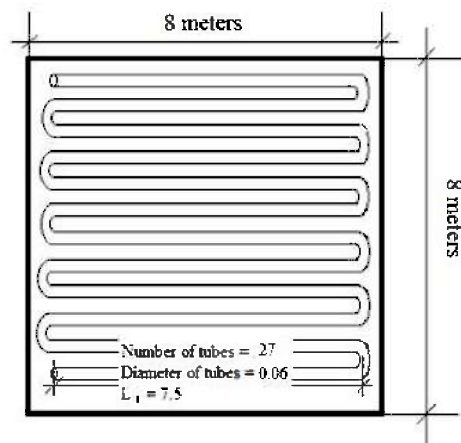


Figure 2.8: Underfloor heating configuration

2.1.4 Boundaries of the system

In this project the boundaries of the system are focused in the collector, the energy storage tank, and the house (underfloor pipes and air of the house).

The heat loss in the pipes that carry water to the house or between the collector and the energy storage tank are not considered, so the equations of the model do not consider that loss of heat, or other kinds of energy inputs, as heating of the walls of the house due to the sun.

Lot of simplifications is assumed when this system is modeled.

2.2 Properties and interesting parameters in each system

In the model studied, some properties and parameter must be estimated.

When the model is built, spring conditions are assumed, the zenith angle that provides, the amount of radiation in these dates, and if the model works in this conditions it is possible to assume that in better conditions the model could heat the tank to the corresponding temperature.

This model is composed of three systems: the collector, the energy storage tank and the underfloor heating; each one has several parameters that must be estimated.

These systems use some fluids of heat transmission in them.

The solar collector uses a heat transfer fluid to transport the energy to the energy storage tank, this fluid is water, and properties of water must be known. The absorber pipe captures heat of the sun, so it has to be in account the properties of heat transmission in the absorber pipe.

The energy of the sun crosses the glass envelope, heating the surface, so have to be in account the energy balance to the glass envelope, and the properties of its components.

The energy storage tank used water to provide energy to the house, so properties of water are interesting in this case too.

The underfloor heating uses this water for heating the house and transmitting heat from the water flowing through the pipe to the house. The temperature of the house is calculated having in account this heat provided by underfloor heating and heat losses through the wall of the house.

2.2.1 Solar collector

The collector is composed by pipes (flow tubes), absorber plate, glass cover and insulated metal box.

These parts are already designed and constructed for different Norwegian companies, like AVENTA SOLAR that has different types of solar collectors, with different sizes, and colors to maintain a high efficiency and to reduce heat loss through thermal radiation.

In this figure it can be seen different colors:



Figure 2.9: Different colors of solar collectors. Figure of: <http://www.avena.no/eng/Solar-Energy/AventaSolar-solar-collector>

Different materials are used in companies for the collectors with important features especially designed for building integration, like:

- ∞ New, but good materials that reduce costs.
- ∞ Low weight solar collector modules to facilitate transport and installation.

- ∞ Aesthetic building integration in roof or façades with several different dimensions and styles.
- ∞ Environmental friendly (low manufacturing energy consumption and complete recyclability)

Information of: [18]

Figure below shows the solar collector pipe:

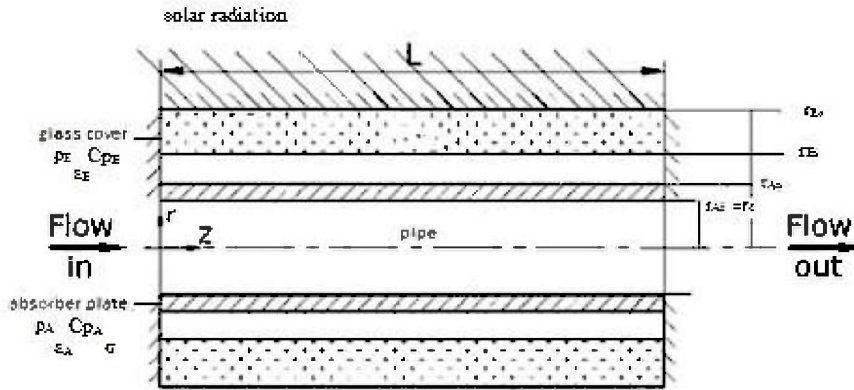


Figure 2.10: Scheme of the solar collector pipe. Modification of figure in [19]

Some properties in the solar collector are:

Table 2.1: Properties of the solar collector

<i>Properties</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
ρ_w	1000	kg/m^3	Density of water of the collector
C_{p_w}	4180	J/kg/K	Heat capacity of water of the collector
η_{coll}	1	-	Efficiency of the collector
ρ_A	8900	kg/m^3	Copper density
C_{p_A}	389	J/kg/K	Heat capacity of copper
ρ_E	2700	kg/m^3	Glass density
C_{p_E}	833	J/kg/K	Heat capacity of glass
ϵ_A	0.01	-	Emissivity of the absorber pipe
ϵ_E	0.92	-	Emissivity of the glass envelope
σ	$5.67 \cdot 10^{-8}$	$\text{W/m}^2/\text{K}^4$	Stefan-Boltzmann constant

[20],[21],[22],[23].

The collector pipe is built of copper, but is supposed that its thickness is neglected; the absorber pipe is too built of copper, but in this case, the thickness is not neglected; the envelope is built of glass.

Depends on these properties, the collector can capture or assign more or less energy.

Parameters of the solar collector are given in the table below:

Table 2.2: Parameters of the solar collector

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
L_c	112.5	m	Length of the collector
r_c	0.025	m	Radius of the collector pipe=radius of the coil (r_c)
D_c	0.05	m	Collector diameter =Coil diameter
r_{Ai}	0.025	m	Inner radius of the absorber pipe=radius of the coil
r_{Ao}	0.030	m	Outer radius of the absorber pipe
r_{Ei}	0.045	m	Inner radius of the glass envelope
r_{Eo}	0.050	m	Outer radius of the glass envelope
e_A	0.005	m	Thickness of the absorber pipe
e_E	0.005	m	Thickness of the glass envelope
P_c	0.157	m	Perimeter of the collector
P_{Ai}	0.157	m	Inner perimeter of the absorber pipe
P_{Ao}	0.188	m	Outer perimeter of the absorber pipe
P_{Eo}	0.314	m	Outer perimeter of the glass envelope
A_c	$4.91 \cdot 10^{-4}$	m^2	Cross sectional area of the collector
A_{A-c}	17.67	m^2	Area of heat transmission in the collector pipe
A_A	$8.64 \cdot 10^{-4}$	m^2	Annular area of the absorber pipe
A_E	$1.49 \cdot 10^{-3}$	m^2	Annular area of the glass envelope
w	0.06	m	Width of horizontal mirror
m_c	55.22	kg	Mass of water inside the collector pipe
\dot{m}_c	variable	kg/s	Mass flow in the collector
m_A	865	kg	Mass of the absorber pipe
m_E	453	kg	Mass of the glass envelope
V_c	0.055	m^3	Volume of the collector

Here:

$$D_c = 2 r_c$$

Eq 2-1

$$D_{Ai} = 2 r_{Ai} \quad \text{Eq 2-2}$$

$$D_{Eo} = 2 r_{Eo} \quad \text{Eq 2-3}$$

$$P_c = 2 \pi r_c \quad \text{Eq 2-4}$$

$$P_{Ai} = 2 \pi r_{Ai} \quad \text{Eq 2-5}$$

$$P_{Ao} = 2 \pi r_{Ao} \quad \text{Eq 2-6}$$

$$P_{Eo} = 2 \pi r_{Eo} \quad \text{Eq 2-7}$$

$$A_c = \frac{\pi}{4} D_c^2 \quad \text{Eq 2-8}$$

$$A_{coll} = 2 \pi r_c L_c \quad \text{Eq 2-9}$$

$$A_A = \pi (r_{Ao}^2 - r_{Ai}^2) \quad \text{Eq 2-10}$$

$$A_E = \pi (r_{Eo}^2 - r_{Ei}^2) \quad \text{Eq 2-11}$$

$$m_c = \rho_w V_c = \rho_w A_c L_c \quad \text{Eq 2-12}$$

$$\dot{m}_c = v_{wc} D_c \rho_w \quad \text{Eq 2-13}$$

$$m_A = \rho_A A_A L_c \quad \text{Eq 2-14}$$

$$m_E = \rho_E A_E L_c \quad \text{Eq 2-15}$$

$$V_c = A_c L_c \quad \text{Eq 2-16}$$

A_A and A_E are the areas of the annulus.

Depends on these radius and lengths the collector can capture or assign more or less energy.

2.2.2 Energy storage tank

The size of the tank depends on the size of the building, and the storage tanks is fully equipped with pumps, valves, controllers and connections to auxiliary heat sources.

The heat storage tank can be heated during day time by solar energy or during night time or cloudy periods by taking advantage of low-cost night tariffs for electricity.

In the next table different configurations are shown for the storage energy tanks depending on the size of the buildings.

Table 2.3: Different sizes of the storage energy tanks Information at [18]

<i>Volume</i> <i>(litre)</i>	<i>Length</i> <i>(cm)</i>	<i>Width</i> <i>(cm)</i>	<i>Height</i> <i>(cm)</i>
1000	170	85	146
1500	230	85	146
2000	170	150	146
3000	230	150	146

AVENTA SOLAR recommends approx. 1000 liter for 100 m² heated floor space.

Some properties in the energy storage tank are shown in the table below:

Table 2.4: Properties of the energy storage tank

<i>Properties</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
ρ_w	1000	kg/m^3	Density of water inside energy storage tank and density of water inside the coil
C_{pw}	4180	J/kg/K	Heat capacity of water inside the energy storage tank and heat capacity of water that flows inside the coil

Depend on the fluid inside the energy storage tank, it would be possible transfer more or less quantity of energy. In this system the fluid is water, so the properties are of the water.

The tank is built of copper, so the conduction through it is very high.

Figure below shows the energy storage tank:

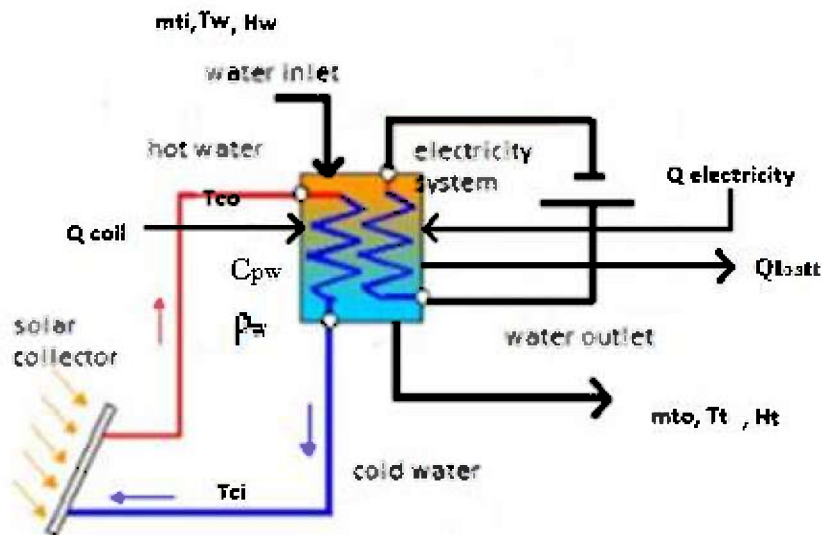


Figure 2.11: Scheme of the solar collector and the tank. Modification of figure in [24].

Parameters of the energy storage tank are given in the table below:

Table 2.5: Parameters of the energy storage tank

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
r_t	0.56	m	Tank radius
D_t	1.13	m	Tank diameter
A_t	1	m ²	Cross sectional area of the tank
P_t	3.55	m	Tank perimeter
V_t	0.9	m ³	Tank volume
\dot{Q}_{el}	2	kW	Heat provided by the electric system
H_t	0.9	m	Total height of the tank
h_{wt}	variable	m	Height of water inside the tank
r_c	0.025	m	Coil radius
L_{coil}	29	m	Total length of coil
D_c	0.05	m	Coil diameter
A_{coil}	4.5	m ²	Area of heat transmission in the coil
v_{wt}	2.5	m/s	Velocity of the water in the tank
v_{wc}	variable	m/s	Velocity of water in the coil
m_{wt}	variable	kg	Mass of water in the tank
m_{coil}	57	kg	Mass of water in the coil
V_{wt}	variable	m ³	Volume of water in the tank
V_{coil}	$5.7 \cdot 10^{-2}$	m ³	Volume of water in the coil
V	220	V	Voltage
I	25	A	Intensity

[25]

Here:

$$D_t = 2 r_t \quad \text{Eq 2-17}$$

$$A_t = \frac{\pi}{4} D_t^2 \quad \text{Eq 2-18}$$

$$P_t = 2 \pi r_t \quad \text{Eq 2-19}$$

$$V_{coil} = \frac{\pi}{4} D_c^2 L_{coil} \quad \text{Eq 2-20}$$

$$m_{coil} = \rho_w A_c L_{coil} \quad \text{Eq 2-21}$$

$$m_{wt} = \rho_w V_{wt} \quad \text{Eq 2-22}$$

$$V_{wt} = A_t h_{wt} \quad \text{Eq 2-23}$$

2.2.3 Underfloor heating

Underfloor heating properties are shown in the table below:

Table 2.6: Underfloor heating properties

<i>Properties</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
ρ_w	1000	kg/m ³	Density of water that flows inside the underfloor pipe
C_{pw}	4180	J/kg/K	Heat capacity of water that flows inside the underfloor pipe
ρ_{air}	1.2	kg/m ³	Air density
C_{pa}	1033	J/kg/K	Heat capacity of air

Depend on the fluid that flows inside the underfloor heating pipe, it would be possible transfer more or less quantity of energy. In this system the fluid is water, so the properties are of the water.

The properties of air are important due to heat losses considered, and the natural convection coefficient from the underfloor heating pipe to the air of the house.

In figure below can be seen the scheme of the underfloor heating:

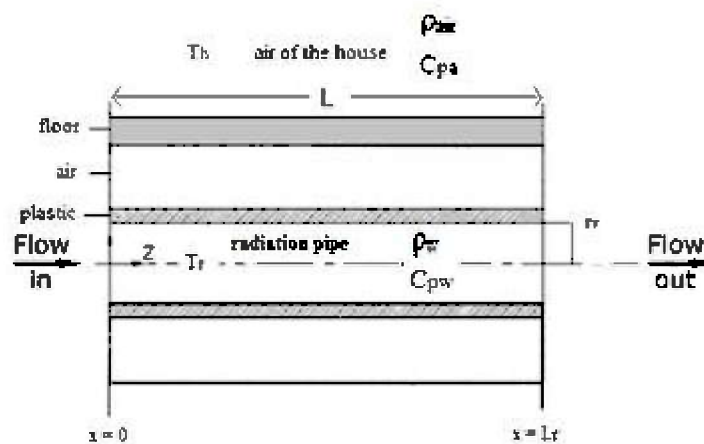


Figure 2.12: Underfloor heating scheme. Modification of figure in [19]

Underfloor heating and house important parameters are given in the table below:

Table 2.7: Parameters of the underfloor heating and the house

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
r_r	0.03	m	Radius of the pipe of underfloor heating
L_r	200	m	Length of the pipe of underfloor heating
A_{wall}	48	m ²	Wall area
A_{roof}	40	m ²	Roof area
A_{lost}	272	m ²	Total area of heat loss in the house
A_r	37.7	m ²	Total area of heat transmission of underfloor heating pipe
A_{floor}	64	m ²	Floor area
T_{wall}	287	K	Wall temperature
V_a	384	m ³	Air volume in the house
m_{ah}	461	kg	Air mass in the house

Here:

$$A_{lost} = 4 A_{wall} + 2 A_{roof} \quad \text{Eq 2-24}$$

$$A_r = 2 \pi r_r L_r \quad \text{Eq 2-25}$$

$$m_{ah} = V_a \rho_{air} \quad \text{Eq 2-26}$$

2.3 Establishing assumptions

In formulation of governing equations, the following assumptions are used:

2.3.1 Assumptions in the solar collector

Some assumptions in the solar collector have to be in account:

- ∞ The fluid that flows in tubes of the collector (heat transfer fluid) is incompressible (water) and uniform in the radial direction.
- ∞ Heat transfer is symmetrical in the radial direction.
- ∞ The thickness of the collector pipe is neglected ($r_c = r_{Ai}$) conduction through the pipe of the collector is neglected (the conduction coefficient is high).
- ∞ The collector has a perfect optical efficiency ($\eta_{coll}=1$).
- ∞ The total energy captured by the collector depends on its area.
- ∞ The solar collector consists of a horizontal mirror.

- ∞ The absorber plate is designed to have high absorptivity and low emissivity, so that it absorbs high amounts of radiation, while minimizing radiative heat losses (this is typically done by applying a selective coating to the outer surface of the pipe).
- ∞ Radial temperature gradients are neglected.
- ∞ The lost of heat between the collector and the energy storage tank are neglected., so, it means, that the temperature at the exit of the solar collector (T_{co}) is the same temperature that temperature at the entrance of the coil; and the temperature at the exit of the coil is the same temperature that temperature at the entrance of the solar collector.
- ∞ The velocity of water inside the collector and inside the coil of the tank is constant; in this model friction forces are neglected.
- ∞ Global heat transfer coefficients in the collector neglects the conduction through the pipe, only have in account convection and radiation coefficients.
- ∞ Convection between the absorber pipe and the glass envelope is neglected due to is assumed vacuum between this two surfaces, so radiation is the dominant mode of heat transmission between this two surfaces.
- ∞ The absorber pipe and the glass envelope have not flow mass, in their respective balances should be considered:

$$\dot{H}_{A,\Delta x} = \dot{H}_{A,x+\Delta x} = 0$$

$$\dot{H}_{E,\Delta x} = \dot{H}_{E,x+\Delta x} = 0$$

- ∞ Temperatures of the ambient air, clouds (T_{air} , T_{cloud}), are approximated to reality.
- ∞ Quantity and number of radiation hours are approximated to reality.

[7], [13], [19].

2.3.2 Assumptions in the energy storage tank

Inside the energy storage tank some hypothesis are assumed, like:

- ∞ The tank has agitation, so the temperature inside the tank is considered constant.
- ∞ The velocity of the stirrer is always the same, so the coefficient of forced convection inside the tank is considered constant, but in this Thesis is neglected.
- ∞ The velocity inside the collector and coil pipe is not always the same so the forced convection coefficient inside the collector and coil pipe changes with the velocity, so the global coefficient (U_{c-t}) only depends on this velocity.
- ∞ The tank is not insulated, so some heat losses are considered; these heat losses are low due to the tank is located inside the house, not outside.
- ∞ Conduction through the wall of the tank is neglected, is built of copper.
- ∞ The density of the water inside the tank and inside the solar collector is considered constant.

- ∞ It is assumed that the temperature at the exit of the collector is the same that the temperature at the entrance of the energy storage tank; so, there are not heat losses in the way of the pipe between the collector and the energy storage tank.
- ∞ Conduction through the wall of the coil is neglected due to the high conductivity of the copper; in the global coefficient only is considered the forced convection coefficients.
- ∞ Velocity of water inside the coil is the same that velocity of the water that flows inside the collector; friction forces are neglected.
- ∞ It is assumed that the contact area between the coil and water of the tank depends on the height of the water inside the tank. The tank is not always full so, the contact area between coil and water of the tank can change.
- ∞ It is assumed that the dimensions of the electric resistance go from top to bottom of the tank, as the coil.
- ∞ Coil length goes from the top to the bottom off the tank.
- ∞ Water consumption in a house (\dot{m}_{ti} , \dot{m}_{to}) are approximated to reality.
- ∞ It is assumed that if the tank has 0.9 meter high, and the surface of heat transmission in the coil is of 4.5 square meters, each 0.1 meter of high there are 0.5 square meters of area of heat transmission in the coil.

2.3.3 Assumptions in the underfloor heating (house)

Some assumptions at home are:

- ∞ Heat losses at home are assumed in the four walls and the roof of the house.
- ∞ There are not inputs or outputs of air at home (is completely closed), so:

$$\dot{H}_{hi} = \dot{H}_{ho} = 0$$
- ∞ The overall coefficient of heat transmission in the house (between the air of the house and the ambient air) only considers the natural convection from the wall to the ambient air. This overall coefficient is assumed constant throughout the day (its value is only approximate).
- ∞ The house is not insulated, only it is considered a wood wall.
- ∞ The volume of air at home is considered the total volume, no furniture is considered, and is assumed no walls inside home.
- ∞ When heat losses are calculated, a constant temperature is assumed at wall and these heat losses only depends on the surface of these walls, the coefficient of heat transmission (is considered constant), the temperature of the wall and the ambient temperature that is variable over time.
- ∞ Radiant floor is heating the total surface of the house (64 m²).
- ∞ Value of properties of air of the house and ambient air, are considered the same.

- ∞ The overall coefficient of heat transmission between the underfloor pipes and the air of the house considers only the natural convection between the underfloor pipe and the air of the house (it is assumed that the pipe is at the same temperature that the fluid that flows inside it), this coefficient is assumed constant too.
- ∞ Heat transferred from the underfloor heating to the house is the same that heat losses of the fluid flowing through the underfloor pipe.

2.3.4 Assumptions of the electricity system, the solar collector system, and the underfloor heating

Some assumptions of the electricity system, solar collector and of the house are summarized here:

- ∞ The electricity system is switched on depending of the heat demand in the tank.
- ∞ The solar collector system is running full time, but depends on the hour with higher o lesser velocity.
- ∞ The underfloor heating is continuously switched on.

2.4 Coefficients and area of heat transmission in each system

Each system has different coefficients of heat transmission (depending on the materials, conditions and assumptions) and different areas; they are:

2.4.1 Coefficients and areas of heat transmission in the solar collector

This system is composed by three different parts: the water that flows inside the collector, the absorber pipe and the glass envelope; each one has it respective balance, so for each one there are different coefficients.

In the next figure can be seen the heat transferred in the solar collector:

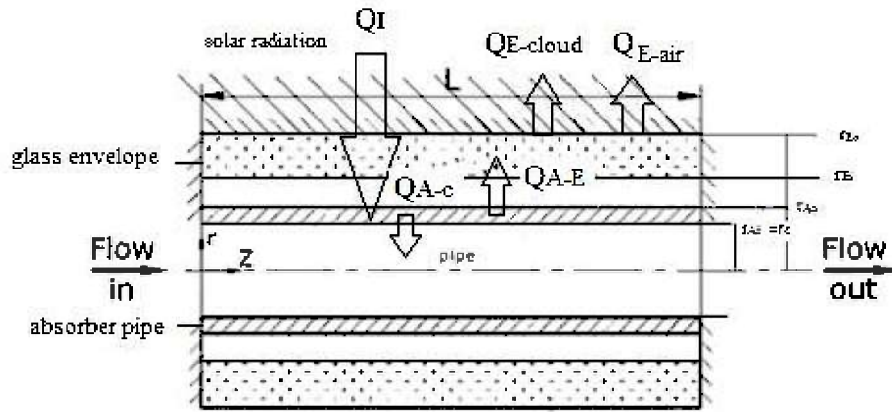


Figure 2.13: Heat transferred between different parts of the collector. Modified of figure in [19]

2.4.1.1 Coefficients and area on heat transmission in the collector water

The water of the collector receives heat (Q_{A-c}) provided of the absorber pipe through the area of heat transmission (A_{A-c}), and thanks to a global coefficient (U_{A-c}); this global coefficient should have in account the conduction through the absorber pipe, the conduction through the It is assumed that the sun's radiation affects only the half pipe, because is a horizontal solar collector, as can be seen in next figure.

wall of the collector pipe and the forced convection inside the collector pipe (h_c).

As can be seen in previous part (assumptions in the system), the thickness of the collector pipe is neglected, so the conduction through this material is neglected, and too, conduction through the absorber pipe due to this material is copper that has a very high conductivity.

So:

$$\dot{Q}_{A-c} = U_{A-c} A_{A-c} (T_A - T_c) \quad \text{Eq 2-27}$$

$$A_{A-c} = P_c L_c \quad \text{Eq 2-28}$$

$$\frac{1}{U_{A-c}} \approx \frac{1}{h_c} \quad \text{Eq 2-29}$$

Table 2.8: Coefficients and areas of the collector water

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{Q}_{A-c}	W	Heat transferred by forced convection between the absorber pipe and the collector water
U_{A-c}	W/m ² /K	Overall coefficient of the collector pipe
A_{A-c}	m ²	Area of heat transmission between the absorber pipe and the collector water
h_c	W/m ² /K	Individual coefficient of forced convection inside the collector pipe

It is supposed that forced convection coefficient of water inside the collector pipe is calculated with the next equation:

$$h_c = 4280 (0.00488\bar{T} - 1) \frac{v_{wc}^{0.8}}{D_c^{0.2}} \quad \text{Eq 2.30 [26]}$$

That is the Dittus-Boelter correlation for water in a turbulent flow in a circular pipe.

Here:

Table 2.9: Forced convection coefficient inside the collector pipe

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\bar{T}	K	Average temperature between input and output of the collector
v_{wc}	m/s	Velocity of water inside the collector
D_c	m	Pipe diameter of the collector

Then:

$$\dot{Q}_{A-c} = h_c P_c L_c (T_A - T_c) \quad \text{Eq 2-31}$$

2.4.1.2 Coefficients and area of heat transmission in the absorber pipe

The absorber pipe receives heat provided from the sun and crosses the glass envelope (\dot{Q}_I^r), transporting heat to the water that flows inside the collector pipe (\dot{Q}_{A-c}), and transporting heat, too, by radiation to the glass envelope (\dot{Q}_{A-E}^r).

The transmission of heat by radiation is governed by radiation equations, like:

$$\dot{Q}_I^r = I_C A_I^r \quad \text{Eq 2-32}$$

$$\dot{Q}_{A-E}^r = \sigma A_{A-E}^r (T_A^4 - T_E^4) \quad \text{Eq 2-33[7]}$$

Area of heat transmission by radiation is:

$$A_I^r = 2 L_c r_{Ao} \quad \text{Eq 2-34}$$

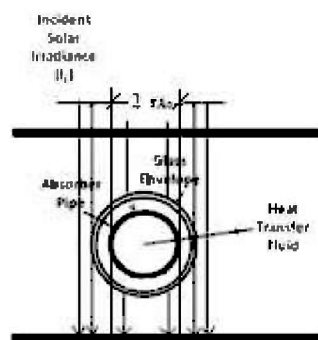


Figure 2.14: Area of solar irradiance

$$A_{A-E}^r = P_{Ao} L_c \quad \text{Eq 2-35}$$

Table 2.10: Heat transferred in the absorber pipe

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{Q}_I^r	W	Heat transferred by radiation of the sun to the absorber pipe
\dot{Q}_{A-E}^r	W	Heat transferred by radiation from the absorber pipe to the glass envelope
I_c	W/m ²	Direct solar irradiance incident on the collector surface

Table 2.11: Area of heat transmission in the absorber pipe

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
A_I^r	m ²	Area of heat transmission by radiation from the sun
A_{A-E}^r	m ²	Area of heat transmission by radiation from the absorber pipe to the glass envelope

The heat transmission to the water flowing inside the collector pipe depends on its area and a global coefficient of heat transmission between the absorber pipe and the collector pipe (U_{A-c}); this coefficient as in the previous case, neglects the conduction through the collector pipe and through the absorber pipe, and only considers the forced convection coefficient to the water that flows inside the collector pipe; so:

$$\frac{1}{U_{A-c}} \approx \frac{1}{h_c} \quad \text{Eq 2-36}$$

As can be seen, the heat transmission coefficient is the same in both parts of the system (collector water and absorber pipe), because conduction through the collector pipe and conduction through absorber pipe are neglected.

2.4.1.3 Coefficients and area of heat transmission in the glass envelope

The glass envelope receives heat by radiation from the absorber pipe (\dot{Q}_{A-E}^r), and transmits heat by radiation to the clouds ($\dot{Q}_{E-cloud}^r$) and heat by natural convection to the air (\dot{Q}_{E-air})

As in the previous cases, heat by radiation is governed by some equation like:

$$\dot{Q}_{E-cloud}^r = \sigma \varepsilon A_{E-cloud}^r (T_E^4 - T_{cloud}^4) \quad \text{Eq 2-37[7]}$$

$$\dot{Q}_{E-air} = U_{E-air} A_{E-air} (T_E - T_{air}) \quad \text{Eq 2-38}$$

Table 2.12: Heat transferred in the glass envelope

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
$\dot{Q}_{E-cloud}^r$	W	Heat transferred by radiation from the glass envelope to the clouds
\dot{Q}_{A-E}^r	W	Heat transferred by radiation from the absorber pipe to the glass envelope
\dot{Q}_{E-air}	W	Heat transferred from the glass envelope to the air

This area of heat transmission is the same area:

$$A_{E-cloud}^r = A_{E-air} = P_{Eo} L_c \quad \text{Eq 2-39}$$

Table 2.13: Areas of heat transmission in the glass envelope

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
A_{A-E}^r	m ²	Area of heat transmission by radiation between the absorber pipe and the glass envelope
$A_{E-cloud}^r$	m ²	Area of heat transmission by radiation between the glass envelope and clouds
A_{E-air}	m ²	Area of heat transmission between the glass envelope and the ambient air

The heat transmitted by natural convection to the ambient air depends on its area and a coefficient of heat transmission between the envelope and the air (U_{E-air}), this coefficient has in account the natural convection between the envelope and the air (h_E);

$$\frac{1}{U_{E-air}} = \frac{1}{h_E} \quad \text{Eq 2-40}$$

Table 2.14: Coefficients of the glass envelope

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
U_{E-air}	W/m ² /K	Overall coefficient of heat transmission between the glass envelope and the air
h_E	W/m ² /K	Individual coefficient of natural convection from the glass envelope to the air

The natural convection coefficient to the air is calculated with the next equation:

$$h_E = 1.31 * \left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \quad \text{Eq 2-41 [26]}$$

Is the individual coefficient by natural convection to the air in vertical planes.

Here:

Table 2.15: Natural convection coefficient between the glass envelope and the air

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
ΔT	K	Temperature increase between the surface of heat transmission and the ambient air (glass envelope wall-air)
L	m	Length of heat transmission (Length of the collector)

This coefficient is assumed constant and equal to $1.27 \text{ W/m}^2/\text{K}$.

2.4.2 Coefficients and area of heat transmission in the energy storage tank

This system has in account the heat transmission from the coil to the tank (\dot{Q}_{c-t}), the transmission thanks to the electric system (\dot{Q}_{el}) and the lost of heat between the tank and the ambient air (\dot{Q}_{t-a}).

In the figure below can be seen the heat transferred thanks to the coil:

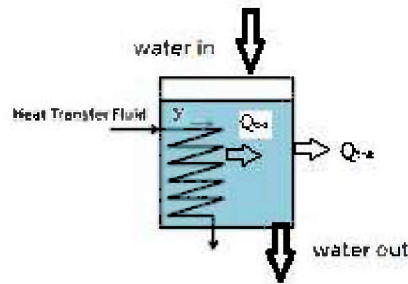


Figure 2.15: Heat transferred from the coil to the tank and lost in the tank. Modification of figure at [13]

The heat transmission from the coil to the tank (\dot{Q}_{c-t}) depends on the contact surface between the coil and the tank and an overall coefficient of heat transmission (U_{c-t}) between both surfaces.

$$\dot{Q}_{c-t} = U_{c-t} A_{c-t} (T_c - T_t) \quad \text{Eq 2-42}$$

$$A_{c-t} = P_c L_{coil} \quad \text{Eq 2-43}$$

This overall coefficient should have in account the conduction through the wall of the coil, the forced convection coefficients of the water inside the coil (h_c), (this coefficient is assumed the same coefficient that in the solar collector case, because the water inside the coil flows at the same velocity that the water inside the collector, the temperature difference are assumed equal, and diameter of both pipes is the same diameter), and the forced convection coefficient due to the agitation of the water inside the tank.

In this case the conduction through the wall of the coil is neglected because the coil is built of copper, and the forced convection of the tank, too.

So:

$$\frac{1}{U_{c-t}} \approx \frac{1}{h_c} \quad \text{Eq 2-44}$$

Table 2.16: Coefficients and areas in the energy storage tank

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
U_{c-t}	W/m ² /K	Overall coefficient of heat transmission between the coil and the water of the tank
A_{c-t}	m ²	Area of heat transmission between the coil pipe and the tank
h_c	W/m ² /K	Individual coefficient of forced convection of the water inside the coil

It is supposed that forced convection coefficient of water inside the coil is calculated with the next equation:

$$h_c = 4280(0.00488\bar{T} - 1) \frac{v_{wc}^{0.8}}{D_c^{0.2}} \quad \text{Eq 2-45 [26]}$$

That is the Dittus-Boelter correlation for water in a turbulent flow in a circular pipe

Here:

Table 2.17: Forced convection coefficients inside the coil pipe

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\bar{T}	K	Average temperature between input and output of the coil
v_{wc}	m/s	Velocity of water inside the coil
D_c	m	Pipe diameter of the coil

In this case, this overall coefficient it is not supposed constant, because inside the coil, the coefficient depends on the velocity of water inside the coil pipe, and this velocity can change.

As can be assumed, coefficients of water of the collector, absorber pipe are the same coefficients (h_c) that forced convection coefficient inside the coil pipe, because is supposed to simplifies the model, this coefficient has the same temperature range, the same velocity and diameter of pipe; so these coefficients are considered by simulation, the same coefficient (h_c).

The heat transmission from the tank to the ambient air (\dot{Q}_{t-a}) depends on the surface of the tank, and the height of water inside the tank (in this case it is considered that the lost of heat in the tank are only in the surface occupied by water) and a global coefficient of heat transmission (U_{c-t}) between tank and air.

$$\dot{Q}_{t-a} = U_{t-a} A_{t-a} (T_t - T_h) \quad \text{Eq 2-46}$$

$$A_{t-a} = P_t h_{wt} \quad \text{Eq 2-47}$$

Table 2.18: Heat transferred from the coil

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
U_{t-a}	$W/m^2/K$	Overall coefficient between the tank and air of the house
A_{t-a}	m^2	Heat transmission area between the tank and the air of the house
T_t	K	Tank temperature
T_h	K	Air temperature of the house

This overall coefficient should have in account the conduction through the wall of the tank and the insulation, the forced convection coefficients of the water inside the tank, and the natural convection coefficient from the tank to the air (h_{cnt}).

In this case the conduction through the wall of the tank is neglected because the tank is built of copper and its conductivity is very high.

And the coefficient of forced convection inside the tank is neglected too, because it is very high compared with the natural convection coefficient, so this coefficient does not control the heat transmission.

So:

$$\frac{1}{U_{t-a}} \approx \frac{1}{h_{cnt}} \quad \text{Eq 2-48}$$

Coefficient of natural convection is calculated thanks to next equation:

$$h_{cnt} = 1.18 \left(\frac{\Delta T}{d_o}\right)^{\frac{1}{4}} \quad \text{Eq 2-49 [26]}$$

Coefficient of natural convection to air, in laminar flow, for a vertical or horizontal pipe.

Here:

Table 2.19: Natural convection coefficient between the tank and the air

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
ΔT	K	Temperature increase between the wall of the tank and the air of the house
d_o	m	Diameter of the tank (is considered a pipe)

In this case, this coefficient is assumed constant and equal to $1.71 W/m^2/K$; this coefficient is low because it is supposed that the tank has insulation.

2.4.3 Coefficients and area of heat transmission in the house

In the house, there are two different heat transmissions: the heating of the house by radiant floor, and the cooling of the house due to heat losses to the ambient air; these two forms are schematized in the picture below.

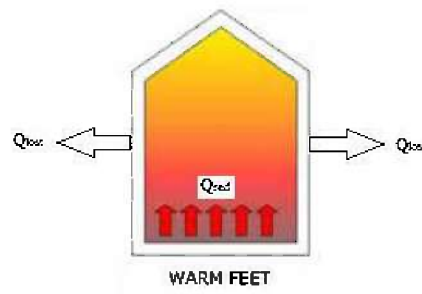


Figure 2.16: Heat transferred in the house. Modified of figure at [27]

2.4.3.1 Coefficients and area of heat transmission of underfloor heating

The heating of the house is achieved thanks to underfloor heating, this allow to warm the house from the bottom to the top, improving heat transmission and decreasing the heat flux needed (\dot{Q}_r).

The global coefficient should has in account individual coefficients, because heat has to cross some surfaces.

In next figure can be seen these surfaces:

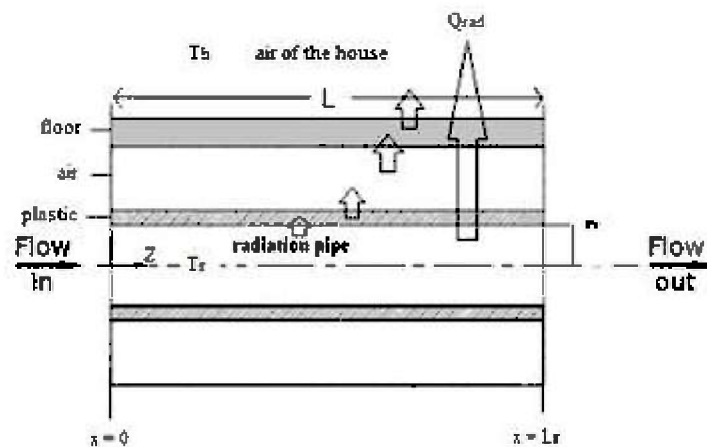


Figure 2.17: Heat transmission of underfloor heating. Modified of figure in [19]

$$\dot{Q}_r = U_r A_r (T_r - T_h) \quad \text{Eq 2-50}$$

Heat transmission between the underfloor heating pipe (in which water is flown) and the air of the house should consider the plastic of the pipe, the air between this and the floor, which normally is built of wood, so global coefficient should consider these different individual coefficients:

Table 2.20: Coefficients of underfloor heating

Symbol	Unit	Comment
U_r	W/m ² /K	Overall coefficient of heat transmission in radiant floor
h_r	W/m ² /K	Individual coefficient of natural convection between pipe and air

All coefficients are important when the overall coefficient is calculated (U_r), but most important coefficients are conduction through plastic and wood, natural convection between plastic and air, and between wood and air. The coefficient of forced convection inside the pipe is neglected because it does not control heat transmission.

To simplified the system is only considered the heat transmission by natural convection from the pipe to the air of the house, considering that the pipe is at the same temperature that the water flowing through it.

$$\frac{1}{U_r} \approx \frac{1}{h_r} \quad \text{Eq 2-51}$$

This coefficient has been calculated thanks to this expression:

$$h_r = 1.18 \left(\frac{\Delta T}{d_o}\right)^{\frac{1}{4}} \quad \text{Eq 2-52 [26]}$$

Coefficient of natural convection to the air for horizontal pipes.

Here:

Table 2.21: Natural convection coefficient between unerfloor pipe and air of the house

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
ΔT	K	Temperature increase between the pipe surface and the air of the house
d_o	m	Diameter of the pipe

So thanks to these simplifications, and considering a temperature inside this pipe as the average temperature between the inlet and the outlet, and a constant temperature in the house, this coefficient is assumed constant and equal to 5 W/m²/K. This coefficient is high because there are metal plates around the pipe which promote heat transmission.

If they were considered the heat transmission through the walls, and the air between the plastic pipe and the wood, this coefficient would be lower.

So the heat flow depends on the coefficient h_r , the area (A_r) of heat transmission, and the average temperature in the underfloor pipe and air of the house.

The area of heat transmission between the plastic pipe and air is:

$$A_r = 2 \pi r_r L_r \quad \text{Eq 2-53}$$

So, before expression would be:

$$\dot{Q}_r = h_r 2 \pi r_r L_r (T_r - T_h) \quad \text{Eq 2-54}$$

2.4.3.2 Coefficients and area of heat transmission to the ambient

Heat losses at home are very important (\dot{Q}_{lost}); in this work is considered the lost of heat through walls of the building and heat losses on the roof.

To simplify the calculations it is assumed that all is wall; it means, there are not windows and doors, the entire surface is considered equal, and the wall is only built in wood, it has not more than one material.

This heat depends on the area of heat transmission, the global coefficient and temperatures between wall and ambient air.

$$\dot{Q}_{lost} = U_{lost}A_{lost}(T_{wall} - T_{air}) \quad \text{Eq 2-55}$$

In the next picture can be seen the heat transferred through the wall of the house:

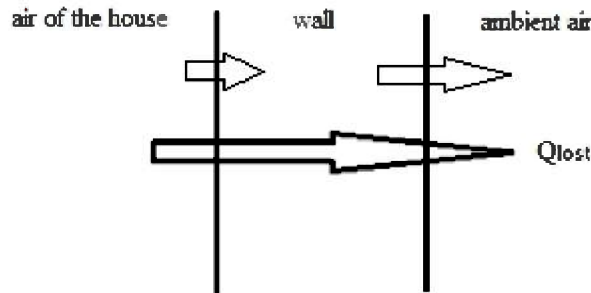


Figure 2.18: Heat transmission by natural convection through the wall of the house (simplified)

This overall coefficient **should has** in account the conduction through the walls of the house, and both natural convections, one inside the house and another one outside. To simplify calculations it is only considered the outside natural convection; the conduction through the wall and the natural convection inside the home is neglected.

$$\frac{1}{U_{lost}} \approx \frac{1}{h_{cn}} \quad \text{Eq 2-56}$$

Table 2.22: Loss coefficient in the house

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
U_{lost}	W/m ² /K	Overall coefficient of heat transmission through walls of the house
h_{cn}	W/m ² /K	Individual coefficient of natural convection to the ambient air

Here:

$$h_{cn} = 1.35 \left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \quad \text{Eq 2-57 [26]}$$

Coefficient of natural convection to the air for vertical planes.

Table 2.23: Natural convection coefficient between wall and air

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
ΔT	K	Temperature increase between the wall surface and the ambient air
L	m	Length of wall

This coefficient is assumed constant and equal to $4 \text{ W/m}^2/\text{K}$. This coefficient is a very high coefficient, because the house is very poorly insulated.

The area of heat transmission by natural convection from the walls of the house to the ambient air considers 4 walls and two roofs; it is assumed that entire surface is wall (no doors and no windows) and the material of the roof is the same that the material of the walls (wood).

$$A_{lost} = 4 A_{wall} + 2 A_{roof} \quad \text{Eq 2-58}$$

3 Model development

When a model is built, some equations should be solved.

Number of equations must be equal to the number of unknowns.

This system is divided in three different systems: the solar collector, the energy storage tank, and the house; in these systems there are 8 unknowns or outputs that are calculated by the computer programs, they are $\rightarrow h_t, T_t, T_c, T_{coil}, T_A, T_E, T_r$ and T_{hou} . These outputs are calculated by simulation of the system by the computer.

The model will be analyzed for three different configurations: completely sunny day, partly cloudy day, and completely cloudy day; each configuration will be analyzed during three days.

Model equations are the same for each configuration; but inputs in each configuration will be different.

3.1 Models

All the systems follow the law of conservation of mass and energy, so, in each system laws of conservation must be considered.

3.1.1 Mass balance

The law of mass conservation states:

$$\frac{dm}{dt} = \dot{m}_i - \dot{m}_o + \dot{m}_g \quad \text{Eq 3-1}$$

Here:

Table 3.1: Mass balance

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{m}_i	kg/s	Mass flow inlet
\dot{m}_o	kg/s	Mass flow outlet
\dot{m}_g	kg/s	Mass flow generated
$\frac{dm}{dt}$	kg/s	Mass change with time

In this system the term corresponding to the mass generated is zero, due to that there are not chemical reactions in the system.

3.1.1.1 Mass balance to the collector

The collector does not need the mass balance due to that is a closed circuit of water working continuously thanks to a pump; this pump draws water from the collector to the coil of the energy storage tank, and water that flows inside this circuit is cooled. This pump has a controller that changes the velocity of the water inside the circuit, depends on the amount of heat that needs to be transferred.

In the next figure it can be seen the pump and the controller that acts over the flow of heat transfer fluid (water) inside the energy storage tank.

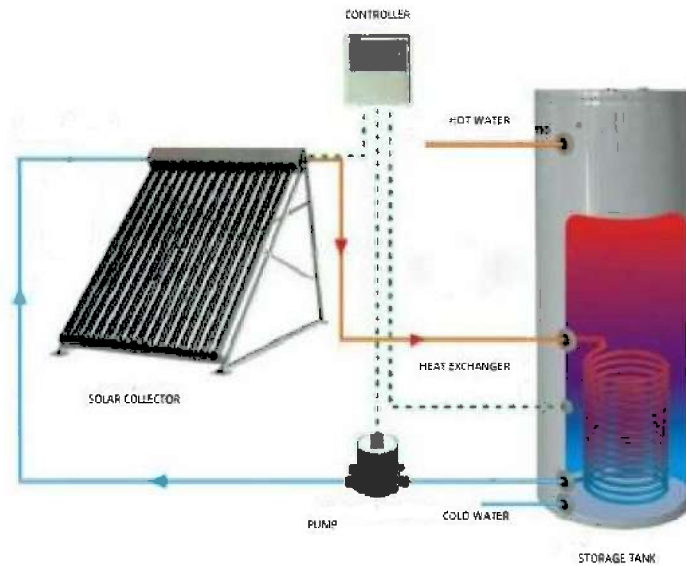


Figure 3.1: Draw of the solar collector controller. Modification figure in [28]

3.1.1.2 Mass balance to the energy storage tank

Firstly, this tank is considered full all first time, but when the time begins, the mass output is not equal to the mass input and the mass inside the energy storage tank is continuously changing, the mass balance to the tank must be considered.

The mass balance to the energy storage tank can be written as:

$$\frac{dm_{wt}}{dt} = \dot{m}_{ti} - \dot{m}_{to} \quad \text{Eq 3-2}$$

Here:

Table 3.2: Mass balance to the energy storage tank

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{m}_{ti}	kg/s	Inlet mass flow to the energy storage tank
\dot{m}_{to}	kg/s	Outlet mass flow from the energy storage tank
$\frac{dm_{wt}}{dt}$	kg/s	Variation of the mass of water inside the tank over time

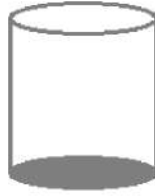


Figure 3.2: Cross sectional area of the energy storage tank

So, the mass balance to the energy storage tank is:

$$\frac{dh_{wt}}{dt} = \frac{4(\dot{m}_{ti} - \dot{m}_{to})}{\pi \rho_w D_t^2} \quad \text{Eq 3-3}$$

3.1.2 Energy balance

The law of energy conservation said that:

$$\frac{dE}{dt} = \dot{E}_I - \dot{E}_o + \dot{Q} + \dot{W} \quad \text{Eq 3-4}$$

Here:

Table 3.3: Energy balance

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{E}_I	kJ/s	Energy input to the system
\dot{E}_o	kJ/s	Energy output to the system
\dot{Q}	kJ/s	Heat transferred to the system
\dot{W}	kJ/s	Work transferred to the system
$\frac{dE}{dt}$	kJ/s	Energy change with the time

Energy balance; enthalpy form:

$$\frac{d(H-pV)}{dt} \approx \frac{dH}{dt} \quad \text{Eq 3-5}$$

In this system \dot{W} is neglected because this term in comparison with \dot{Q} is negligible; there are pumps and stirrers in the system that provide to the system of kinetic energy, but in the global balance, this quantity is so small that can be neglected.

3.1.2.1 Energy balance to the solar collector

The modeling of this system requires computing energy balances for the heat transfer fluid (water), the absorber pipe and the glass envelope.

The energy balance to the collector must consider the input of energy to the system from solar radiation, the output of energy to the energy storage tank and loss to the ambient.

The water inside the collector moves thanks to a pump; this pump has a controller that change the velocity of circulation of the water (heat transfer fluid) inside the pipe; depending on this velocity the fluid captures or transfers to the system more or less energy.

Depending on the temperature of the water inside the energy storage tank and the temperature of the output of the heat transfer fluid (water) of the collector, the pump drives more or less heat transfer fluid to the coil of the energy storage tank, in order to maintain the temperature inside the energy storage tank as high as possible.

Therefore model has in account the energy balance to the glass envelope, the absorber pipe, and the heat transfer fluid (water) of the collector.

Energy balance in enthalpy form:

$$\frac{dH_c}{dt} = \dot{H}_{ci} - \dot{H}_{co} + \dot{Q}' + W'; \quad (W' \approx 0) \quad \text{Eq 3-6}$$

Here:

Table 3.4: Energy balance to the collector

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{H}_{ci}	kJ/s	Inlet enthalpy to the collector
\dot{H}_{co}	kJ/s	Outlet enthalpy from the collector
\dot{Q}'	kJ/s	Heat absorbed by the collector
W'	kJ/s	Work transferred to the collector
$\frac{dH_c}{dt}$	kJ/s	Enthalpy change in the collector with the time

The energy captured by the collector is transferred to the energy storage tank, and the work transferred in the collector is neglected, because this term is very low in comparison with the other terms.

The solar collector is modeled of this way:

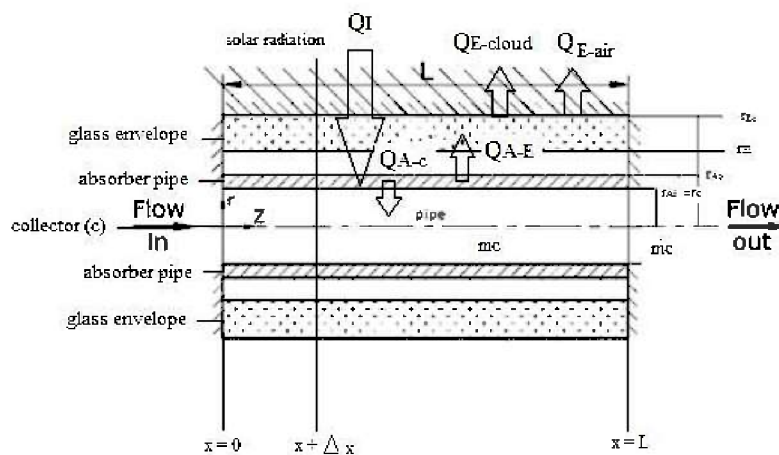


Figure 3.3: Complete model of the solar collector. Modified of figure in [19]

The energy model of the water of the collector, the absorber pipe, and the glass envelope is shown below:

3.1.2.1.1 Energy balance to the water of the collector

The total energy balance to the water flowing inside the collector is:

Energy balance, enthalpy form:

$$\frac{dH_c}{dt} = \dot{H}_{ci} - \dot{H}_{co} + \dot{Q}' + W'; \quad (W' \approx 0) \quad \text{Eq 3-7}$$

That is the same that:

$$\frac{dH_{c,\Delta x}}{dt} = \dot{H}_{c,x} - \dot{H}_{c,x+\Delta x} + \dot{Q}_{\Delta x} \quad \text{Eq 3-8}$$

Here:

$$H_{c,\Delta x} = m_{c,x+\Delta x} \hat{H}_{c,x+\Delta x} \quad \text{Eq 3-9}$$

$$\dot{H} = \dot{m}_c \hat{H}_c \quad \text{Eq 3-10}$$

$$\dot{H}_{c,x} = \dot{m}_{c,i} \hat{H}_{c,x} \quad \text{Eq 3-11}$$

$$\dot{H}_{c,x+\Delta x} = \dot{m}_{c,o} \hat{H}_{c,x+\Delta x} \quad \text{Eq 3-12}$$

In the collector, the mass flow of the water is:

$$\dot{m}_{ci} = \dot{m}_{co} = \dot{m}_c \quad \text{Eq 3-13}$$

$$\dot{Q}_{\Delta x} = \dot{Q}_{A-c} \quad \text{Eq 3-14}$$

And thanks to equation 2-31 can be obtained:

$$m_c \frac{d\hat{H}_{c,x+\Delta x}}{dt} = \dot{m}_c (\hat{H}_{c,x} - \hat{H}_{c,x+\Delta x}) + h_c P_c L_c (T_{A,x+\Delta x} - T_{c,x+\Delta x}) \quad \text{Eq 3-15}$$

If:

$$d\hat{H} \approx \hat{C}_p dT \quad \text{Eq 3-16}$$

then:

$$m_c \hat{C}_{pw} \frac{dT_{c,x+\Delta x}}{dt} = \dot{m}_c \hat{C}_{pw} (T_{c,x} - T_{c,x+\Delta x}) + h_c P_c L_c (T_{A,x+\Delta x} - T_{c,x+\Delta x}) \quad \text{Eq 3-17}$$

$$\frac{dT_{c,x+\Delta x}}{dt} = \frac{\dot{m}_c}{m_c} (T_{c,x} - T_{c,x+\Delta x}) + \frac{h_c P_c L_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{m_c \hat{C}_{p,w}} \quad \text{Eq 3-18}$$

Here:

Table 3.5: Energy balance to the water flowing inside the collector

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
v_{wc}	m/s	Velocity of water that flows inside the collector
\dot{m}_{ci}	kg/s	Inlet mass flow of water to the collector
\dot{m}_{co}	kg/s	Outlet mass flow of water from the collector
\dot{m}_c	kg/s	Mass flow of water in the collector
m_c	kg	Total mass of water inside the collector
T_A	K	Temperature of the absorber pipe
T_c	K	Temperature of the water inside the collector

The system is divided in control volumes, and each control volume:

$$N = \frac{L_c}{dx} \quad \text{Eq 3-19}$$

In this system $N=10$

This system is divided in 10 different parts; the solar collector has a length of 112.5 meters, so if this pipe is divided in 10 parts, each part has 11.25 meters. It is necessary to do the balance for each part.

In appendix 1 is shown the equations for each control volume.

Thanks to equation 2-12 and 3-19:

$$\frac{dT_{c,x+\Delta x}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,x} - T_{c,x+\Delta x}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{c}_{p,w}} \quad \text{Eq 3-20}$$

As it can be seen, depending on the temperature of the absorber pipe, and the velocity of the water inside the collector, the temperature of the water that flows inside the collector can be variable, because the rest of parameters are constant.

So, at the boundary of the system, $x = 0$.

$$\frac{dT_{c,\Delta x}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,i} - T_{c,\Delta x}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{c}_{p,w}} \quad \text{Eq 3-21}$$

In anyone place of the system, $x = N$

$$\frac{dT_{c,N}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,(N-1)\Delta x} - T_{c,N\Delta x}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{c}_{p,w}} \quad \text{Eq 3-22}$$

If $\Delta x \rightarrow 0$

$$\frac{\partial T_c}{\partial t} = -\frac{\dot{m}_c}{\rho_w A_c} \frac{\partial T_c}{\partial x} + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{c}_{p,w}} (T_A - T_c) \quad \text{Eq 3-23[13]}$$

The spatial discretization scheme is shown in next figure, where each cylindrical segment has a length of Δx .

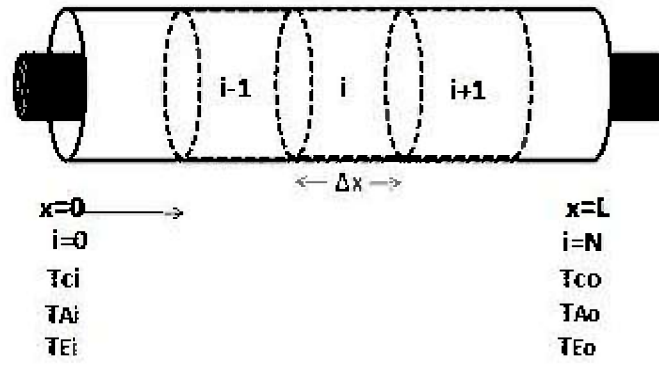


Figure 3.4: A side view of the collector pipe assembly illustrating discretization for numerical simulation.

Modification of figure in [13]

In appendix 1 is shown the equations for each control volume.

3.1.2.1.2 Energy balance to the absorber pipe

The energy balance to the absorber pipe is:

$$\frac{dH_{A,\Delta x}}{dt} = \dot{H}_{A,i} - \dot{H}_{A,o} + \dot{Q}'_{\Delta x} \quad \text{Eq 3-24}$$

$$\frac{dH_{A,\Delta x}}{dt} = \dot{H}_{A,x} - \dot{H}_{A,x+\Delta x} + \dot{Q}'_{\Delta x} \quad \text{Eq 3-25}$$

$$H_{A,\Delta x} = m_A \hat{H}_{A,x+\Delta x} \quad \text{Eq 3-26}$$

$$\dot{H}_{A,x} = \dot{H}_{A,x+\Delta x} = 0 \quad \text{Eq 3-27}$$

$$\dot{Q}'_{\Delta x} = \dot{Q}_I^r - \dot{Q}_{A-E}^r - \dot{Q}_{A-c} \quad \text{Eq 3-28}$$

And thanks to equations 2-31, 2-32, 2-33, 2-34, 2-35, can be obtained:

$$\rho_A A_A L_c \frac{d\hat{H}_{A,x+\Delta x}}{dt} = I_c 2 L_c r_{Ao} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} P_{Ao} L_c (T_{A,x+\Delta x}^4 - T_{E,x+\Delta x}^4) - h_c P_{Ai} L_c (T_{A,x+\Delta x} - T_{c,x+\Delta x}) \quad \text{Eq 3-29}$$

If is applied equation 3-16 for the absorber pipe:

$$\frac{dT_{A,x+\Delta x}}{dt} = \frac{2 I_c r_{Ao}}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,x+\Delta x}^4 - T_{E,x+\Delta x}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A} \quad \text{Eq 3-30}$$

If $\Delta x \rightarrow 0$:

$$\frac{\partial T_A}{\partial t} = \frac{2 I_c r_{Ao}}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_A^4 - T_E^4) - \frac{h_c P_{Ai}}{\rho_A \hat{C}_{pA} A_A} (T_A - T_c) \quad \text{Eq 3-31[13]}$$

As it can be seen the temperature of the absorber pipe is dependent of the radiation of the sun (I_c), the forced convection coefficient in the collector pipe (h_c), and the temperature of the glass envelope (T_E), the rest of parameters are considered constant parameters.

In appendix 1 is shown the equations for each control volume.

3.1.2.1.3 Energy balance to the glass envelope

The energy balance to the glass envelope is:

$$\frac{dH_{E,\Delta x}}{dt} = \dot{H}_{E,i} - \dot{H}_{E,o} + \dot{Q}''_{\Delta x} \quad \text{Eq 3-32}$$

$$\frac{dH_{E,\Delta x}}{dt} = \dot{H}_{E,x} - \dot{H}_{E,x+\Delta x} + \dot{Q}''_{\Delta x} \quad \text{Eq 3-33}$$

$$\dot{H}_{E,\Delta x} = m_E \hat{H}_{E,x+\Delta x} \quad \text{Eq 3-34}$$

$$\dot{H}_{E,x} = \dot{H}_{E,x+\Delta x} = 0 \quad \text{Eq 3-35}$$

$$\dot{Q}''_{\Delta x} = \dot{Q}^r_{A-E} - \dot{Q}^r_{E-cloud} - \dot{Q}^r_{E-air} \quad \text{Eq 3-36}$$

Thanks to equations 2-33, 2-35, 2-37, 2-38, 2-39, .is obtained:

$$m_E \frac{d\hat{H}_{E,x+\Delta x}}{dt} = \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} P_{Ao} L_c (T_{A,x+\Delta x}^4 - T_{E,x+\Delta x}^4) - \sigma \varepsilon_E P_{Eo} L_c (T_{E,x+\Delta x}^4 - T_{cloud}^4) - h_E P_{Eo} L_c (T_{E,x+\Delta x} - T_{air}) \quad \text{Eq 3-37}$$

If equation 3-16 is applied to the glass envelope:

$$\rho_E A_E \hat{C}_{pE} \frac{dT_{E,x+\Delta x}}{dt} = \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} P_{Ao} (T_{A,x+\Delta x}^4 - T_{E,x+\Delta x}^4) - \sigma \varepsilon_E P_{Eo} (T_{E,x+\Delta x}^4 - T_{cloud}^4) - h_E P_{Eo} (T_{E,x+\Delta x} - T_{air}) \quad \text{Eq 3-38}$$

$$\frac{dT_{E,x+\Delta x}}{dt} = \frac{\sigma}{\rho_E \hat{C}_{pE} A_E} \left[\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right) P_{Ao} (T_{A,x+\Delta x}^4 - T_{E,x+\Delta x}^4) - \sigma \varepsilon_E P_{Eo} (T_{E,x+\Delta x}^4 - T_{cloud}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,x+\Delta x} - T_{air}) \right] \quad \text{Eq 3-39}$$

If $\Delta x \rightarrow 0$:

$$\frac{\partial T_E}{\partial t} = \frac{\sigma}{\rho_E \hat{C}_{pE} A_E} \left[\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} \left(\frac{r_{Ao}}{r_{Ei}}\right) P_{Ao} (T_A^4 - T_E^4) - \sigma \varepsilon_E P_{Eo} (T_E^4 - T_{cloud}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_E - T_{air}) \right] \quad \text{Eq 3-40[13]}$$

Table 3.6: Energy balance to the glass envelope

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
T_c	K	Temperature of the water inside the collector
T_A	K	Temperature of the absorber pipe
T_E	K	Temperature of the glass envelope
T_{cloud}	K	Temperature of the cloud
T_{air}	K	Temperature of the air ambient

And, the relation between the temperature of the clouds and the temperature of the air is:

$$T_{cloud} = T_{air} - 9.84 \cdot 10^{-3} \cdot h_{cloud} \quad \text{Eq 3-41 [29]}$$

As it can be seen in these equations, the temperature of the glass envelope depends on the temperature of the absorber pipe, the temperature of clouds and air, and the natural convection coefficient between the envelope and the air (h_E).

In appendix 1 is shown the equations for each control volume.

3.1.2.2 Energy balance to the energy storage tank

The energy storage tank is modeled by dynamic mass balance and energy balance for mixed tank (constant temperature).

The input of energy to the energy storage tank depends on the velocity of the heat transfer fluid (water) inside the coil, and its temperature.

3.1.2.2.1 Energy balance to the energy storage tank

Energy balance in enthalpy form:

$$\frac{dH_t}{dt} = \dot{H}_{ti} - \dot{H}_{to} + \dot{Q}'' + W''; \quad (W'' = 0) \quad \text{Eq 3-42}$$

Here:

Table 3.7: Energy balance to the energy storage tank

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\dot{H}_{ti}	kJ/s	Enthalpy of the incoming water flow to the tank
\dot{H}_{to}	kJ/s	Enthalpy of the output water flow from the tank
\dot{Q}''	kJ/s	Heat transferred to/from the tank
W''	kJ/s	Work transferred to the tank
$\frac{dH_t}{dt}$	kJ/s	Enthalpy change in the tank with the time

Here, these terms are:

$$\dot{H}_{ti} = \dot{m}_{ti} \hat{H}_w \quad \text{Eq 3-43}$$

$$\dot{H}_{to} = \dot{m}_{to} \hat{H}_t \quad \text{Eq 3-44}$$

$$\dot{Q}'' = \dot{Q}_{c-t} + \dot{Q}_{el} - \dot{Q}_{t-a} \quad \text{Eq 3-45}$$

Table 3.8: Heat transferred into the tank

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\hat{H}_w	kJ/kg	Mass enthalpy of the incoming water flow to the tank
\hat{H}_t	kJ/kg	Mass enthalpy of the output water flow from the tank
\dot{Q}_c	kJ	Heat transferred by the coil of the collector to the tank
\dot{Q}_{el}	kJ	Heat transferred by the electricity system to the tank
\dot{Q}_{t-a}	kJ	Heat transferred from the tank to the air of the house

and:

$$\dot{Q}_{elec} = \frac{h_t}{H_t} \dot{Q}_{elec} \quad \text{Eq 3-46}$$

Applying equations 2-42, 2-43, 2-46, 2-47, 3-46 and having in account that the enthalpy inside the tank is:

$$H_t = m_{wt} \hat{H}_t \quad \text{Eq 3-47}$$

$$\frac{d(m_{wt} \hat{H}_t)}{dt} = \dot{m}_{ti} \hat{H}_w - \dot{m}_{to} \hat{H}_t + U_{c-t} A_{c-t} (T_{c,x+\Delta x} - T_t) + \frac{h_t}{H_t} \dot{Q}_{elec} - U_{t-a} A_{t-a} (T_t - T_{hou}) \quad \text{Eq 3-48}$$

Here:

Table 3.9: Enthalpy balance

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
\hat{H}_t	kJ/kg	Mass enthalpy inside the tank
\hat{H}_w	kJ/kg	Water mass enthalpy that enters to the tank

So the enthalpy change inside the tank is:

$$\frac{d(m_{wt} \hat{H}_t)}{dt} = m_{wt} \frac{d\hat{H}_t}{dt} + \hat{H}_t \frac{dm_{wt}}{dt} \quad \text{Eq 3-49}$$

$$m_{wt} \frac{d\hat{H}_t}{dt} + \hat{H}_t (\dot{m}_{ti} - \dot{m}_{to}) \quad \text{Eq 3-50}$$

$$m_{wt} \frac{d\hat{H}_t}{dt} + \hat{H}_t (\dot{m}_{ti} - \dot{m}_{to}) = \dot{m}_{ti} \hat{H}_w - \dot{m}_{to} \hat{H}_t + U_{c-t} A_{c-t} (T_{c,x+\Delta x} - T_t) + \frac{h_t}{H_t} \dot{Q}_{elec} - U_{t-a} A_{t-a} (T_t - T_{hou}) \quad \text{Eq 3-51}$$

so:

$$m_{wt} \frac{d\hat{H}_t}{dt} = \dot{m}_{ti} (\hat{H}_w - \hat{H}_t) + U_{c-t} A_{c-t} (T_{c,x+\Delta x} - T_t) + \frac{h_t}{H_t} \dot{Q}_{el} - U_{t-a} A_{t-a} (T_t - T_{hou}) \quad \text{Eq 3-52}$$

Applying equation 3-16 for a tank, and if C_{pw} is considered constant:

$$(\hat{H}_w - \hat{H}_t) = \int_{\hat{H}_t}^{\hat{H}_w} dH \approx \int_{T_t}^{T_w} C_{pw} dT \approx C_{pw}(T_w - T_t) \quad \text{Eq 3-53}$$

Therefore the energy balance is:

$$m_{wt} C_{pw} \frac{dT_t}{dt} = \dot{m}_{ti} C_{pw} (T_w - T_t) + U_{c-t} A_{c-t} (T_{c,x+\Delta x} - T_t) + \frac{h_t}{H_t} \dot{Q}_{el} - U_{t-a} A_{t-a} (T_t - T_{hou}) \quad \text{Eq 3-54}$$

Here A_{c-t} is the contact area of the coil with the water of the tank inside the heat exchanger (energy storage tank), is function of the height of the water inside the tank: $A_{c-t} = f(h_t)$.

So, after some simplifications:

$$\frac{dT_t}{dt} = \frac{\dot{m}_{ti}(T_w - T_t)}{m_{wt}} + \frac{2 \pi r_c L_{coil} U_{c-t} (T_{c,x+\Delta x} - T_t)}{m_{wt} C_{pw}} + \frac{\frac{h_t}{H_t} \dot{Q}_{el}}{m_{wt} C_{pw}} - \frac{h_{cnt} A_{t-a} (T_t - T_{hou})}{m_{wt} C_{pw}} \quad \text{Eq 3-55}$$

In modeling is needed the energy balance to the coil that provides energy to the tank. Thanks to this balance it is possible calculate the temperature of the water that flows inside the coil; this temperature is the same temperature that enters to the collector because in this model there are not lost of heat between the energy storage tank and the collector; they are neglected.

3.1.2.2.2 Energy balance to the coil

The energy balance in enthalpy form for the coil is:

$$\frac{dH_{coil,x+\Delta x}}{dt} = \dot{H}_{coil,x} - \dot{H}_{coil,x+\Delta x} - \dot{Q}_{c-t} \quad \text{Eq 3-56}$$

$$H_{coil,\Delta x} = m_{coil,x+\Delta x} \hat{H}_{c,x+\Delta x} \quad \text{Eq 3-57}$$

$$\dot{H} = \dot{m}_{coil} \hat{H}_c \quad \text{Eq 3-58}$$

$$\dot{H}_{coil,x} = \dot{m}_{coil} \hat{H}_{c,x} \quad \text{Eq 3-59}$$

$$\dot{H}_{coil,x+\Delta x} = \dot{m}_c \hat{H}_{c,x+\Delta x} \quad \text{Eq 3-60}$$

$$\frac{dH_{coil}}{dt} = \dot{m}_{coil} (\hat{H}_{coil,x} - \hat{H}_{coil,x+\Delta x}) - \dot{Q}_{c-t} \quad \text{Eq 3-61}$$

Here, thanks to equation 3-16 applied for the coil, the equations 2-21, 2-42, 2-43, and if the total pipe is divided in control volumes:

$$dy = \frac{L_{coil}}{N} \quad \text{Eq 3-62}$$

so:

$$\frac{dT_{coil,x+\Delta x}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,x} - T_{coil,x+\Delta x}) - \frac{h_c P_c}{\rho_w A_c \hat{c}_{pw}} (T_{coil,x+\Delta x} - T_t) \quad \text{Eq 3-63}$$

so, at the boundary of the system, $x=0$.

$$\frac{dT_{coil,\Delta x}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{co} - T_{coil,\Delta x}) - \frac{h_c P_c}{\rho_w A_c \hat{c}_{pw}} (T_{coil,\Delta x} - T_t) \quad \text{Eq 3-64}$$

In anyone place of the system, $x = N$

$$\frac{dT_{coil,N}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,(N-1)} - T_{coil,N}) - \frac{h_c P_c}{\rho_w A_c \hat{c}_{pw}} (T_{coil,N} - T_t) \quad \text{Eq 3-65}$$

If $\Delta x \rightarrow 0$

$$\frac{\partial T_{coil}}{\partial t} = \frac{\dot{m}_c}{\rho_w A_c} \frac{\partial T_{coil}}{\partial y} - \frac{h_c P_c}{\rho_w A_c \hat{c}_{pw}} (T_{coil} - T_t) \quad \text{Eq 3-66}$$

Here:

Table 3.10: Energy balance to the water that flows inside the coil

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
V_c	m^3	Coil volume
v_{wc}	m/s	Velocity of water flowing inside the coil
\dot{m}_c	kg/s	Water mass flow in the coil
m_c	kg	Water total mass inside the coil

In this system $N=10$

This system is divided in 10 different parts; the coil has a length of 9 meters, so if this pipe is divided in 10 parts, each part has 0,9 meters. It is necessary to do the balance for each part.

The spatial discretization scheme is shown in next figure, in it, each cylindrical segment has a length of Δx .

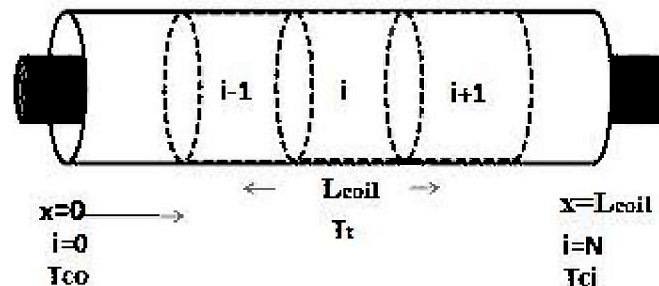


Figure 3.5: A side view of the coil pipe assembly illustrating discretization for numerical simulation. Modification of figure in [13]

3.1.2.3 Energy balance to the house

There are two heat flows in the house, one heating and another one cooling.

The heating to the house is thanks to the radiant floor and cooling of the house is due to heat losses through the walls.

3.1.2.3.1 Energy balance to the air of the house

In chapter 2 some assumptions are declared to model this system (house), so, the appropriate balance is:

$$\frac{dH_{hou}}{dt} = \dot{H}_{hi} - \dot{H}_{ho} + \dot{Q}''' + W'''; \quad (W''' = 0) \quad \text{Eq 3-67}$$

It is assumed that there are not inputs or outputs of air at home (is completely closed), so:

$$\dot{H}_{hi} = \dot{H}_{ho} = 0$$

Entrance of heat in the house is by radiant floor and outputs of heat are due to losses of heat through walls.

$$H_{hou} = m_{ah} \hat{H}_h \quad \text{Eq 3-68}$$

$$\dot{Q}''' = \dot{Q}_r + \dot{Q}_{lost} \quad \text{Eq 3-69}$$

And thanks to the equation 3-16 applied for the air of the house, and equations 2-26, 2-66, 2-67, and 2-69 can be obtained:

$$m_{ah} \hat{C}_{pa} \frac{dT_{hou}}{dt} = h_r A_r (T_r - T_{airh}) - h_{cn} A_{lost} (T_{wall} - T_{air}) \quad \text{Eq 3-70}$$

So:

$$\frac{dT_{hou}}{dt} = \frac{h_r A_r (T_{wood} - T_{air})}{m_{ah} \hat{C}_{pa}} - \frac{h_{cn} A_{lost} (T_{wall} - T_{air})}{m_{ah} \hat{C}_{pa}} \quad \text{Eq 3-71}$$

3.1.2.3.2 Energy balance to the water that flows through the underfloor pipes.

The energy balance to this system is the same that energy balance to the water that flows inside the coil of the tank, the unique difference is that in this case, heat is transmitted to air, not to water; so coefficient of heat transmission in this alternative is the coefficient of natural convection to the air; some assumptions in this case has been carried out.

$$\frac{dT_{r,x+\Delta x}}{dt} = \frac{\dot{m}_r}{\rho_w A_r dz} (T_{r,x} - T_{r,x+\Delta x}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_{r,x+\Delta x} - T_{airh}) \quad \text{Eq 3-72}$$

so, at the boundary of the system, $x = 0$.

$$\frac{dT_{r,\Delta x}}{dt} = \frac{\dot{m}_r}{\rho_w A_r dz} (T_t - T_{r,\Delta x}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_{r,\Delta x} - T_{airh}) \quad \text{Eq 3-73}$$

In anyone place of the system, $x = N$

$$\frac{dT_{r,N}}{dt} = \frac{\dot{m}_r}{\rho_w A_r dz} (T_{r,(N-1)} - T_{r,N}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_{r,N} - T_{airh}) \quad \text{Eq 3-74}$$

If $\Delta x \rightarrow 0$

$$\frac{\partial T_r}{\partial t} = \frac{\dot{m}_r}{\rho_w A_r} \frac{\partial T_{coil}}{\partial z} - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_r - T_{airh}) \quad \text{Eq 3-75}$$

So, for any control volume this equation would be:

$$\frac{dT_{r,i}}{dt} = \frac{\dot{m}_r}{\rho_w A_r dz} (T_{r,i-1} - T_{r,i}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_{r,i} - T_{airh}) \quad \text{Eq 3-76}$$

3.2 Inputs and outputs of the system

There are some inputs in the solar collector, the energy storage tank, and at home; depend on these inputs the system will transfer greater or lesser quantity of energy; these inputs are:

3.2.1 Inputs in the solar collector

There are some inputs in the solar collector; they are given in the table below:

Table 3.11: Inputs in the solar collector

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
I_c	0→200	W/m ²	Direct solar irradiance incident on the collector surface
T_{air}	278→289	K	Air ambient temperature
T_{cloud}	268→279	K	Clouds temperature
v_{wc}	0→2.5	m/s	Water velocity inside the collector

Depending on the temperature of the air, clouds, and the incident solar irradiance, the temperature in the absorber pipe, and in the water that flows inside the collector pipe will be greater or lesser.

And depending on the velocity inside the collector pipe, the water that flows inside the collector pipe will gain and will transfer more or less quantity of heat.

3.2.2 Inputs in the energy storage tank

There are some inputs in the energy storage tank; are given in the table below:

Table 3.12: Inputs in the energy storage tank

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
\dot{m}_{ti}	0→0.195	kg/s	Water feed mass flow to the tank
\dot{m}_{to}	0→0.195	kg/s	Water feed mass flow from the tank
T_w	278→280	K	Temperature of feed mass flow to the water tank
v_{wc}	0→2.5	m/s	Water velocity inside the coil
\dot{Q}_{elec}	0→2000	W	Heat provided by electricity system

Depending on the mass flow and the temperature of this mass flow that enter or departure of the tank, the temperature inside it will be greater or lesser.

Depending on the \dot{Q}_{elec} the tank will be heated more or less, and depending on the velocity inside the coil, the water that flows inside it will transfer more or less quantity of energy.

3.2.3 Inputs in the underfloor heating

There is only two inputs in the radiant floor because other parameters are considered constant, like T_{wall} and coefficients of heat transmission (h_{cn} , h_r); is given in the table below:

Table 3.13: Inputs in the underfloor heating

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>	<i>Comment</i>
T_{air}	278→289	K	Temperature of the ambient air
v_{wr}	0→2.5	m/s	Velocity of the water that flows inside the underfloor pipe

Depending on the temperature of the ambient air; the losses of heat at home will be greater or lesser, due to the temperature of the wall is constant.

All these inputs can be measured in the system, and depending on the values of them, the system has different outputs that are computed by the model.

3.2.4 Outputs of the solar collector

There are some outputs in the solar collector; are given in the table below:

Table 3.14: Outputs in the solar collector

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
T_c	K	Water temperature that flows inside the collector
T_A	K	Absorber pipe temperature
T_E	K	Glass envelope temperature

3.2.5 Outputs of the energy storage tank

There are some outputs in the energy storage tank; are given in the table below:

Table 3.15: Outputs in the energy storage tank

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
T_t	K	Temperature of the feed mass flowing from the tank
h_t	m	Height of the tank
T_{coil}	K	Temperature of the water flowing inside the coil

3.2.6 Outputs of the radiant floor

There are some outputs in the radiant floor; they are given in the table below:

Table 3.16: Outputs in the underfloor heating

<i>Symbol</i>	<i>Unit</i>	<i>Comment</i>
T_r	K	Temperature of the water flowing inside the underfloor pipe
T_{hou}	K	House temperature

Depending of the inputs for these three cases (sunny, partly cloudy, and completely cloudy), the outputs of the system will be different.

3.2.7 Initial conditions

To start the simulation of the system, some initial conditions must be considered; they are:

Table 3.17: Initial conditions of state parameters

<i>Symbol</i>	<i>Value</i>	<i>Unit</i>
h_t	0.9	m
T_t	278	K
T_c	278	K
T_A	278	K
T_E	278	K
T_r	278	K
T_{hou}	288	K

3.3 Accuracy of the model

The accuracy of the model depends on some assumptions in each system, these assumptions are:

- ∞ The model neglects the conduction through the pipes; the model considers a good conductivity.
- ∞ The model neglects the losses of heat between the pipes that connect the collector and the energy storage tank.
- ∞ The model neglects the kinetic and potential energy in the system due to that in comparison with the heat transferred, those terms are smaller.

- ∞ The accuracy in the weather conditions (T_{air} , T_{cloud} , T_w , I_c) has been modeled with some lacks, because weather conditions are continuously changed and has been impossible modeled with greater accuracy.
- ∞ The accuracy of the model has in account some simplifications in overall coefficients of heat transmission; in respective chapter (2.4) was considered.

3.4 Validation of the model

When a model is built, number of equations must be equal to the number of unknown states, so, in this model there are 8 unknowns, they are: T_t , h_t , T_A , T_E , T_c , T_{coil} , T_r and T_{hou} so the system needs 8 equations to solve it.

To validate the model these 8 equations shall be computed in the respective computer program.

1.
$$\frac{dT_{c,i}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,i-1} - T_{c,i}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}}$$
2.
$$\frac{dT_{coil,i}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,(i-1)} - T_{coil,i}) - \frac{h_c P_c}{\rho_w A_c \hat{C}_{p,w}} (T_{coil,i} - T_t)$$
3.
$$\frac{dT_{A,i}}{dt} = \frac{2 I_c r_{Ao}}{\rho_A \hat{C}_{pAA}} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1-\varepsilon_E}{\varepsilon_E} (\frac{r_{Ao}}{r_{Ei}})} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pAA}} (T_{A,i}^4 - T_{E,i}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_A \hat{C}_{pAA}}$$
- 4.
5.
$$\frac{dh_t}{dt} = \frac{4(\dot{m}_{ti} - \dot{m}_{to})}{\pi \rho_w D_t^2}$$
6.
$$\frac{dT_t}{dt} = \frac{\dot{m}_{ti}(T_w - T_t)}{m_{wt}} + \frac{2 \pi r_c L_{coil} U_{c-t} (T_{c,x+\Delta x} - T_t)}{m_{wt} C_{pw}} + \frac{\frac{h_t}{H_t} \dot{Q}_{el}}{m_{wt} C_{pw}} - \frac{h_{cnt} A_{t-a} (T_t - T_{hou})}{m_{wt} C_{pw}}$$
7.
$$\frac{dT_{hou}}{dt} = \frac{h_r A_r (T_r - T_{airh})}{m_{ah} \hat{C}_{pa}} - \frac{h_{cn} A_{lost} (T_{wall} - T_{air})}{m_{ah} \hat{C}_{pa}}$$
8.
$$\frac{dT_{r,i}}{dt} = \frac{\dot{m}_r}{\rho_w A_r dz} (T_{r,i-1} - T_{r,i}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{p,w}} (T_{r,i} - T_{airh})$$

Equation number 1 and 2 are equations for the same fluid (water) but this fluid depends on the part of the system, and is modeled with different equations.

The model is validated through simulation with computer programs; these programs are Matlab, Python or Modelica; in this project Open Modelica is going to be used.

One time simulation is validated, next step has been consider all inputs in the system, like: T_{air} , T_{cloud} , T_w , \dot{m}_{ti} , \dot{m}_{to} , I_c , v_{wc} , \dot{Q}_{el} that are continuously changing over time, and the simulation is performed with Open Modelica.

These inputs: T_{air} , T_{cloud} , T_w , I_c are fixed by the weather conditions, while these inputs are fixed by human consumptions: \dot{m}_{ti} , \dot{m}_{to} .

The only inputs that man can manipulated are: v_{wc} , \dot{Q}_{el} , depending on these inputs, the temperature of the tank will vary.

4 Simulation and verification

Simulation and verification of the results is carried out in next chapter.

4.1 Simulation

These systems (collector, energy storage tank and house) have been simulated by Open Modelica on a clear day, partly cloudy day, and on a completely cloudy day in a period of three days.

Solar irradiance has not the same value, this value depends on the day; in a sunny day, solar irradiance will be higher than in a partly cloudy day, and this will be greater than in a completely cloudy day. In a completely cloudy day the highest radiation is carried out in the central hours of the day, when the sun is as high as possible; in this configuration the first day is completely sunny, while the second and third day is completely cloudy.

In this study is supposed that at the beginning the tank is full of water at the supply temperature (278K), so the first day the heat captured by the collector is used to heat the tank; at the same time the house is at 288 K so the first day the house is on a heating period; after this period the house is heated as much as possible.

Depending on different inputs the outputs have been different, and the temperatures of the tank and the house will reach different temperatures in each case.

Code of simulation by Open Modelica program for each case is attached in the Appendix 2.

4.1.1 Simulation on a clear day

This simulation consists in a three day simulation, in which are completely sunny.

Inputs are different depending on the day (sunny, partly cloudy or completely cloudy). In the system analyzed T_{air} , T_{cloud} , T_w , m_{to} have the same value in these three cases, because the need of water in a house does not depend on the day, and it is assumed that a spring day, has the same temperatures of water, cloud and air.

Here is attached the inputs for a clear day: T_w , T_{air} , T_{cloud} , I_c , Q_{elec} , m_{ti} , m_{to} , V_{wc} , and V_{wr} .

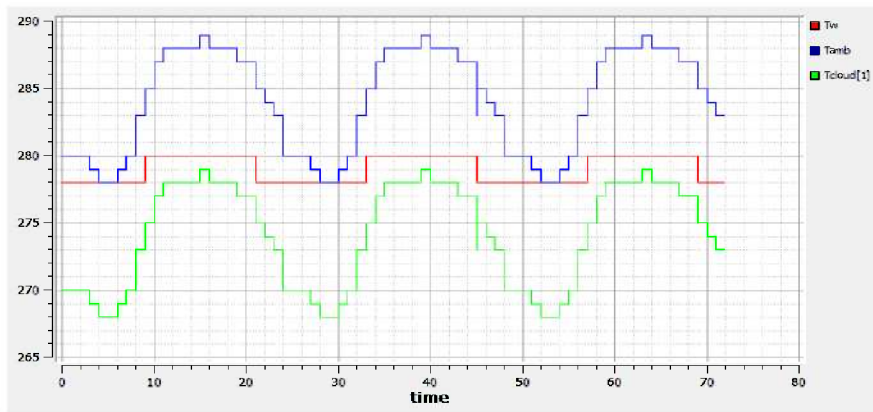


Fig 4.1: Inputs in a sunny day: T_w , T_{air} , T_{cloud} (K).

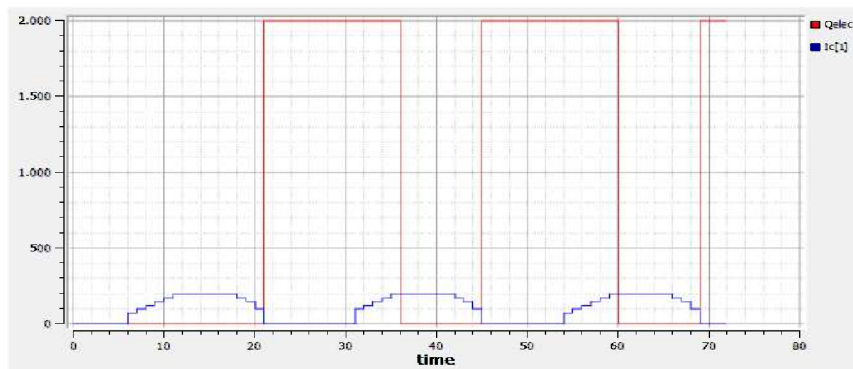


Fig 4.2: Inputs in a sunny day: Q_{elec} (W), I_c (W/m^2).

Regarding to the electric energy supplied for the electricity system of the tank: if the temperature of the tank needs to be higher because the heat transmission due to the underfloor pipe does not transmit the energy enough to maintain the temperature of the house to 294K, the electricity system will be switched on, while if the temperature of the tank is high enough, the electricity system will be switched off.

Depending on the day (sunny, partly cloudy or completely cloudy), the entrance of water to the tank (m_{ti}) will be at different hours, in order to maintain as high as possible the temperature inside the tank; in a sunny day, this entrance does not depend of the hour of the day, but in a partly cloudy day it will better to do in the hours with highest radiation, and in completely cloudy days it will be better to load the tank in the central hours of the day, with higher temperatures and the highest solar irradiance.

In all cases the outlet of the tank reaches its highest value between 6 and 7 a.m. in the morning by showering of four people; the second highest value of outlet of the tank is at the hour of the lunch at home, and wash dishes, this consume is between 11 a.m and 12 a.m., while the last consume of water in a day is due to have dinner at home and the wash machine. Constant consume throughout the day is due to the underfloor heating with a constant value of 0.025 kg/s.

Most important inlet of water to the tank is carried out at the central hours of the day, when the sun radiates more strongly, between 11 a.m. and 13 p.m, but between 8 a.m. and 16 p.m.

is continuously entered water to the tank. Between 6 a.m. and 8 a.m. the tank is only emptied due to the low solar radiation in those hours.

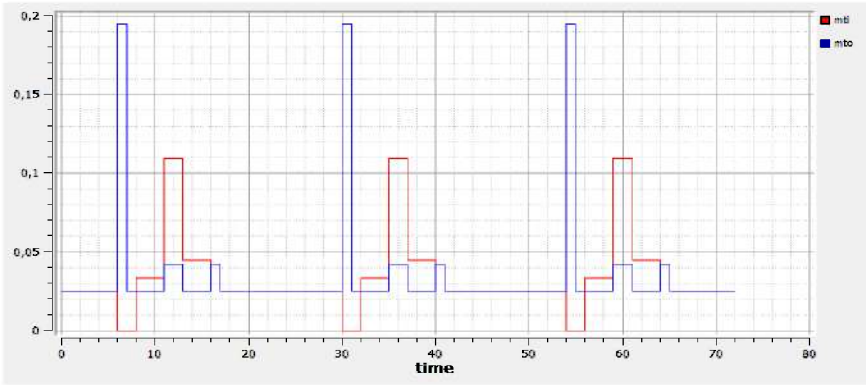


Fig 4.3: Inputs in a sunny day: m_{ti} , m_{to} (kg/s).

About the velocity in the collector pipe, or the velocity in the underfloor pipe, depending of the need of heat within the system, the velocity will be higher or lower.

In sunny case the velocity of the water that flows inside the collector is of 2 m/s in the hours in which the sun radiates and has a minimum value of 0.1 m/s at hours in which the sun is not radiating.

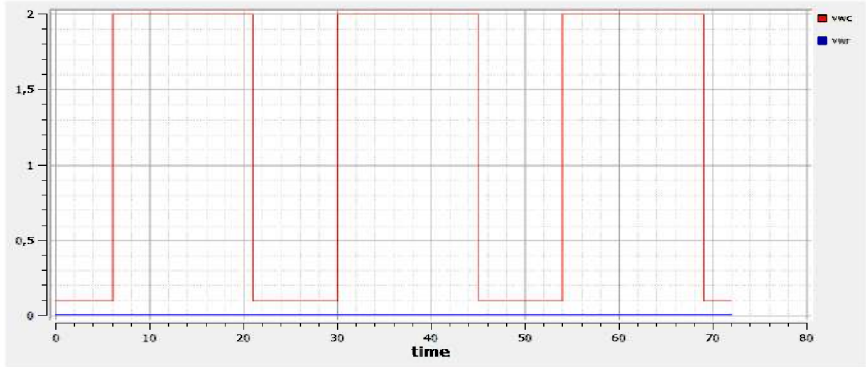


Fig 4.4: Inputs in a sunny day: v_{wc} , v_{wf} (m/s).

And the next results have been obtained:

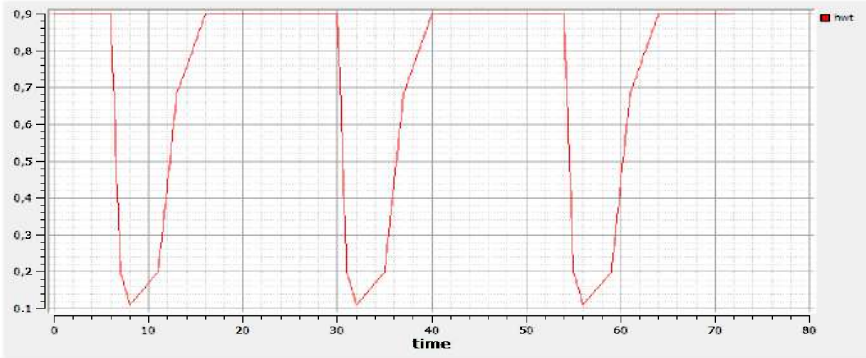


Fig 4.5: Outputs in a sunny day: h_{wt} (m).

It can be seen in this figure the most important outlet of water from the tank is carried out at 6 a.m., to have a shower, and then during the day, and the sun is radiating, the tank is continuously filling.

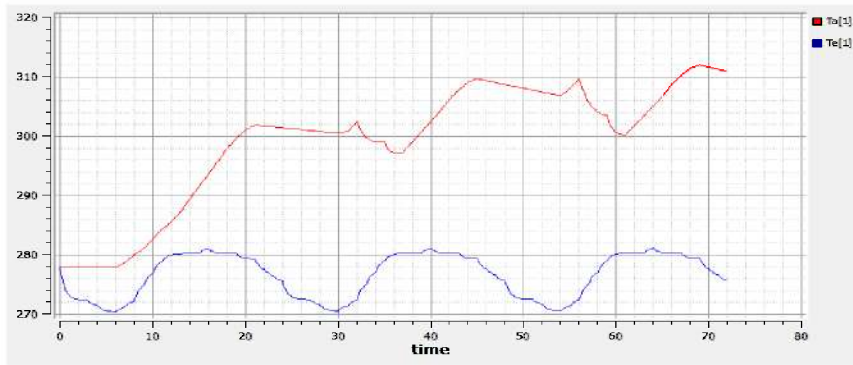


Fig 4.6: Outputs in a sunny day: T_A , T_E (K).

Here the absorber pipe is heating during the day, and cooling during the night periods. Between 11 a.m. and 13p.m. (second and third day) enters to the tank very much water (cold), and the temperature of the absorber pipe, decreased; this is due to the absorber pipe, yields all of the heat to the water circulating inside the collector, and this water lose much temperature in the tank

Between 6 a.m. and 8 a.m. the absorber pipe is heating, because the tank is almost empty and the electricity system provides lot of hot to this water; this water heats the coil, so the temperature at the entrance of the collector is continuously increasing in this period of time; then, at 8 a.m. the tank starts to fill with cold water and the temperature of the tank decrease a lot, so the temperature of the absorber pipe, logically, decrease too. When the tank is filled more than half, the area of heat transmission between the coil and the tank is high enough to elevate the temperature of the water of the tank, and the temperature of the absorber pipe, is increased in this period of time (when the tank is almost full).

The temperature of the glass envelope is continuously repeated.

At night periods, the absorber pipe is not able to cool down to the initial temperature, so is continuously heating, but in less quantity each day

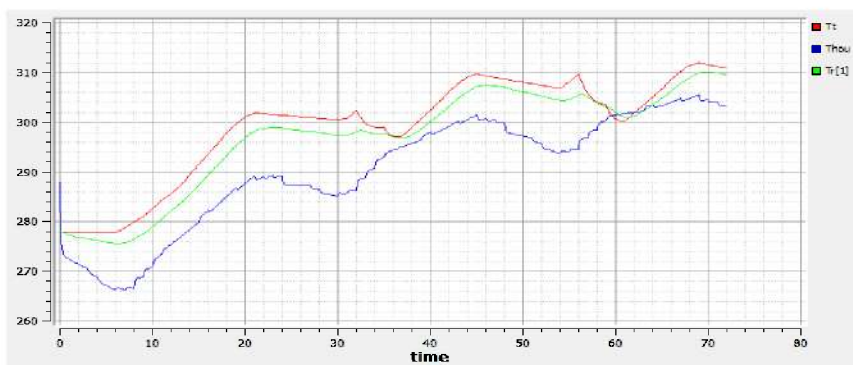


Fig 4.7: Outputs in a sunny day: T_t , T_{hou} , T_r (K)

As shown in Fig 4.7 the temperature of the tank is continuously heating each day, and is cooling each night; heat lost at night is less than the heat gain during the day, so the tank each day is hotter.

At night the temperature of the tank decreased although the electricity system is switched on due to the tank is full at night and electricity is not enough to maintain constant the temperature of the tank.

In the second and third day, the temperature of the tank is increased between 6 a.m. and 8 a.m. due to the electricity system and the low level of water in the tank; then, between 8 a.m. and 12 a.m. the tank decrease its temperature due to the low area of heat transmission between the coil and the water of the tank, and the entrance of cold water to the tank, to replace the water expended during the morning.

First day the tank is in a heating period, but second and third day the tank reaches enough temperature for supplying water to the needs of home, more than 300 K; with this temperature is possible to have a shower in the morning, clean dishes at lunch or to switch on the wash machine after lunch (this last homework, depends on the program).

The underfloor heating is always switched on, so, the temperature of the house is continuously increased due to the temperature of the tank is continuously increased, too; so would be possible to maintain continuously the house heating by this system during sunny days.

Each day, the temperature of the tank and the temperature of the house are increasing less that previous day, so it is possible that steady state is achieved with the passage of time.

The temperature in the underfloor pipe (T_r) is increasing and decreasing at the same time that the tank; in the first control volume ($T_r[1]$) the temperature is slightly lower than the temperature of the tank, but in the last volume control ($T_r[10]$) the temperature decrease a lot.

In the third day the temperature of the tank decrease very much between the hours of replacing the water of the tank, but the temperature of the house is increasing, this is due to the temperature of the tank drops quickly, and the temperature of the house cannot drop as fast, and also, the house is heating by the ambient air in this period of time.

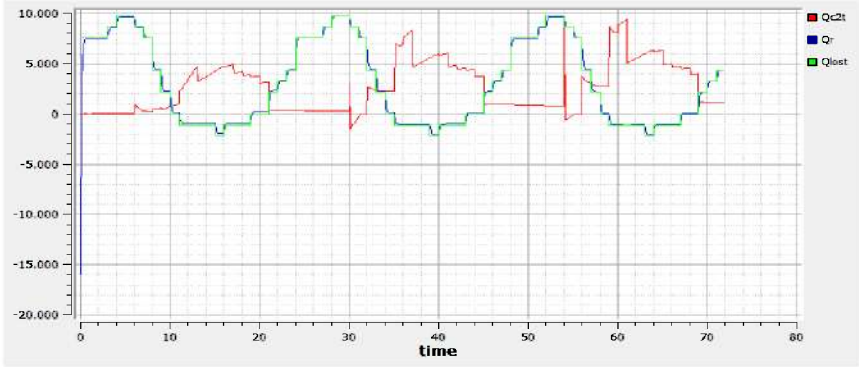


Fig 4.8: Outputs in a sunny day: Q_{c-t} , Q_r , Q_{lost} (W).

The results of heat transmission in the house and in the tank are shown in Fig 4.8, in which the heat transmission can be seen between the coil and the tank (Q_{c-t}), and in the house (Q_r , Q_{lost}). During the day the losses of heat in the house are negative (the ambient is hotter that

the wall of the house); at night the losses of heat at home are important (air temperature decrease at night), and the underfloor heating transmit heat to the house.

As heat transfer from the underfloor pipe is calculated as the sum of the temperatures of the underfloor pipes and the temperature of the house, this can be negative, because there are more control volumes in the pipe with a lower temperature than the temperature of the house; this heat depends a lot of the velocity of the water inside the underfloor pipe.

Negative peaks of heat in the coil are shown in Fig 4.8 due to in the first hours of the day the temperature of the tank is higher than temperature in the coil pipe, this is due to electric system that maintains the temperature of the tank at night; in this period of time the temperature of the water that flows inside the coil decrease its temperature during the night by heat losses of the collector, that cooled the glass envelope and the absorber pipe and these cool the water that flows inside the collector pipe; this is due to a constant but low velocity, that is maintained inside the collector pipe at night.

Highest heat transmission in the coil is between 11 a. m. and 13 p.m. in which the flow of water that enters to the tank is highest and the radiation in those hours is maximum.

Between the 6 a.m. and 8 a.m the heat transmission between the coil and the tank is negative due to in these hours the electricity system of the tank is switched on and a low level of water is in the tank, so there are higher temperature in the tank, than the coil .

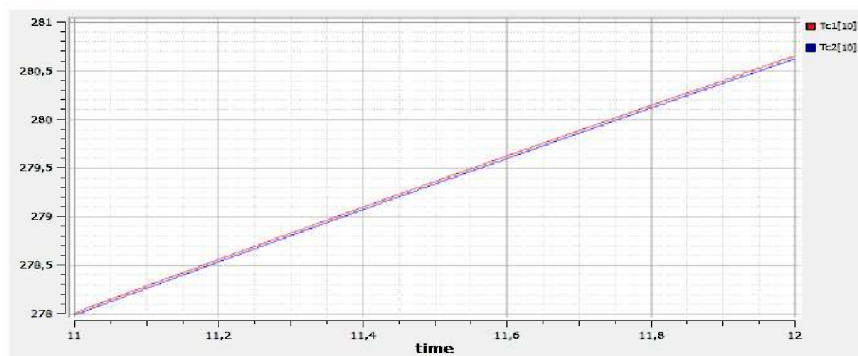


Fig 4.9: Outputs in a sunny day: T_{c1} , T_{c2} (K).

Heat transmission in the coil can be seen in Fig 4.9, in which are shown temperatures at the entrance and the exit of the coil. The temperature difference between the inlet and the outlet is so small due to the velocity of the water inside the pipe (2m/s), when the velocity decreased, the temperatures difference is increased.

In this case, in one hour, the temperature is increased about 2.6 K, with a total radiation of 200 W/m^2 , the maximum radiation reached in a day.

4.1.2 Simulation in a partly cloudy day

In next figures, values of inputs are drawn in a partly cloudy day: I_c , Q_{elec} , m_{ti} , m_{to} , v_{wc} , and v_{wr} ; T_w , T_{air} , T_{cloud} are the same that in the previous case.

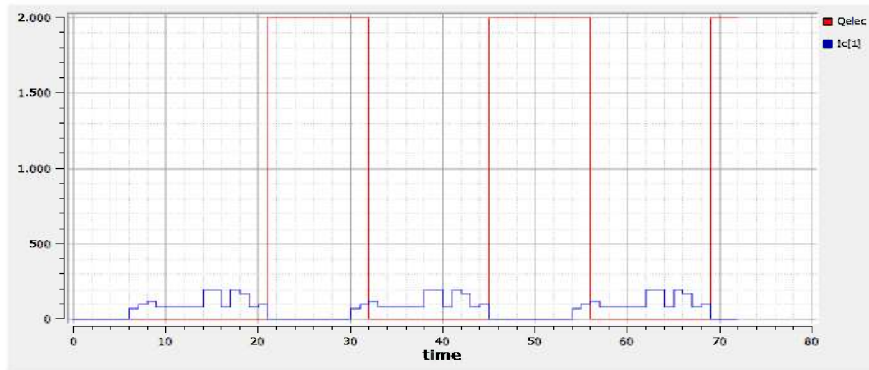


Fig 4.10: Inputs in a partly cloudy day: Q_{elec} (W), I_c (W/m^2)

In this case Q_{elec} does not have a null value; the electric system is switched on during the night with a value of 2000 W/m^2 . As it can be seen, electricity system is switched on between 21 p.m. and 8 a.m. and is not switched off until 6 a.m. because the radiation of the sun at these hours is very low and the solar collector takes a few hours to warm up.

About I_c as it can be seen only reaches a maximum value of 200 W/m^2 in three hours of the day, the rest of the time has a medium value of 100 W/m^2 more or less.

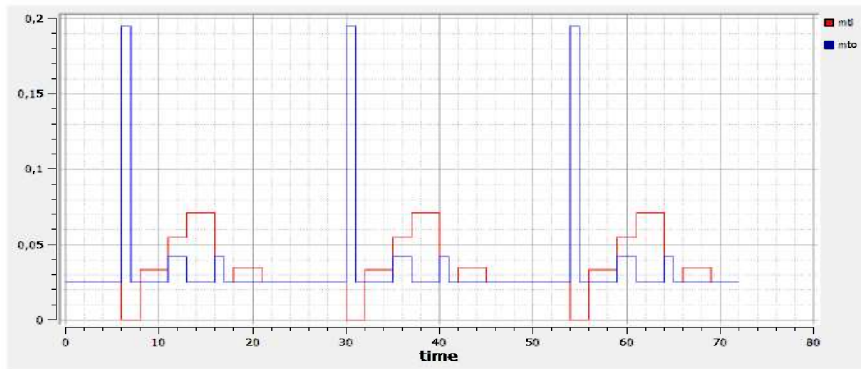


Fig 4.11: Inputs in a partly cloudy day: m_{ti} , m_{to} (kg/s).

As it can be seen in a partly cloudy day, the outlet of water of the tank is carried out at the same hours that in a sunny day, but the inlet of water to the tank is different; this is due because the radiation is not as high as in a sunny day, and the flow entrance to the tank must be done more slowly, because the temperature of the tank drops quickly with a fast entrance. Most important entrance of water to the tank is carried out at the central hours of the day (between 11 a.m. and 16 p.m.).

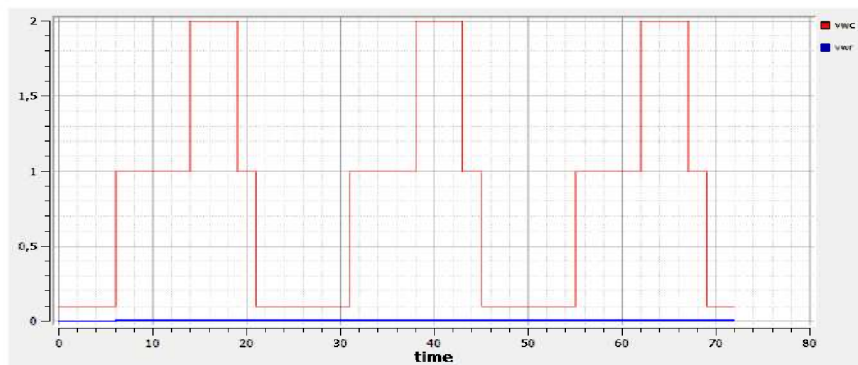


Fig 4.12: Inputs in a partly cloudy day: v_{wc} , v_{wr} (m/s).

The highest velocity (2 m/s) throughout the day is at the hours in which the radiation is highest, between 14 p.m. and 19 p.m. At the rest of the day hours the systems runs with a medium velocity of 1 m/s; at night this system is almost offline.

And the next results have been obtained:

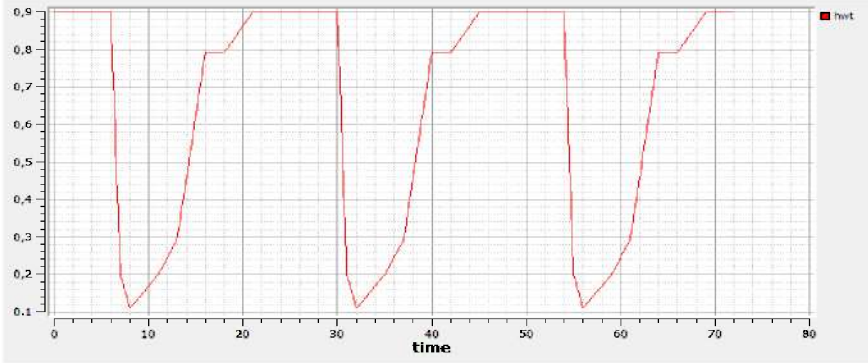


Fig 4.13: Outputs in a partly cloudy day: $h_{wt}(m)$.

As it can be seen in this figure the most important outlet of water from the tank is carried out at 6 a.m., to have a shower, like in a sunny day, and then during the day, and the sun radiates, the tank is continuously filling, in this case the inlet of water to the tank is realized in more hours than in a sunny day because the low radiation in these days is not enough to increase the temperature of the absorption pipe at a high value and consequence of this, is a lower heat transmission to the tank. If the inlet of water to the tank is realized in more time, the temperature of the tank will decrease less than with a fast entrance of water.

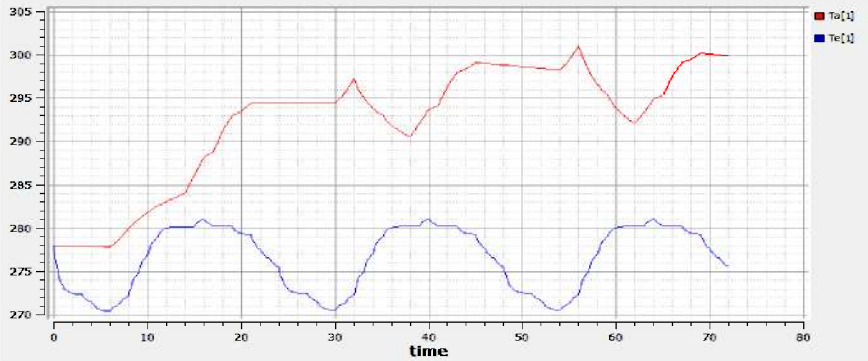


Fig 4.14: Outputs in a partly cloudy day: $T_A, T_E(K)$.

Here the absorber pipe is heating during the day, and cooling during the night and in filling periods; in this case the electricity system is switched on at night and the temperature of the tank, and the absorber pipe almost does not decrease. The greatest entrance of water to the tank is realized between 13 a.m. and 16 p.m. but is not as high as in the sunny day, therefore, the level of the tank is very low in much of the day, so the heat transmission by the coil pipe is very low during these hours, and the temperature of the coil and the absorber pipe decrease. When the tank is almost full (more than half) the heat transmission by the coil is increased, so the temperature of the tank, coil, and absorber pipe is increased too.

Due to the low radiation in this case in comparison with sunny day, the absorber pipe does not reach the same temperature, the temperature of the absorber pipe in this case is lower.

The heating of the tank by the electricity system is shown in the temperature of the absorption pipe, when at night its temperature does not decrease much.

The temperature of the glass envelope is continuously repeated.

At night periods, the absorber pipe is not able to cool down to the initial temperature, so is continuously heating.

As in previous case, between 6 a.m. and 8 a.m. the temperature of the absorber pipe increases due to the heating of the tank (electricity system), and the only output of water in the tank, no inputs in these hours.

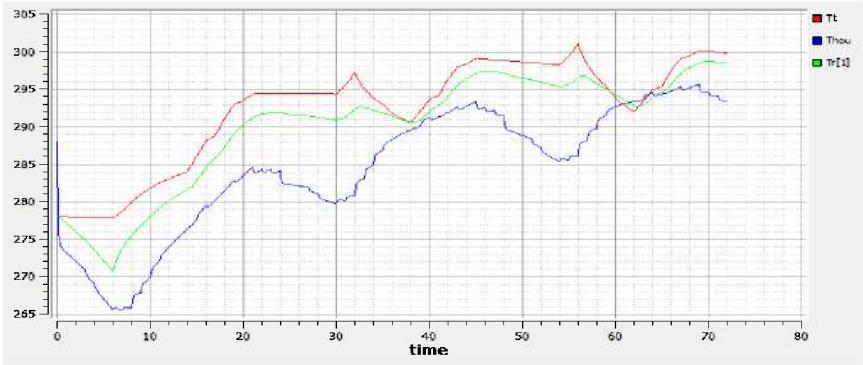


Fig 4.15: Outputs in a partly cloudy day: T_t , T_{hou} , T_r (K).

As it can be seen in Fig 4.15 the heat losses at night are higher than heat provided by the underfloor heating, so the temperature of the house decreased.

Temperatures of the tank and the first control volume of the underfloor pipe look like a lot; at night these temperatures almost do not decrease a lot due to the electricity system.

At this case, the velocity in the underfloor pipe is zero in the six first hours of the first day and it causes the rapid drop in temperature of the underfloor heating pipe and the house during six first hours of the first day; the second and third day, this system is always connected so the temperature of the house is increasing during the day, and decrease a bit at night.

Temperature in the house is continuously increasing, but each day less; it is possible that in the next days this temperature reach a steady state. This temperature is between than 286 K , and 295 K, and it is possible that next days will be between 290 K and 295 K, a suitable temperature to live, so in this case it would be possible heating the house with the underfloor heating.

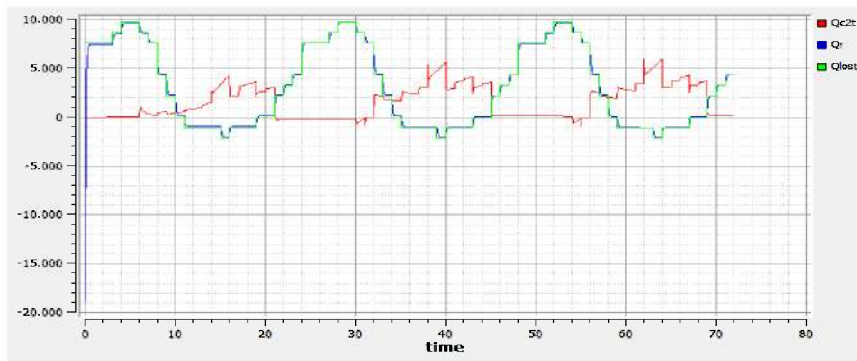


Fig 4.16: Outputs in a partly cloudy day: Q_{c-t} , Q_r , Q_{lost} (W)

As show Fig 4.16 the heat lost is negative throughout the day due to the temperature of the air is higher than the temperature on the wall. The highest heat transmission from the coil to the tank takes place in the hours of the day in which the radiation is maximum (14 p.m. to 16 p.m., and 17 p.m. to 19 p.m.), the rest of the hours this heat transmission is lower.

Negative heat peaks exist in the system of heat transmission between the coil and he tank due to in the first hours of the day the temperature of the tank is higher than temperature in the coil pipe, this is due to electric system that maintains the temperature of the tank at night; in this period of time the temperature of the water that flows inside the coil decrease its temperature during the night by heat losses of the collector, that cooled the glass envelope and the absorber pipe and these cool the water that flows inside the collector pipe; this is due to a constant but low velocity, that is maintained inside the collector pipe at night.

Positive heat peaks in transmission between the coil and the tank are at 14p.m. due to the high difference of temperatures between the coil and the tank in that hour.

In this case, highest heat transmission between the coil and the tank is carried out between 14p.m. and 16p.m. when the radiation is maximum and the entrance of water to the tank is maximum, too.

Heat provided by the underfloor heating is higher than losses during the day due to the high temperature of the tank, but losses of heat of the house are higher than underfloor heating during the night, due to the ambient temperature and the temperature of the tank is decreasing..

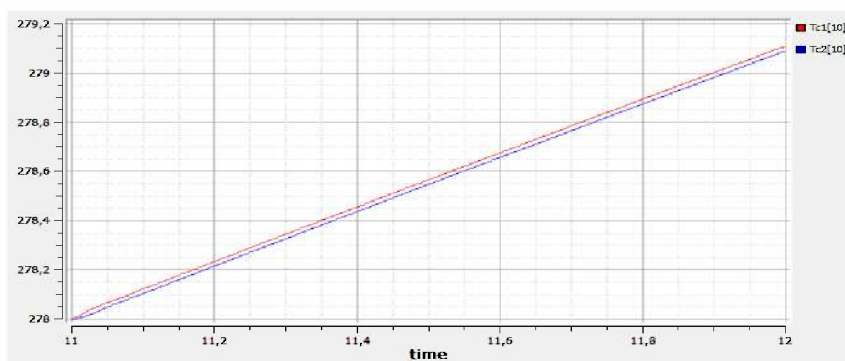


Fig 4.17: Outputs in a partly cloudy day: T_{c1} , T_{c2} (K).

Heat transmission in the coil can be seen in Fig 4.17, in which are shown temperatures at the entrance and the exit of the coil. The difference of temperature between the inlet and the outlet is so small due to the velocity of the water inside the pipe (2m/s), when the velocity decreased, the difference of temperature is increased because the water has more time of heat transmission, may transfer more heat.

In this case the temperature is increased about 1.1 K in one hour, less than in previous case because the radiation between this hours is 50 % less than the radiation in the same hours in a completely sunny day (100 W/m²).

4.1.3 Simulation in a completely cloudy day

In next figures, values of inputs are drawn for a completely cloudy day: I_c , Q_{elec} , m_{ti} , m_{to} , v_{wc} , and v_{wr} ; T_w , T_{air} , T_{cloud} are the same that previous cases.

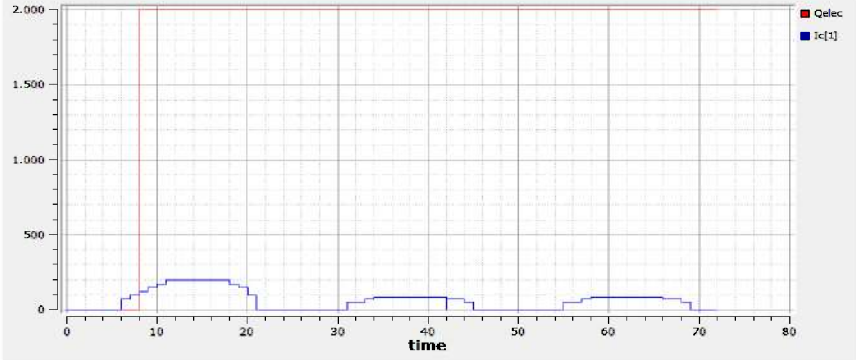


Fig 4.18: Inputs in a completely cloudy day: Q_{elec} , I_c .

In this case electricity system is switched on during all the day, because the radiation of the sun is not high enough to maintain the temperature of the tank in at acceptable level.

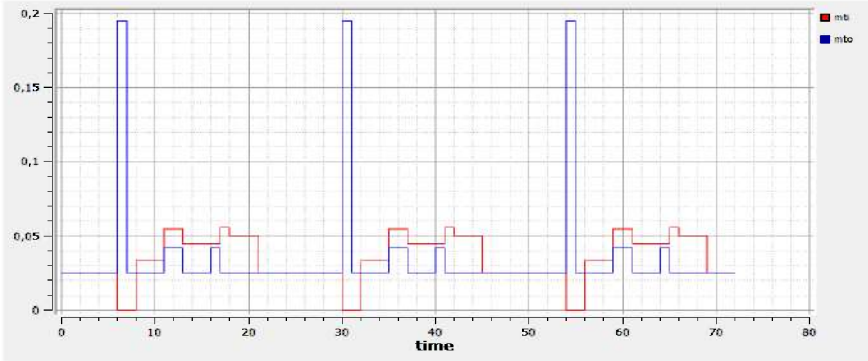


Fig 4.19: Inputs in a completely cloudy day: m_{ti} , m_{to} .

In this case the inlet of water to the tank is carried out more slowly because if not, the temperature of the tank drops drastically, due to the low radiation of the sun in these days.

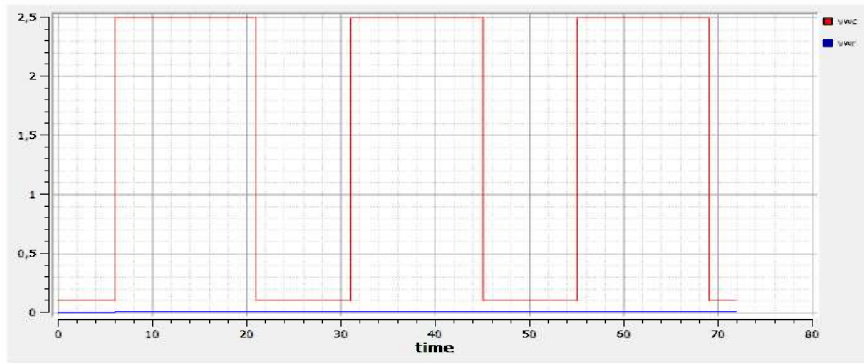


Fig 4.20: Inputs in a completely cloudy day: v_{wc} , v_{wt} .

Here, the velocity of water inside the collector pipe is the highest possible during the day due to low radiation; at night this velocity decreased a lot, because in these hours the heat transmission from the coil to the tank is not suitable, because it cools the tank.

And the next results have been obtained:

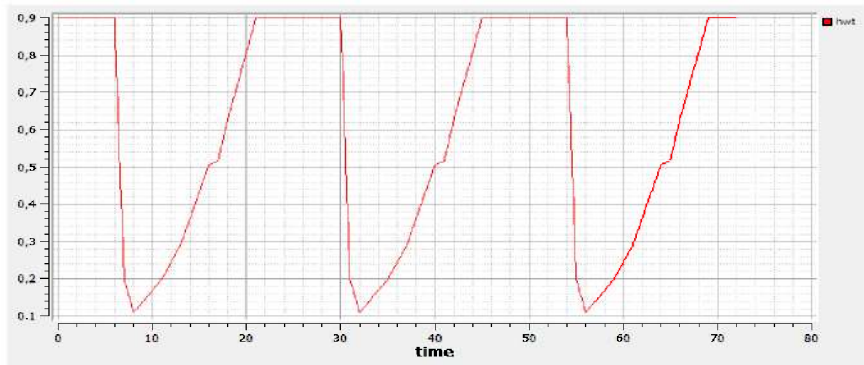


Fig 4.21: Outputs in a completely cloudy day: h_{wt} (m).

Figure 4.21 shows that the entrance of water to the tank, in this case are carried out more slowly than in previous cases, continuously during 13 hours (8a.m. and 21 p.m., the maximum time of heat transmission by the sun) due to the low radiation throughout the day.

This slow entry of water causes minimal diminution in the temperature of the water of the tank.

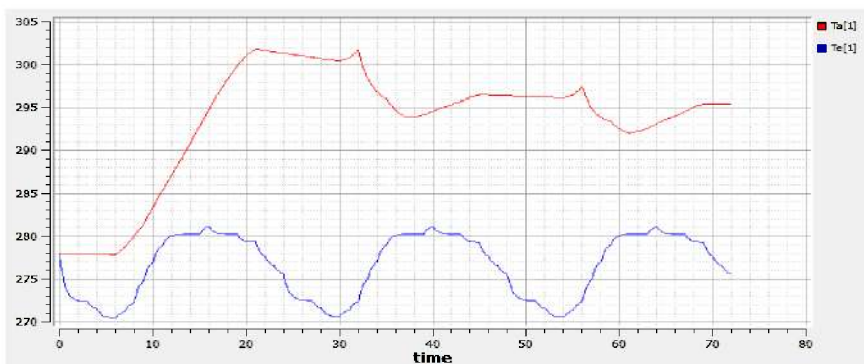


Fig 4.22: Outputs in a completely cloudy day: T_A , T_E (K)

In this case, temperature of absorber pipe is maintained at night due to the electricity system, but between the hours in which the tank is practically empty this temperature drops, because

the collector does not provides heat enough, and the area of transmission of that heat in the tank is very low, due to the level of the tank at these hours.

Temperature of the glass envelope is practically the same in two previous cases.

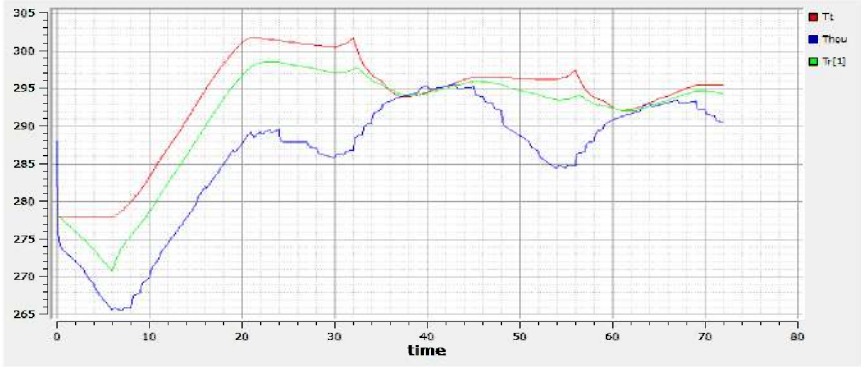


Fig 4.23: Outputs in a completely cloudy day: T_t , T_{hou} , T_r (K).

As it can be seen in Fig 4.23 the temperature of the tank is continuously increasing during the first day, because this day is sunny, but in next days that are completely cloudy the temperature of the tank is decreasing due to the continuous entry of water to the tank; at night this temperature decreased a bit because the tank is full and the electricity system is not enough to maintain the temperature inside the tank constant.

The temperature of the tank is enough in the second and third day to have a shower or clean dishes. The wash machine is not valid to this process, and this water needs to be heated more. Regarding to the heating of the house, the temperature at home is enough to live good during the central hours of the day, because is of 294K, but as it can be seen the temperature is continuously decreasing inside tank, and at home, so it is sure that the tank cannot maintain an adequate temperature in the following days.

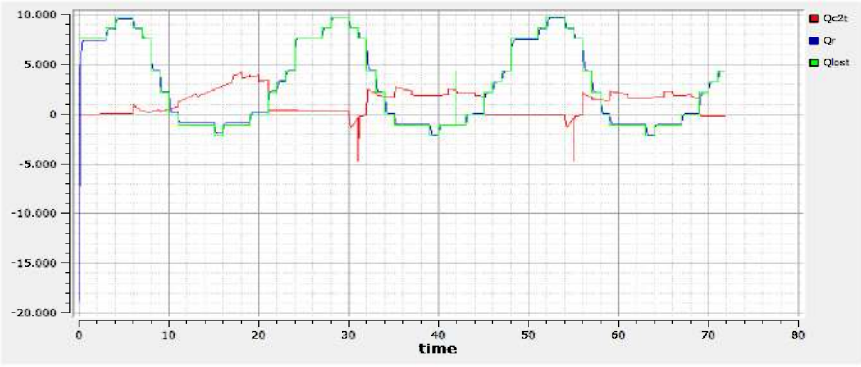


Fig 4.24: Outputs in a completely cloudy day: Q_{c-t} , Q_r , Q_{lost} .

As in previous cases the heat losses during the day are negative due to the air has higher temperature than the wall of the house; at night the heat losses are positive, logically.

The heat provided by the coil is positive during the day and during the night, due to the water that flows inside the coil have more temperature that the tank. Between 6a.m. and 8 a.m. the heat provided by the coil has a negative value due to the tank is warmer than the coil, due to the electric system. The value of this heat transmission (coil-tank) is constant in the second and third day due to during the day, there are the same value of radiation .

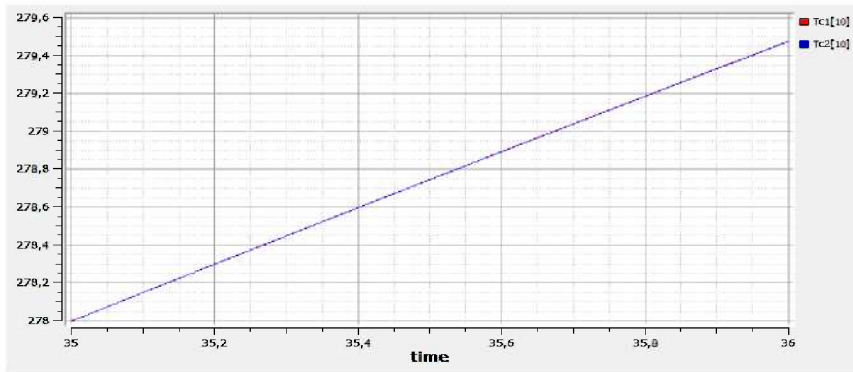


Fig 4.25: Outputs in a completely cloudy day: T_{c1} , T_{c2} .

Heat transmission in the coil can be seen in Fig 4.25, in which are shown temperatures at the entrance and the exit of the coil during 11 a.m. and 12 p.m of the second day. The temperature difference between the inlet and the outlet is so small due to the velocity of the water inside the pipe (2.5 m/s), when the velocity decreased, the temperature difference is increased because the water has more time of heat transmission and could transfer more heat.

In this case the temperature increases about 1.4 K per hour, more than previous case (partly cloudy) due to the velocity in this case is higher.

4.2 Verification of the results

As can be seen in previous figures, the results for each simulation are different; these results depend on the different inputs for each system and different assumption in each one.

Depending on the solar radiation incident in the collector for each case, the temperature of absorber pipe increase more or less.

In a sunny day the sun is radiating during fifteen hours with almost a constant irradiance of 200 W/m^2 , while in a partly cloudy day only in three hours of fifteen there are a solar irradiance of 200 W/m^2 ; in a completely cloudy day there is no time with this solar radiation, so, the temperature in the absorber pipe will be lesser in each experience respectively. It can be seen in Fig 4.6, Fig 4.14, and Fig 4.22.

These figures shown the absorber pipe temperature increase between 6 a.m. and 8 p.m. because the sun is irradiating, the tank is emptying, and the electricity system running; this temperature decreases between the hours in which the tank is filling (normally between 8 a.m. and 14 .a.m.) due to the low area of heat transmission by the coil and the electricity system, and return to increase between 14 p.m. and 21 p.m., thanks to the irradiation of the sun and the area of heat transmission by the coil.

Temperature of the absorber pipe does not only depends on the radiation of the sun, also depends on the temperature of water flowing through the collector pipe; depending on this temperature, the absorber pipe will yield greater or lesser amount of heat; if the absorber pipe provides great amount of heat to the collector pipe, its temperature decrease a lot, while if the

absorber pipe provides less amount of heat, its temperature decrease a bit (with the same quantity of radiation).

The temperature of the glass envelope is almost constant in the three experiences; this temperature depends on temperature of the absorber pipe, clouds and air; temperature of clouds and air are constant in the three experiences.

The height of water in the tank is related to water consumption of the house; at the beginning of a day the tank should be full due to the higher need of hot water in a day, it is in the morning, due to it is the moment for having a shower, so the tank should be full at this time. Depend on the case, the radiation is greater or lesser, so in a sunny day is practically equal the hours in which the tank is filled, but in a partly or completely cloudy day, these hours should be discussed. In a partly cloudy day, it would be better to fill the tank in the hours with more radiation, and in a completely cloudy day this mass flow should be divided in the maximum period of time in order to maintain as much as possible the tank temperature (this water is around 278K, too cold). It can be seen in figures 4.5, 4.13, 4.21.

About the temperature of the tank, in figures 4.7, 4.15, 4.23 it can be seen that in a sunny day the tank reaches a higher temperature than in a partly cloudy day, and in this case reaches a higher temperature than in a completely cloudy day. This temperature depends mainly on the heat transmission in the coil; if the radius and the length of the coil are the same in the three cases, this heat transmission depends on the velocity of the water flowing inside the coil (collector pipe), and the temperature of this water. The temperature of this water (collector or coil pipe), depends on the quantity of solar radiation absorbed by the absorber pipe, so it depends on the radiation of the sun, and the temperature achieved by the absorber pipe. Sunny day reaches the highest temperature of the absorber pipe, so the highest temperature of the water flowing inside the coil will be in a sunny day, therefore the highest temperature of the tank will be in a sunny day.

In the rest of cases with low radiation, if the velocity of the water flowing inside the coil pipe is increased, the forced convection coefficient will be increased (h_c), too, and the heat transmission between these systems will be better

Temperature in the house and temperature of the underfloor pipe is closely related with the temperature of the tank, because it is this tank which provides water to the underfloor pipe.

Highest temperature will be the temperature of the tank, then, the temperature in the first volume control of the underfloor pipe, then, the second volume control, third, etc.

The temperature of the underfloor pipe depends on the temperature of the tank and the heat transmission between this pipe and the air of the house, coefficient of natural convection in the house, h_r , and area of heat transmission; this coefficient is assumed constant in this thesis so the temperature of the underfloor pipe only depends on the temperature of the tank. The velocity of the water flowing through this pipe is important due to the temperature difference between the entrance and the exit of the water. As it can be seen in Appendix 3 in Fig 4-26

and 4-27 the house reaches a greater temperature when the water flows at higher velocity inside the underfloor pipe than at a lower velocity, but the difference of temperature between the entrance and the exit of this pipe will be lesser at high velocity than at low velocity; it can be seen in Fig 4-28 and 4-29, in Appendix 3. As can be seen the temperature of the house is higher than the temperature of the tank during sunny hours; this can be by the heat transmission from the ambient to the house, in the central hours of the day.

The temperature of the house only depends on the entrance of heat from the underfloor pipe and the exit of heat due to heat losses. These heat transmission is not exact due to the house is assumed perfectly closed over time and this is never possible, because of the window, doors, etc. In this Thesis is assumed perfectly closed to the ambient and only heat losses through the walls are considered, Underfloor heating is all the day running and the house is continuously heating thanks to this system. The heat transfer coefficients do not have in account conductions through materials, and a lot of simplifications in the construction of the house are assumed (walls, windows, doors, floor, etc).

As it can be seen in figures 4.7, 4.15, 4.23 the temperature of the house decrease a lot in the first six hours in all cases, this is due to in this hours the tank has a low temperature that provide to the underfloor pipe a low temperature, too, during six hours; this could reduced the temperature of the house a lot during these six hours, then the tank increased its temperature thanks to the sun, and the temperature of the house begins to rise.

About heat transmission, in each case is different.

Heat transmission between the coil and the tank is function of the length of the coil, radius, the coefficient of heat transmission between coil and tank, area of heat transmission and the temperature of the coil pipe and the tank; in all cases the radius and the length of the pipe are the same, so this heat transmission only depends on the velocity of the water that flows inside that pipe that affects to the coefficient of heat transmission, the area of heat transmission and the temperature difference between coil and tank.

Temperature of the coil pipe depends on the temperature of the water that flows inside the collector, and this temperature depends in turn on the temperature of the absorber pipe, which depends on the radiation of the sun. So the temperature of the water that flows inside the coil will be greater on a sunny day than in a cloudy day, so this heat transmission will be greater in a sunny day, then, in a partly cloudy day, and finally in a completely cloudy day.

The area of heat transmission by the coil in a sunny day is higher than the area of heat transmission in a partly cloudy or completely cloudy day, due to in these days the tank fills slower than in a sunny day.

Depending on the temperature of the tank, this heat transmission will be greater or lesser.

As can be seen in figures 4.9, 4.17, 4.25 the temperatures at the entrance of the coil and the exit of this are different depending on the case study. The maximum heat transmission is carried out in a sunny day, when the temperature of the coil pipe is higher.

Radius of the pipes and length of these make the system greater heat transmission, during the day, and during the night. Heat transmission is higher if radius or length is increased.

The velocity of the water inside the coil is an important factor too; in the two first cases (sunny and partly cloudy) the velocity is the same, but in the third case, the velocity is increased to 2.5 m/s to improve the heat transmission. This heat transmission can be seen in figures 4.8, 4.16, 4.24.

About losses of heat at home, in the three cases are the same due to the three cases have assumed the same conditions (T_{wall} , T_{air} , A_{lost} , h_{cn}). It can be seen in figures 4.8, 4.16, 4.24.

These losses of heat are negative throughout the day, this is due to the temperature of the air in some hours is greater than the temperature of the wall of the house, so, heat transmission in these hours is from the ambient to the house.

The temperature of the underfloor pipe depends on the temperature of the tank and the heat transmission between this pipe and the air of the house, coefficient of natural convection in the house, h_r , and area of heat transmission; this coefficient is assumed constant in this thesis so the temperature of the underfloor pipe only depends on the temperature of the tank. The velocity of the water flowing through this pipe is important due to the temperature difference between the entrance and the exit of the water. As it can be seen in Appendix 4 in Fig 4-26 and 4-27 the house reaches a greater temperature when the water flows at higher velocity inside the underfloor pipe than at a lower velocity, but the difference of temperature between the entrance and the exit of this pipe will be lesser at high velocity than at low velocity; it can be seen in Fig 4-28 and 4-29, in Appendix 4. As can be seen the temperature of the house is higher than the temperature of the tank during sunny hours; this can be by the heat transmission from the ambient to the house, in the central hours of the day.

About underfloor heating, The temperature of the underfloor pipe depends on the temperature of the tank and the heat transmission between this pipe and the air of the house, coefficient of natural convection in the house, h_r , and area of heat transmission. In all cases the dimensions and the coefficient of heat transmission are considered equal, but the temperature difference is different for each case.

Temperature in the underfloor pipe depends on the temperature of the tank, if this temperature increases the temperature of the underfloor pipe increases too, and if this temperature decreases, the temperature in the underfloor pipe decreases, too.

The variations in the temperatures of the collector pipe, the coil and the underfloor pipe is calculated thanks to the Euler method, so the variations in this variables may take some time to be reflected, it means; it is possible that the temperature of the tank drops quickly, but the temperature of the underfloor pipe or the house do not reflect this variation simultaneously.

5 Optimized operation

Optimization of operation could not carry out due to lack of time in the making of this Thesis.

6 Discussion and conclusions

Available of the power of the sun is the most important parameter in this system, and depends on quantity of this power, all previous temperatures will be greater or lesser; this system is unable to function without sun energy.

Logically the system will function better in sunny conditions than in cloudy conditions.

This system is a complex system due to all the temperatures is related. Temperature of absorber pipe depends on the sun radiation, temperature of the collector pipe depends on the temperature of the absorber pipe; temperature of the coil pipe depends on the temperature in the collector pipe; temperature in the tank depends on the temperature of the coil pipe; temperature of the underfloor pipe depends on the temperature of the tank, and temperature at home depends on the temperature of the underfloor pipe; so all temperatures are related.

Velocities, lengths and radius are very important parameters when the system is modeled, due to the difference heat transferred in them; in this thesis some of these conditions are fixed like constant conditions like radius, lengths, temperatures or heat transmission areas.

In the experimentation of the model in this Thesis has been found that the length of the coil used was not adequate, because other lengths improve the heat transmission.

Changes in the diameter, length or velocity of the coil, collector pipe, or underfloor pipe provide very different results; this results are not the ideal results, and are not the results which can obtained the better temperature in the tank.

Better results have been obtained in different experiments with the model, but diameters of the coil was not ideal diameters for the dimensions of the tank, and several simplification had been carried out.

Coefficients of heat transmission are very important parameters too, because depending of them, the temperatures achieve in each pipes or places will be different; some assumption and simplifications in them are carried out; is possible that some of them are not correct, but, to simplify the model, these simplifications have been carried out.

Heat provided by electricity system does not provide the heat enough to increase the temperature of the tank, is this is full, but when the tank is half, the temperature can be maintained with this type of heat transmission.

Area of heat transmission in the tank is a very important parameter and it is possible that the configuration of heights in the tank is not the better configuration, because it would be better that during the hours of the day with high transmission of radiation the tank was completely filled.

Velocity inside the pipes modifies these coefficients in order to maintain a high heat transmission. These velocities, in this Thesis, have not been zero in any moment, because if these velocities are zero high peaks of heat appear in the system, due to the difference of temperatures between the water of the coil and the tank, the absorber pipe and the coil; the

water that flows inside the underfloor pipe and the house, etc. It is possible that the collector works better when the velocity of the water flowing through it is zero at night hours.

The real model has to take into account all these simplifications to get closer to reality.

Height of water in the tank is, also, a very important parameter because the tank must be filled in the times when hot water is needed. The main consume of hot water at home is in the morning in order to have a shower, at lunch to wash dishes and wash clothes in the wash machine; the temperature of these homeworks are different for each one, but it is assume that with around 313 K is possible to realize all these homeworks. The tank system provides a complementary electricity system to achieve this temperature if the solar collector system cannot achieve. In this Thesis the electricity system has been used as less as possible due to the cost of the energy and because it is supposed that is a form of green energy, but if in some moments the electricity system has to be connected in order to maintain a higher temperature inside the tank, the electricity system can be used.

In the system modeled with the inputs established only achieves that temperature in sunny days, and is lower than 313 K; in partly cloudy and completely cloudy days was impossible achieves that temperature, I think is due to the poor configuration of the entrance of the water to the tank, that do not permit increase this temperature.

Entrance of water to the tank low it temperature quickly, due to the temperature of this water is only 278K, a very low temperature (because is Norway). In order to maintain the temperature of the tank as much constant as possible the entrance of water must be done as slow as possible in partly and completely cloudy days.

Consumes of water are higher than normal consumes in order to oversize the power consumption of water and having hot water for other purposes, in the case it could be necessary.

About the velocity inside the underfloor pipes or the velocity of the water flowing inside the collector pipe or coil pipe, depend on this velocity each system will transfer more or less energy; it is possible that with a fast velocity the water flowing inside the pipe cannot transfer all the possible energy, because of the time (length of 9 m, and velocity of 2m/s only states 4.5 seconds); and if the velocity inside these pipes is very slow, the heat transfered will be more than required, it means, if this water is cooled, it is possible that with very low velocity the pipe at the end of the tour can be heated, due to transfer all the heat possible and more than this, so finally the water finish heating. It can be seen in the undefloor pipe that has a great length and if the velocity is very slow at the end of the pipe the house transfer heat to the pipe and not the pipe transfer heat to the house.

In sunny days, the tank is continuously heating, day by day; if the temperature of the tank is approximated to 373 K the heat input to the tank should be stopped because the water of the tank cannot achieve that temperature. To control this temperature a control system can be established in a set point of temperature of the tank; if this temperature is exceeded, the

controller stop the heat input to the tank; this is achieved stopping the velocity of the water flowing through the collector and coil pipe, so the coefficient of heat transmission is zero and the heat transferred between the coil and the tank (Q_{c-t}) will be zero.

On the other hand a temperature sensor should be set to the output of the underfloor pipe, in order to change the speed of water inside this pipe, to avoid an incorrect heat transmission.

In the underfloor heating can be also used as controller with a set point. If the temperature of the house is higher than 294K the underfloor heating is stopped and the temperature of the underfloor pipe and the temperature of the house start to decrease. In the other hand, if the temperature of the house decreased of 291K the underfloor heating starts to run and the temperature of the house is increased; if at this time the temperature in the tank is not high enough to increase the temperature of the house the electricity system is switched on and the tank increase its temperature in order to maintain the temperature of the house in the suitable values.

Several simplifications have been carried out in this Thesis, like efficiency of the collector, coefficients of heat transmission that make the model differs quite from reality.

Calculating the constant coefficients is performed assuming constant temperatures and speeds.

Lower consume of electricity has been searched in this Thesis, so better conditions and inputs has been established in order to decrease consume of this type of energy. It is possible that some assumptions and simplifications are not the as better simplifications as possible, and some equation do not define the system as better as possible; having in account those things those results have been obtained.

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Appendices

Appendix 1: Thesis topic



Telemark University College

Faculty of Technology

FMH606 Master's Thesis

Title: Thermal solar energy use: modeling and optimization

TUC supervisor: Bernt Lie

External partner: Universitetet i Agder (prof. Hans-Georg Beyer)

Task description:

The following describes the thesis:

1. An *overview* should be given of basic solar irradiation, including the amount available in Southern Norway, and how it varies during the season/day, and with cloud level. (In the work, the actual data will be made available from another project.)
2. The main study is on a collector of solar energy and the storage of hot water. An overview should be given of such a system, together with the use of alternative energy sources (e.g. electricity). A typical use of the energy should be described, e.g. heating a house (floor heating). The need for level of detail in a building model should be discussed.
3. The system for collecting and storing thermal energy together with typical consumption of such energy should be described in a dynamic model. Numerical values for parameters and typical operational data should be chosen, and the model should be verified through simulation.
4. A cost function for optimizing the use of hot water should be developed, including future consumption, energy prices, and available solar energy – typically on a 1-2 day horizon. The possibility of harvesting as much solar energy as possible should be studied.
5. The work should be documented in a written report (the thesis).

Task background:

In a developing world with limitation in availability of energy, it is important to use every available energy source. To avoid negative influence on the environment, renewable energy forms should be favoured. Two important sources of energy are solar energy and wind energy;

these are freely available, both are independent of the carbon cycle, but share the problem of being intermittent in nature: their availability is fluctuating and can only be predicted on a

relatively short time horizon. Solar energy can be directly used as thermal energy, or can be converted to electric energy utilizing photo voltaic (pv) technology.

In a project involving personell at University of Agder and Telemark University College, the goal is to study how the use of such intermittent (fluctuating) energy can be expanded by storing the energy. Sometimes such intermittent energy produce more power than can be used at the moment, while at other times, it produces less power than what is needed. By storing the surplus production, intermittent energy can be used when it is needed. As it is difficult to store electric energy, other forms of storage are sought, e.g storage as thermal energy (e.g. hot water), hydrogen (electrolysis of water), or potential energy (pumping water up into high head water reservoirs). All such storage involves some loss of energy. However, as this is free energy that is not otherwise utilized, harvesting some of it is better than harvesting none of it.

In order to use the intermittent energy in an optimal way, one should really know the future consumption and price of energy, as well as the future availability of these intermittent energy forms.

In this thesis, the main emphasis is on the storage of solar energy in the form of hot water. This is achieved by using solar radiation to heat up water. Furthermore, assuming that the future consumption and price is known, as well as that future solar radiation is known, the emphasis of the thesis is to find the optimal use of the energy.

In a parallel thesis at University of Agder, prediction models for solar radiation will be studied.

Also, some work will be carried out at Telemark University College on characterising energy consumption (visiting PhD student).

Student category:

The thesis can be solved by EET, PT, and SCE students with a decent understanding of modeling of dynamic systems. Also, part of the work deals with optimization of the operation over a given time horizon. This can also be handled by EET, PT and SCE students.

Practical arrangements:

The working place will be Telemark University College, Campus Kjølnes in Porsgrunn.

Signatures:

Student (date and signature):

Supervisor (date and signature):

Appendix 2: Equations for each control volume

Water of the collector:

$$\begin{aligned}\frac{dT_{c,1}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{ci} - T_{c,1}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,2}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c1} - T_{c,2}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,3}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c2} - T_{c,3}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,4}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c3} - T_{c,4}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,5}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c4} - T_{c,5}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,6}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,5} - T_{c,6}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,7}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,6} - T_{c,7}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,8}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,7} - T_{c,8}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{c,9}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,8} - T_{c,9}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}} \\ \frac{dT_{co}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dx} (T_{c,9} - T_{co}) + \frac{h_c P_c (T_{A,x+\Delta x} - T_{c,x+\Delta x})}{\rho_w A_c \hat{C}_{p,w}}\end{aligned}$$

Coil pipe:

$$\begin{aligned}\frac{dT_{coil,1}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{co} - T_{coil,1}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,1} - T_t) \\ \frac{dT_{coil,2}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,1} - T_{coil,2}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,2} - T_t) \\ \frac{dT_{coil,3}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,2} - T_{coil,3}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,3} - T_t) \\ \frac{dT_{coil,4}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,3} - T_{coil,4}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,4} - T_t) \\ \frac{dT_{coil,5}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,4} - T_{coil,5}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,5} - T_t) \\ \frac{dT_{coil,6}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,5} - T_{coil,6}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,6} - T_t) \\ \frac{dT_{coil,7}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,6} - T_{coil,7}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,7} - T_t) \\ \frac{dT_{coil,8}}{dt} &= \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,7} - T_{coil,8}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,8} - T_t)\end{aligned}$$

$$\frac{dT_{coil,9}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,8} - T_{coil,9}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{coil,9} - T_t)$$

$$\frac{dT_{ci}}{dt} = \frac{\dot{m}_c}{\rho_w A_c dy} (T_{coil,9} - T_{ci}) - \frac{U_{c-t} P_c}{\rho_w A_c \hat{C}_{pw}} (T_{ci} - T_t)$$

Absorber pipe:

$$\frac{dT_{A,1}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,1}^4 - T_{E,1}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,2}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,2}^4 - T_{E,2}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,3}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,3}^4 - T_{E,3}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,4}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,4}^4 - T_{E,4}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,5}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,5}^4 - T_{E,5}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,6}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,6}^4 - T_{E,6}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,7}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,7}^4 - T_{E,7}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,8}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,8}^4 - T_{E,8}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,9}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,9}^4 - T_{E,9}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

$$\frac{dT_{A,10}}{dt} = \frac{I_c w}{\rho_A \hat{C}_{pA} A_A} - \frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)} \cdot \frac{P_{Ao}}{\rho_A \hat{C}_{pA} A_A} (T_{A,10}^4 - T_{E,10}^4) - \frac{h_c P_{Ai} (T_{A,x+\Delta x} - T_{C,x+\Delta x})}{\rho_A \hat{C}_{pA} A_A}$$

Glass envelope:

$$\frac{dT_{E,1}}{dt} = \frac{\frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,1}^4 - T_{E,1}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,1}^4 - T_{cloud}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,1} - T_{air})$$

$$\frac{dT_{E,2}}{dt} = \frac{\frac{\sigma}{\frac{1}{\varepsilon_A} + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}}\right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,2}^4 - T_{E,2}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,2}^4 - T_{cloud}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,2} - T_{air})$$

$$\begin{aligned} \frac{dT_{E,3}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,3}^4 - T_{E,3}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,3}^4 - T_{cloud}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,3} - T_{air}) \\ \frac{dT_{E,4}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,4}^4 - T_{E,4}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,4}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,4} - T_{air}) \\ \frac{dT_{E,5}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,5}^4 - T_{E,5}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,5}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,5} - T_{air}) \\ \frac{dT_{E,6}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,6}^4 - T_{E,6}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,6}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,6} - T_{air}) \\ \frac{dT_{E,7}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,7}^4 - T_{E,7}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,7}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,7} - T_{air}) \\ \frac{dT_{E,8}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,8}^4 - T_{E,8}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,8}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,8} - T_{air}) \\ \frac{dT_{E,9}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,9}^4 - T_{E,9}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,9}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,9} - T_{air}) \\ \frac{dT_{E,10}}{dt} &= \frac{\frac{\sigma}{\varepsilon_A + \frac{1 - \varepsilon_E}{\varepsilon_E} \left(\frac{r_{AO}}{r_{Ei}} \right)}}{\rho_E \hat{C}_{pE} A_E} P_{Ao} (T_{A,10}^4 - T_{E,10}^4) - \frac{\sigma \varepsilon_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,10}^4 - T_{clouds}^4) - \frac{h_E P_{Eo}}{\rho_E \hat{C}_{pE} A_E} (T_{E,10} - T_{air}) \end{aligned}$$

Underfloor pipe:

$$\begin{aligned} \frac{dT_{r,1}}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_t - T_1) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_1 - T_{airh}) \\ \frac{dT_2}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_1 - T_2) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_2 - T_{airh}) \\ \frac{dT_3}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_2 - T_3) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_3 - T_{airh}) \\ \frac{dT_4}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_3 - T_4) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_4 - T_{airh}) \\ \frac{dT_5}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_4 - T_5) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_5 - T_{airh}) \end{aligned}$$

$$\begin{aligned} \frac{dT_6}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_5 - T_6) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_6 - T_{airh}) \\ \frac{dT_7}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_6 - T_7) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_7 - T_{airh}) \\ \frac{dT_8}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_7 - T_8) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_8 - T_{airh}) \\ \frac{dT_9}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_8 - T_9) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_9 - T_{airh}) \\ \frac{dT_{10}}{dt} &= \frac{\dot{m}_r}{\rho_w A_r dz} (T_9 - T_{10}) - \frac{h_r P_r}{\rho_w A_r \hat{C}_{pw}} (T_{10} - T_{airh}) \end{aligned}$$

Appendix 3: Code written in Modelica

Completely sunny day:

```
model solarsunnyfinal
```

```
// Constants
```

```
constant Real PI = 3.141592654 "pi, -";
```

```
constant Real sbc = 0.0000000567 "Stefan Boltzmann constant, W/m2/K4";
```

```
constant Real emissa = 0.01 "Emissivity of the absorber pipe,-";
```

```
constant Real emisse = 0.92 "Emissivity of the glass envelope,-";
```

```
constant Real densw = 1000.0 "Density of water, kg/m3";
```

```
constant Real densa = 8900.0 "Density of absorber pipe, kg/m3";
```

```
constant Real dense = 2700.0 "Density of glass envelope, kg/m3";
```

```
constant Real densair = 1.2 "Density of air, kg/m3";
```

```
constant Real hcair = 1033 "Heat capacity of air, J/kg/K";
```

```
constant Real hcw = 4180.0 "Heat capacity of water, J/kg/K";
```

```
constant Real hca = 389.0 "Heat capacity of absorber pipe, J/kg/K";
```

```
constant Real hce = 833 "Heat capacity of glass envelope, J/kg/K";
```

```
// Parameters
```

```
parameter Real rc = 0.025 "Radius of the solar collector and the coil, m";
```

```
parameter Real Dc = 0.05 "Diameter of the collector";
```

```
parameter Real rai = 0.025 "Inner radius of the absorber pipe, m";
```

```
parameter Real rao = 0.03 "Outer radius of the absorber pipe, m";
```

```
parameter Real rei = 0.045 "Inner radius of the glass envelope, m";
```

```
parameter Real reo = 0.05 "Outer radius of the glass envelope, m";
```

```
parameter Real rr = 0.03 "Inner radius of the underfloor pipe, m";
```

```
parameter Real rt = 0.565 "Radius of the tank, m";
```

```
parameter Real Dt = 1.13 "Diameter of the tank, m";
```

```
parameter Real Dr = 0.06 "Diameter of the underfloor pipe, m";
```

```
parameter Real Ht = 0.9 "Total height of the tank, m";
```

```
parameter Real he = 1.27 "Individual coefficient of natural convection from the envelope to the air, W/m2/K";
```

```
parameter Real hr = 4.24 "Natural convection coefficient from the underfloor pipe to the air of the house, W/m2/K";
```

parameter Real hcn = 4.0 "Natural convection coefficient from the wall of the house to the ambient air, W/m²/K";

parameter Real hcnt = 1.71 "Natural convection coefficient from the tank to the air of the house, W/m²/K";

parameter Real L = 112.5 "Length of the collector pipe, m";

parameter Real Lcoil = 29 "Length of the coil pipe, m";

parameter Real Lr = 200 "Length of the underfloor pipe, m";

parameter Real Vair = 384 "Air volume in the house, m³";

parameter Integer N = 10 "Number of control volumes";

parameter Real dx = L / N "Length of each control volume in the collector, m";

parameter Real dy = Lcoil / N "Length of each control volume in the coil, m";

parameter Real dz = Lr / N "Length of each control volume in the underfloor pipe, m";

parameter Real sigma = sbc / (1 / emissa + (1 - emisse) / emisse * rao / rei) "Radiation coefficient";

parameter Real Ac = PI / 4 * Dc ^ 2 "Cross sectional area of the collector, m²";

parameter Real At = PI / 4 * Dt ^ 2 "Cross sectional area of the tank, m²";

parameter Real Ar = PI / 4 * Dr ^ 2 "Cross sectional area of the radiation pipe, m²";

parameter Real Alost = 272 "Area of lost in the house, m²";

parameter Real Pc = 2 * PI * rc "Perimeter of the collector, m";

parameter Real Aa = PI * (rao ^ 2 - rai ^ 2) "Cross sectional area of the absorber pipe, m²";

parameter Real Pai = 2 * PI * rai "Inner perimeter of the absorber pipe, m";

parameter Real Pao = 2 * PI * rao "Outer perimeter of the absorber pipe, m";

parameter Real Peo = 2 * PI * reo "Outer perimeter of the glass envelope, m";

parameter Real Pr = 2 * PI * rr "Inner perimeter of the underfloor pipe, m";

parameter Real Ae = PI * (reo ^ 2 - rei ^ 2) "Cross sectional area of the glass envelope, m²";

parameter Real mair = Vair * densair "Mass of air in the house";

parameter Real Twall = 287 "Temperature of the wall fo the house";

// Initial state parameters

parameter Real Tc1i = 278 "Initial temperature of the water that flows inside the collector, K";

parameter Real Tc2i = 278 "Initial temperature of the water that flow inside the coil, K";

parameter Real Tai = 278 "Initial temperature of the absorber pipe, K";

parameter Real Tei = 278 "Initial temperature of the glass envelope, K";

parameter Real Tti = 278 "Initial temperature of the tank, K";

parameter Real hwti = 0.9 "Initial value of the height of water inside the tank, m";

```

parameter Real Tri = 278 "Initial temperature of the underfloor pipe, K";
parameter Real Thoui = 288 "Initial temperature of the house, K";
// Input parameters
parameter Real Twi = 278 "Value of the inlet temperature of water to the tank, K";
parameter Real Tairi = 280 "Value of the ambient air, K";
parameter Real Tambi = 280 "Value of the ambient air, K";
parameter Real Tcloudi = 270 "Value of the temperature of the clouds, K";
parameter Real Ici = 0.0 "Total energy provided by the sun, W";
parameter Real Qelec = 2000.0 "Total heat provided by the electricity system, W";
parameter Real vwci = 2 "Velocity of water inside the collector and coil pipe, m/s";
parameter Real mtii = 0.025 "Inlet mass flow to the tank, kg/s";
parameter Real mtoi = 0.025 "Outlet mass flow from the tank, kg/s";
parameter Real Qri = 0.0 "Heat transferred by the underfloor pipe, W";
parameter Real vwri = 0.005 "Velocity of the water that flows inside the underfloor pipe,
m/s";
// Variables
Real Qc2t "Heat provided by the coil, W";
Real mwt "Mass of water inside the tank, kg";
Real mc "Mass flow inside the collector";
Real mr "Mass flow inside the radiation pipe, kg/s";
Real hc "Forced convective heat transfer coefficient inside the collector pipe";
Real Qlost "lost of heat from the house to the ambient air, W";
Real a "Heat transferred by the underfloor pipe, W";
// Declaring N state variables in an array, setting initial (start) values
Real Tc1[N](each start = Tc1i) "Temperature in collector conduit, K";
Real Tc2[N](each start = Tc2i) "Temperature in conduit in heat exchanger through tank, K";
Real Ta[N](each start = Tai) "Temperature in absorber, K";
Real Te[N](each start = Tei) "Temperature in *envelope*??, K";
Real Tt(start = Tti) "Temperature in tank, K";
Real hwt(start = hwti) "Level/height of tank, m";
Real Tr[N](each start = Tri) "Temperature of the underfloor pipe, K";
Real Thou(start = Thoui) "Temperature in the house, K";
// Declaring input variables
Real Tw "Value of the inlet temperature of water to the tank, K";

```

```

Real Tair[N] "Value of the ambient air, K";
Real Tamb "Temperature of the ambient air, K";
Real Tcloud[N] "Value of the temperature of the clouds, K";
Real Ic[N] "Total energy provided by the sun, W";
Real Qelec "Total heat provided by the electricity system, W";
Real vwc "Velocity of water inside the collector and coil pipe, m/s";
Real mti "Inlet mass flow to the tank, kg/s";
Real mto "Outlet mass flow from the tank, kg/s";
Real Qr "Heat transferred by the underfloor pipe, W";
Real vwr "Velocity of the water that flows inside the underfloor pipe";
equation
// Heat input to tank
Qc2t = (hwt * 5 * hc * (sum(Tc2) - N * Tt));
//Heat transferred by underfloor pipe
a = 2 * PI * rr * Lr * hr * (sum(Tr) - N * Thou);
// Lost of heat to the ambient air
Qlost = Alost * hcn * (Twall - Tamb);
// Coefficients of heat transfer
hc = 4280 * (0.00488 * ((303 + 363) / 2) - 1) * (vwc ^ 0.8) / (Dc ^ 0.2);
// Mass of water inside the tank
mwt = At * hwt * densw;
// Mass flow inside the collector
mc = vwc * Ac * densw;
//Mass flow inside the underfloor pipe
mr = vwr * Ar * densw;
// Differential equations
der(Tc1[1]) = (mc / densw / Ac / dx * (Tc2[N] - Tc1[1]) + (hc * Pc) / densw / Ac / hcw *
(Ta[1] - Tc1[1])) * 3600;
der(Tc1[2:end]) = (mc / densw / Ac / dx * (Tc1[1:end - 1] - Tc1[2:end]) + (hc * Pc) / densw /
Ac / hcw * (Ta[2:end] - Tc1[2:end])) * 3600;
der(Tc2[1]) = (mc / densw / Ac / dy * (Tc1[N] - Tc2[1]) - (hc * Pc) / densw / Ac / hcw *
(Tc2[1] - Tt)) * 3600;
der(Tc2[2:end]) = (mc / densw / Ac / dy * (Tc2[1:end - 1] - Tc2[2:end]) - (hc * Pc) / densw /
Ac / hcw * (Tc2[2:end] - Tt * ones(N - 1))) * 3600;

```

```

der(Ta) = ((Ic * 2 * rao) / densa / hca / Aa - (sigma * Pao) / densa / hca / Aa * (Ta .^ 4 - Te
.^ 4) - (hc * Pai) / densa / hca / Aa * (Ta - Tc1)) * 3600;
der(Te) = ((sigma * Pao) / dense / hce / Ae * (Ta .^ 4 - Te .^ 4) - (sbc * emisse * Peo) / dense
/ hce / Ae * (Te .^ 4 - Tcloud .^ 4) - (he * Peo) / dense / hce / Ae * (Te - Tair)) * 3600;
der(Tt) = (mti / mwt * (Tw - Tt) + Qc2t / mwt / hcw + hwt / Ht * Qelec / mwt / hcw - 2 * PI
* rt * hwt * hent / mwt / hcw * (Tt - Thou)) * 3600;
der(hwt) = ((mti - mto) / densw / At) * 3600;
der(Tr[1]) = (mr / densw / Ar / dz * (Tt - Tr[1]) - (hr * Pr) / densw / Ar / hcw * (Tr[1] -
Thou)) * 3600;
der(Tr[2:end]) = (mr / densw / Ar / dz * (Tr[1:end - 1] - Tr[2:end]) - (hr * Pr) / densw / Ar /
hcw * (Tr[2:end] - Thou * ones (N - 1))) * 3600;
der(Thou) = (Qr / mair / hcair - Qlost / mair / hcair) * 3600;
// Inlet values
vwr = vwri;
Qr = if Thou < 294 then a
else a;
vwc = if time < 6 then 0.1
else if time > 6 and time < 8 then vwci
else if time > 8 and time < 16 then vwci
else if time > 16 and time < 21 then vwci
else if time > 21 and time < 30 then 0.1
else if time > 30 and time < 32 then vwci
else if time > 32 and time < 40 then vwci
else if time > 40 and time < 45 then vwci
else if time > 45 and time < 54 then 0.1
else if time > 54 and time < 56 then vwci
else if time > 56 and time < 64 then vwci
else if time > 64 and time < 69 then vwci
else 0.1;
Tw = if time < 9 then Twi
else if time > 9 and time < 21 then 280.0
else if time > 21 and time < 33 then Twi
else if time > 33 and time < 45 then 280.0
else if time > 45 and time < 57 then Twi
else if time > 57 and time < 69 then 280.0

```

else Twi;

Tair = if time < 1 then Tairi * ones(N)

else if time > 1 and time < 2 then 280.0 * ones(N)

else if time > 2 and time < 3 then 280.0 * ones(N)

else if time > 3 and time < 4 then 279.0 * ones(N)

else if time > 4 and time < 5 then 278.0 * ones(N)

else if time > 5 and time < 6 then 278.0 * ones(N)

else if time > 6 and time < 7 then 279.0 * ones(N)

else if time > 7 and time < 8 then 280.0 * ones(N)

else if time > 8 and time < 9 then 283.0 * ones(N)

else if time > 9 and time < 10 then 285.0 * ones(N)

else if time > 10 and time < 11 then 287.0 * ones(N)

else if time > 11 and time < 12 then 288.0 * ones(N)

else if time > 12 and time < 13 then 288.0 * ones(N)

else if time > 13 and time < 14 then 288.0 * ones(N)

else if time > 14 and time < 15 then 288.0 * ones(N)

else if time > 15 and time < 16 then 289.0 * ones(N)

else if time > 16 and time < 17 then 288.0 * ones(N)

else if time > 17 and time < 18 then 288.0 * ones(N)

else if time > 18 and time < 19 then 288.0 * ones(N)

else if time > 19 and time < 20 then 287.0 * ones(N)

else if time > 20 and time < 21 then 287.0 * ones(N)

else if time > 21 and time < 22 then 285.0 * ones(N)

else if time > 22 and time < 23 then 284.0 * ones(N)

else if time > 23 and time < 24 then 283.0 * ones(N)

else if time > 24 and time < 25 then Tairi * ones(N)

else if time > 25 and time < 26 then 280.0 * ones(N)

else if time > 26 and time < 27 then 280.0 * ones(N)

else if time > 27 and time < 28 then 279.0 * ones(N)

else if time > 28 and time < 29 then 278.0 * ones(N)

else if time > 29 and time < 30 then 278.0 * ones(N)

else if time > 30 and time < 31 then 279.0 * ones(N)

else if time > 31 and time < 32 then 280.0 * ones(N)

else if time > 32 and time < 33 then 283.0 * ones(N)

else if time > 33 and time < 34 then 285.0 * ones(N)
else if time > 34 and time < 35 then 287.0 * ones(N)
else if time > 35 and time < 36 then 288.0 * ones(N)
else if time > 36 and time < 37 then 288.0 * ones(N)
else if time > 37 and time < 38 then 288.0 * ones(N)
else if time > 38 and time < 39 then 288.0 * ones(N)
else if time > 39 and time < 40 then 289.0 * ones(N)
else if time > 40 and time < 41 then 288.0 * ones(N)
else if time > 41 and time < 42 then 288.0 * ones(N)
else if time > 42 and time < 43 then 288.0 * ones(N)
else if time > 43 and time < 44 then 287.0 * ones(N)
else if time > 44 and time < 45 then 287.0 * ones(N)
else if time > 45 and time < 46 then 285.0 * ones(N)
else if time > 46 and time < 47 then 284.0 * ones(N)
else if time > 47 and time < 48 then 283.0 * ones(N)
else if time > 48 and time < 49 then Tairi * ones(N)
else if time > 49 and time < 50 then 280.0 * ones(N)
else if time > 50 and time < 51 then 280.0 * ones(N)
else if time > 51 and time < 52 then 279.0 * ones(N)
else if time > 52 and time < 53 then 278.0 * ones(N)
else if time > 53 and time < 54 then 278.0 * ones(N)
else if time > 54 and time < 55 then 279.0 * ones(N)
else if time > 55 and time < 56 then 280.0 * ones(N)
else if time > 56 and time < 57 then 283.0 * ones(N)
else if time > 57 and time < 58 then 285.0 * ones(N)
else if time > 58 and time < 59 then 287.0 * ones(N)
else if time > 59 and time < 60 then 288.0 * ones(N)
else if time > 60 and time < 61 then 288.0 * ones(N)
else if time > 61 and time < 62 then 288.0 * ones(N)
else if time > 62 and time < 63 then 288.0 * ones(N)
else if time > 63 and time < 64 then 289.0 * ones(N)
else if time > 64 and time < 65 then 288.0 * ones(N)
else if time > 65 and time < 66 then 288.0 * ones(N)
else if time > 66 and time < 67 then 288.0 * ones(N)

else if time > 67 and time < 68 then 287.0 * ones(N)
else if time > 68 and time < 69 then 287.0 * ones(N)
else if time > 69 and time < 70 then 285.0 * ones(N)
else if time > 70 and time < 71 then 284.0 * ones(N)
else 283 * ones(N);

Tamb = if time < 1 then Tambi

else if time > 1 and time < 2 then 280.0
else if time > 2 and time < 3 then 280.0
else if time > 3 and time < 4 then 279.0
else if time > 4 and time < 5 then 278.0
else if time > 5 and time < 6 then 278.0
else if time > 6 and time < 7 then 279.0
else if time > 7 and time < 8 then 280.0
else if time > 8 and time < 9 then 283.0
else if time > 9 and time < 10 then 285.0
else if time > 10 and time < 11 then 287.0
else if time > 11 and time < 12 then 288.0
else if time > 12 and time < 13 then 288.0
else if time > 13 and time < 14 then 288.0
else if time > 14 and time < 15 then 288.0
else if time > 15 and time < 16 then 289.0
else if time > 16 and time < 17 then 288.0
else if time > 17 and time < 18 then 288.0
else if time > 18 and time < 19 then 288.0
else if time > 19 and time < 20 then 287.0
else if time > 20 and time < 21 then 287.0
else if time > 21 and time < 22 then 285.0
else if time > 22 and time < 23 then 284.0
else if time > 23 and time < 24 then 283.0
else if time > 24 and time < 25 then Tambi
else if time > 25 and time < 26 then 280.0
else if time > 26 and time < 27 then 280.0
else if time > 27 and time < 28 then 279.0
else if time > 28 and time < 29 then 278.0

else if time > 29 and time < 30 then 278.0
else if time > 30 and time < 31 then 279.0
else if time > 31 and time < 32 then 280.0
else if time > 32 and time < 33 then 283.0
else if time > 33 and time < 34 then 285.0
else if time > 34 and time < 35 then 287.0
else if time > 35 and time < 36 then 288.0
else if time > 36 and time < 37 then 288.0
else if time > 37 and time < 38 then 288.0
else if time > 38 and time < 39 then 288.0
else if time > 39 and time < 40 then 289.0
else if time > 40 and time < 41 then 288.0
else if time > 41 and time < 42 then 288.0
else if time > 42 and time < 43 then 288.0
else if time > 43 and time < 44 then 287.0
else if time > 44 and time < 45 then 287.0
else if time > 45 and time < 46 then 285.0
else if time > 46 and time < 47 then 284.0
else if time > 47 and time < 48 then 283.0
else if time > 48 and time < 49 then Tambi
else if time > 49 and time < 50 then 280.0
else if time > 50 and time < 51 then 280.0
else if time > 51 and time < 52 then 279.0
else if time > 52 and time < 53 then 278.0
else if time > 53 and time < 54 then 278.0
else if time > 54 and time < 55 then 279.0
else if time > 55 and time < 56 then 280.0
else if time > 56 and time < 57 then 283.0
else if time > 57 and time < 58 then 285.0
else if time > 58 and time < 59 then 287.0
else if time > 59 and time < 60 then 288.0
else if time > 60 and time < 61 then 288.0
else if time > 61 and time < 62 then 288.0
else if time > 62 and time < 63 then 288.0

else if time > 63 and time < 64 then 289.0
else if time > 64 and time < 65 then 288.0
else if time > 65 and time < 66 then 288.0
else if time > 66 and time < 67 then 288.0
else if time > 67 and time < 68 then 287.0
else if time > 68 and time < 69 then 287.0
else if time > 69 and time < 70 then 285.0
else if time > 70 and time < 71 then 284.0
else 283;

Tcloud = if time < 1 then Tcloudi * ones(N)

else if time > 1 and time < 2 then 270.0 * ones(N)
else if time > 2 and time < 3 then 270.0 * ones(N)
else if time > 3 and time < 4 then 269.0 * ones(N)
else if time > 4 and time < 5 then 268.0 * ones(N)
else if time > 5 and time < 6 then 268.0 * ones(N)
else if time > 6 and time < 7 then 269.0 * ones(N)
else if time > 7 and time < 8 then 270.0 * ones(N)
else if time > 8 and time < 9 then 273.0 * ones(N)
else if time > 9 and time < 10 then 275.0 * ones(N)
else if time > 10 and time < 11 then 277.0 * ones(N)
else if time > 11 and time < 12 then 278.0 * ones(N)
else if time > 12 and time < 13 then 278.0 * ones(N)
else if time > 13 and time < 14 then 278.0 * ones(N)
else if time > 14 and time < 15 then 278.0 * ones(N)
else if time > 15 and time < 16 then 279.0 * ones(N)
else if time > 16 and time < 17 then 278.0 * ones(N)
else if time > 17 and time < 18 then 278.0 * ones(N)
else if time > 18 and time < 19 then 278.0 * ones(N)
else if time > 19 and time < 20 then 277.0 * ones(N)
else if time > 20 and time < 21 then 277.0 * ones(N)
else if time > 21 and time < 22 then 275.0 * ones(N)
else if time > 22 and time < 23 then 274.0 * ones(N)
else if time > 23 and time < 24 then 273.0 * ones(N)
else if time > 24 and time < 25 then Tcloudi * ones(N)

else if time > 25 and time < 26 then 270.0 * ones(N)
else if time > 26 and time < 27 then 270.0 * ones(N)
else if time > 27 and time < 28 then 269.0 * ones(N)
else if time > 28 and time < 29 then 268.0 * ones(N)
else if time > 29 and time < 30 then 268.0 * ones(N)
else if time > 30 and time < 31 then 269.0 * ones(N)
else if time > 31 and time < 32 then 270.0 * ones(N)
else if time > 32 and time < 33 then 273.0 * ones(N)
else if time > 33 and time < 34 then 275.0 * ones(N)
else if time > 34 and time < 35 then 277.0 * ones(N)
else if time > 35 and time < 36 then 278.0 * ones(N)
else if time > 36 and time < 37 then 278.0 * ones(N)
else if time > 37 and time < 38 then 278.0 * ones(N)
else if time > 38 and time < 39 then 278.0 * ones(N)
else if time > 39 and time < 40 then 279.0 * ones(N)
else if time > 40 and time < 41 then 278.0 * ones(N)
else if time > 41 and time < 42 then 278.0 * ones(N)
else if time > 42 and time < 43 then 278.0 * ones(N)
else if time > 43 and time < 44 then 277.0 * ones(N)
else if time > 44 and time < 45 then 277.0 * ones(N)
else if time > 45 and time < 46 then 275.0 * ones(N)
else if time > 46 and time < 47 then 274.0 * ones(N)
else if time > 47 and time < 48 then 273.0 * ones(N)
else if time > 48 and time < 49 then Tcloudi * ones(N)
else if time > 49 and time < 50 then 270.0 * ones(N)
else if time > 50 and time < 51 then 270.0 * ones(N)
else if time > 51 and time < 52 then 269.0 * ones(N)
else if time > 52 and time < 53 then 268.0 * ones(N)
else if time > 53 and time < 54 then 268.0 * ones(N)
else if time > 54 and time < 55 then 269.0 * ones(N)
else if time > 55 and time < 56 then 270.0 * ones(N)
else if time > 56 and time < 57 then 273.0 * ones(N)
else if time > 57 and time < 58 then 275.0 * ones(N)
else if time > 58 and time < 59 then 277.0 * ones(N)

else if time > 59 and time < 60 then 278.0 * ones(N)
 else if time > 60 and time < 61 then 278.0 * ones(N)
 else if time > 61 and time < 62 then 278.0 * ones(N)
 else if time > 62 and time < 63 then 278.0 * ones(N)
 else if time > 63 and time < 64 then 279.0 * ones(N)
 else if time > 64 and time < 65 then 278.0 * ones(N)
 else if time > 65 and time < 66 then 278.0 * ones(N)
 else if time > 66 and time < 67 then 278.0 * ones(N)
 else if time > 67 and time < 68 then 277.0 * ones(N)
 else if time > 68 and time < 69 then 277.0 * ones(N)
 else if time > 69 and time < 70 then 275.0 * ones(N)
 else if time > 70 and time < 71 then 274.0 * ones(N)
 else 273 * ones(N);

Ic = if time < 6 then Ici * ones(N)

else if time > 6 and time < 7 then 70.0 * ones(N)
 else if time > 7 and time < 8 then 100.0 * ones(N)
 else if time > 8 and time < 9 then 120.0 * ones(N)
 else if time > 9 and time < 10 then 150.0 * ones(N)
 else if time > 10 and time < 11 then 170.0 * ones(N)
 else if time > 11 and time < 12 then 200.0 * ones(N)
 else if time > 12 and time < 13 then 200.0 * ones(N)
 else if time > 13 and time < 14 then 200.0 * ones(N)
 else if time > 14 and time < 15 then 200.0 * ones(N)
 else if time > 15 and time < 16 then 200.0 * ones(N)
 else if time > 16 and time < 17 then 200.0 * ones(N)
 else if time > 17 and time < 18 then 200.0 * ones(N)
 else if time > 18 and time < 19 then 170.0 * ones(N)
 else if time > 19 and time < 20 then 150.0 * ones(N)
 else if time > 20 and time < 21 then 100.0 * ones(N)
 else if time > 21 and time < 30 then Ici * ones(N)
 else if time > 31 and time < 31 then 70.0 * ones(N)
 else if time > 31 and time < 32 then 100.0 * ones(N)
 else if time > 32 and time < 33 then 120.0 * ones(N)
 else if time > 33 and time < 34 then 150.0 * ones(N)

else if time > 34 and time < 35 then 170.0 * ones(N)
else if time > 35 and time < 36 then 200.0 * ones(N)
else if time > 36 and time < 37 then 200.0 * ones(N)
else if time > 37 and time < 38 then 200.0 * ones(N)
else if time > 38 and time < 39 then 200.0 * ones(N)
else if time > 39 and time < 40 then 200.0 * ones(N)
else if time > 40 and time < 41 then 200.0 * ones(N)
else if time > 41 and time < 42 then 200.0 * ones(N)
else if time > 42 and time < 43 then 170.0 * ones(N)
else if time > 43 and time < 44 then 150.0 * ones(N)
else if time > 44 and time < 45 then 100.0 * ones(N)
else if time > 45 and time < 54 then Ici * ones(N)
else if time > 54 and time < 55 then 70.0 * ones(N)
else if time > 55 and time < 56 then 100.0 * ones(N)
else if time > 56 and time < 57 then 120.0 * ones(N)
else if time > 57 and time < 58 then 150.0 * ones(N)
else if time > 58 and time < 59 then 170.0 * ones(N)
else if time > 59 and time < 60 then 200.0 * ones(N)
else if time > 60 and time < 61 then 200.0 * ones(N)
else if time > 61 and time < 62 then 200.0 * ones(N)
else if time > 62 and time < 63 then 200.0 * ones(N)
else if time > 63 and time < 64 then 200.0 * ones(N)
else if time > 64 and time < 65 then 200.0 * ones(N)
else if time > 65 and time < 66 then 200.0 * ones(N)
else if time > 66 and time < 67 then 170.0 * ones(N)
else if time > 67 and time < 68 then 150.0 * ones(N)
else if time > 68 and time < 69 then 100.0 * ones(N)

else Ici * ones(N);

Qelec = if time < 8 then 0.0

else if time > 8 and time < 21 then 0.0
else if time > 21 and time < 36 then Qelec
else if time > 36 and time < 45 then 0.0
else if time > 45 and time < 60 then Qelec
else if time > 60 and time < 69 then 0.0

```

else Qeleci;
mti = if time < 6.0 then mtii
      else if time > 6.0 and time < 7.0 then 0.0
      else if time > 7.0 and time < 8.0 then 0.0
      else if time > 8.0 and time < 11.0 then 0.03333333
      else if time > 11.0 and time < 12.0 then 0.1095
      else if time > 12.0 and time < 13.0 then 0.1095
      else if time > 13.0 and time < 16.0 then 0.045
      else if time > 16.0 and time < 17.0 then 0.042
      else if time > 17.0 and time < 18.0 then mtii
      else if time > 18.0 and time < 21.0 then mtii
      else if time > 21.0 and time < 30.0 then mtii
      else if time > 30.0 and time < 31.0 then 0.0
      else if time > 31.0 and time < 32.0 then 0.0
      else if time > 32.0 and time < 35.0 then 0.0333333333
      else if time > 35.0 and time < 36.0 then 0.1095
      else if time > 36.0 and time < 37.0 then 0.1095
      else if time > 37.0 and time < 40.0 then 0.045
      else if time > 40.0 and time < 41.0 then 0.042
      else if time > 41.0 and time < 42.0 then mtii
      else if time > 42.0 and time < 45.0 then mtii
      else if time > 45.0 and time < 54.0 then mtii
      else if time > 54.0 and time < 55.0 then 0.0
      else if time > 55.0 and time < 56.0 then 0.0
      else if time > 56.0 and time < 59.0 then 0.033333333
      else if time > 59.0 and time < 60.0 then 0.1095
      else if time > 60.0 and time < 61.0 then 0.1095
      else if time > 61.0 and time < 64.0 then 0.045
      else if time > 64.0 and time < 65.0 then 0.042
      else if time > 65.0 and time < 66.0 then mtii
      else if time > 66.0 and time < 69.0 then mtii
      else mtii;
mto = if time < 6.0 then mtoi
      else if time > 6.0 and time < 7.0 then 0.195

```

```
else if time > 7.0 and time < 8.0 then mtoi
else if time > 8.0 and time < 11.0 then mtoi
else if time > 11.0 and time < 12.0 then 0.042
else if time > 12.0 and time < 13.0 then 0.042
else if time > 13.0 and time < 16.0 then mtoi
else if time > 16.0 and time < 17.0 then 0.042
else if time > 17.0 and time < 18.0 then mtoi
else if time > 18.0 and time < 21.0 then mtoi
else if time > 21.0 and time < 30.0 then mtoi
else if time > 30.0 and time < 31.0 then 0.195
else if time > 31.0 and time < 32.0 then mtoi
else if time > 32.0 and time < 35.0 then mtoi
else if time > 35.0 and time < 36.0 then 0.042
else if time > 36.0 and time < 37.0 then 0.042
else if time > 37.0 and time < 40.0 then mtoi
else if time > 40.0 and time < 41.0 then 0.042
else if time > 41.0 and time < 42.0 then mtoi
else if time > 42.0 and time < 45.0 then mtoi
else if time > 42.0 and time < 54.0 then mtoi
else if time > 54.0 and time < 55.0 then 0.195
else if time > 55.0 and time < 56.0 then mtoi
else if time > 56.0 and time < 59.0 then mtoi
else if time > 59.0 and time < 60.0 then 0.042
else if time > 60.0 and time < 61.0 then 0.042
else if time > 61.0 and time < 64.0 then mtoi
else if time > 64.0 and time < 65.0 then 0.042
else if time > 65.0 and time < 66.0 then mtoi
else if time > 66.0 and time < 69.0 then mtoi
else mtoi;
end solarsunnyfinal;
```

Partly cloudy day:

model solarcloudyfinal

// Constants

constant Real PI = 3.141592654 "pi, -";

constant Real sbc = 0.0000000567 "Stefan Boltzmann constant, W/m²/K⁴";

constant Real emissa = 0.01 "Emissivity of the absorber pipe,-";

constant Real emisse = 0.92 "Emissivity of the glass envelope,-";

constant Real densw = 1000.0 "Density of water, kg/m³";

constant Real densa = 8900.0 "Density of absorber pipe, kg/m³";

constant Real dense = 2700.0 "Density of glass envelope, kg/m³";

constant Real densair = 1.2 "Density of air, kg/m³";

constant Real hcair = 1033 "Heat capacity of air, J/kg/K";

constant Real hcw = 4180.0 "Heat capacity of water, J/kg/K";

constant Real hca = 389.0 "Heat capacity of absorber pipe, J/kg/K";

constant Real hce = 833 "Heat capacity of glass envelope, J/kg/K";

// Parameters

parameter Real rc = 0.025 "Radius of the solar collector and the coil, m";

parameter Real Dc = 0.05 "Diameter of the collector";

parameter Real rai = 0.025 "Inner radius of the absorber pipe, m";

parameter Real rao = 0.03 "Outer radius of the absorber pipe, m";

parameter Real rei = 0.045 "Inner radius of the glass envelope, m";

parameter Real reo = 0.05 "Outer radius of the glass envelope, m";

parameter Real rr = 0.03 "Inner radius of the underfloor pipe, m";

parameter Real rt = 0.565 "Diameter of the tank, m";

parameter Real Dt = 1.13 "Diameter of the tank, m";

parameter Real Dr = 0.06 "Diameter of the underfloor pipe, m";

parameter Real Ht = 0.9 "Total height of the tank, m";

parameter Real he = 1.27 "Individual coefficient of natural convection from the envelope to the air, W/m²/K";

parameter Real hr = 5.0 "Natural convection coefficient from the underfloor pipe to the air of the house, W/m²/K";

parameter Real hcn = 4.0 "Natural convection coefficient from the wall of the house to the ambient air, W/m²/K";

parameter Real hcnt = 1.71 "Individual coefficient of heat transmission by natural convection between the tank and iar of the house, W/m²/K";

```

parameter Real L = 112.5 "Length of the collector pipe, m";
parameter Real Lcoil = 29 "Lenght of the coil pipe, m";
parameter Real Lr = 200 "Length of the underfloor pipe, m";
parameter Real Vair = 384 "Air volume in the house, m3";
parameter Integer N = 10 "Number of control volumes";
parameter Real dx = L / N "Length of each control volume in the collector, m";
parameter Real dy = Lcoil / N "Length of each control volume in the coil, m";
parameter Real dz = Lr / N "Length of each control volume in the underfloor pipe, m";
parameter Real sigma = sbc / (1 / emissa + (1 - emisse) / emisse * rao / rei) "Radiation
coefficient";
parameter Real Ac = PI / 4 * Dc ^ 2 "Cross sectional area of the collector, m2";
parameter Real At = PI / 4 * Dt ^ 2 "Cross sectional area of the tank, m2";
parameter Real Ar = PI / 4 * Dr ^ 2 "Cross sectional area of the radiation pipe, m2";
parameter Real Alost = 272 "Area of lost in the house, m2";
parameter Real Pc = 2 * PI * rc "Perimeter of the collector, m";
parameter Real Aa = PI * (rao ^ 2 - rai ^ 2) "Cross sectional area of the absorber pipe, m2";
parameter Real Pai = 2 * PI * rai "Inner perimeter of the absorber pipe, m";
parameter Real Pao = 2 * PI * rao "Outer perimeter of the absorber pipe, m";
parameter Real Peo = 2 * PI * reo "Outer perimeter of the glass envelope, m";
parameter Real Pr = 2 * PI * rr "Inner perimeter of the underfloor pipe, m";
parameter Real Ae = PI * (reo ^ 2 - rei ^ 2) "Cross sectional area of the glass envelope, m2";
parameter Real mair = Vair * densair "Mass of air in the house";
parameter Real Twall = 287 "Temperature of the wall fo the house";
// Initial state parameters
parameter Real Tcli = 278 "Initial temperature of the water that flows inside the collector,
K";
parameter Real Tc2i = 278 "Initial temperature of the water that flow inside the coil, K";
parameter Real Tai = 278 "Initial temperature of the absorber pipe, K";
parameter Real Tei = 278 "Initial temperature of the glass envelope, K";
parameter Real Tti = 278 "Initial temperature of the tank, K";
parameter Real hwti = 0.9 "Initial value of the height of water inside the tank, m";
parameter Real Tri = 278 "Initial temperature of the underfloor pipe, K";
parameter Real Thoui = 288 "Initial temperature of the house, K";
// Input parameters

```

```

parameter Real Twi = 278 "Value of the inlet temperature of water to the tank, K";
parameter Real Tairi = 280 "Value of the ambient air, K";
parameter Real Tambi = 280 "Value of the ambient air, K";
parameter Real Tcloudi = 270 "Value of the temperature of the clouds, K";
parameter Real Ici = 0.0 "Total energy provided by the sun, W";
parameter Real Qelec = 2000.0 "Total heat provided by the electricity system, W";
parameter Real vwci = 2 "Velocity of water inside the collector and coil pipe, m/s";
parameter Real mtii = 0.025 "Inlet mass flow to the tank, kg/s";
parameter Real mtoi = 0.025 "Outlet mass flow from the tank, kg/s";
parameter Real Qri = 0.0 "Heat transferred by the underfloor pipe, W";
parameter Real vwri = 0.005 "Velocity of the water that flows inside the underfloor pipe,
m/s";

```

```
// Variables
```

```

Real Qc2t "Heat provided by the coil, W";
Real mwt "Mass of water inside the tank, kg";
Real mc "Mass flow inside the collector";
Real mr "Mass flow inside the radiation pipe, kg/s";
Real hc "Forced convective heat transfer coefficient inside the collector pipe";
Real Qlost "lost of heat from the house to the ambient air, W";
Real a "Heat transferred by the underfloor pipe, W";

```

```
// Declaring N state variables in an array, setting initial (start) values
```

```

Real Tc1[N](each start = Tc1i) "Temperature in collector conduit, K";
Real Tc2[N](each start = Tc2i) "Temperature in conduit in heat exchanger through tank, K";
Real Ta[N](each start = Tai) "Temperature in absorber, K";
Real Te[N](each start = Tei) "Temperature in *envelope*??, K";
Real Tt(start = Tti) "Temperature in tank, K";
Real hwt(start = hwti) "Level/height of tank, m";
Real Tr[N](each start = Tri) "Temperature of the underfloor pipe, K";
Real Thou(start = Thoui) "Temperature in the house, K";

```

```
// Declaring input variables
```

```

Real Tw "Value of the inlet temperature of water to the tank, K";
Real Tair[N] "Value of the ambient air, K";
Real Tamb "Temperature of the ambient air, K";
Real Tcloud[N] "Value of the temperature of the clouds, K";

```

Real Ic[N] "Total energy provided by the sun, W";
Real Qelec "Total heat provided by the electricity system, W";
Real vwc "Velocity of water inside the collector and coil pipe, m/s";
Real mti "Inlet mass flow to the tank, kg/s";
Real mto "Outlet mass flow from the tank, kg/s";
Real Qr "Heat transferred by the underfloor pipe, W";
Real vwr "Velocity of the water that flows inside the underfloor pipe";
equation
// Heat input to tank

$$Qc2t = (hwt * 5 * hc * (\text{sum}(Tc2) - N * Tt));$$
//Heat transferred by underfloor pipe

$$a = 2 * PI * rr * Lr * hr * (\text{sum}(Tr) - N * Thou);$$
// Lost of heat to the ambient air

$$Qlost = Alost * hcn * (Twall - Tamb);$$
// Coefficients of heat transfer

$$hc = 4280 * (0.00488 * ((303 + 363) / 2) - 1) * (vwc ^ 0.8) / (Dc ^ 0.2);$$
// Mass of water inside the tank

$$mwt = At * hwt * densw;$$
// Mass flow inside the collector

$$mc = vwc * Ac * densw;$$
//Mass flow inside the underfloor pipe

$$mr = vwr * Ar * densw;$$
// Differential equations

$$\text{der}(Tc1[1]) = (mc / densw / Ac / dx * (Tc2[N] - Tc1[1]) + (hc * Pc) / densw / Ac / hcw * (Ta[1] - Tc1[1])) * 3600;$$

$$\text{der}(Tc1[2:\text{end}]) = (mc / densw / Ac / dx * (Tc1[1:\text{end} - 1] - Tc1[2:\text{end}]) + (hc * Pc) / densw / Ac / hcw * (Ta[2:\text{end}] - Tc1[2:\text{end}])) * 3600;$$

$$\text{der}(Tc2[1]) = (mc / densw / Ac / dy * (Tc1[N] - Tc2[1]) - (hc * Pc) / densw / Ac / hcw * (Tc2[1] - Tt)) * 3600;$$

$$\text{der}(Tc2[2:\text{end}]) = (mc / densw / Ac / dy * (Tc2[1:\text{end} - 1] - Tc2[2:\text{end}]) - (hc * Pc) / densw / Ac / hcw * (Tc2[2:\text{end}] - Tt * \text{ones}(N - 1))) * 3600;$$

$$\text{der}(Ta) = ((Ic * 2 * rao) / densa / hca / Aa - (\text{sigma} * Pao) / densa / hca / Aa * (Ta .^ 4 - Te .^ 4) - (hc * Pai) / densa / hca / Aa * (Ta - Tc1)) * 3600;$$

$$\text{der}(Te) = ((\text{sigma} * Pao) / dense / hce / Ae * (Ta .^ 4 - Te .^ 4) - (sbc * emisse * Peo) / dense / hce / Ae * (Te .^ 4 - Tcloud .^ 4) - (he * Peo) / dense / hce / Ae * (Te - Tair)) * 3600;$$

der(Tt) = (mti / mwt * (Tw - Tt) + Qc2t / mwt / hcw + hwt / Ht * Qelec / mwt / hcw - 2 * PI
* rt * hwt * hcnt / mwt / hcw * (Tt - Thou)) * 3600;

der(hwt) = ((mti - mto) / densw / At) * 3600;

der(Tr[1]) = (mr / densw / Ar / dz * (Tt - Tr[1]) - (hr * Pr) / densw / Ar / hcw * (Tr[1] -
Thou)) * 3600;

der(Tr[2:end]) = (mr / densw / Ar / dz * (Tr[1:end - 1] - Tr[2:end]) - (hr * Pr) / densw / Ar /
hcw * (Tr[2:end] - Thou * ones (N - 1))) * 3600;

der(Thou) = (Qr / mair / hcair - Qlost / mair / hcair) * 3600;

// Inlet values

vwr = if time < 6 then 0.0

else vwri;

Qr = if Thou < 294 then a

else a;

vwc = if time < 6 then 0.1

else if time > 6 and time < 9 then 1.0

else if time > 9 and time < 14 then 1.0

else if time > 14 and time < 16 then vwci

else if time > 16 and time < 17 then vwci

else if time > 17 and time < 19 then vwci

else if time > 19 and time < 21 then 1.0

else if time > 21 and time < 31 then 0.1

else if time > 31 and time < 33 then 1.0

else if time > 33 and time < 38 then 1.0

else if time > 38 and time < 40 then vwci

else if time > 40 and time < 41 then vwci

else if time > 41 and time < 43 then vwci

else if time > 43 and time < 45 then 1.0

else if time > 45 and time < 55 then 0.1

else if time > 55 and time < 57 then 1.0

else if time > 57 and time < 62 then 1.0

else if time > 62 and time < 64 then vwci

else if time > 64 and time < 65 then vwci

else if time > 65 and time < 67 then vwci

else if time > 67 and time < 69 then 1.0

```

else 0.1;
Tw = if time < 9 then Twi
      else if time > 9 and time < 21 then 280.0
      else if time > 21 and time < 33 then Twi
      else if time > 33 and time < 45 then 280.0
      else if time > 45 and time < 57 then Twi
      else if time > 57 and time < 69 then 280.0
      else Twi;
Tair = if time < 1 then Tairi * ones(N)
        else if time > 1 and time < 2 then 280.0 * ones(N)
        else if time > 2 and time < 3 then 280.0 * ones(N)
        else if time > 3 and time < 4 then 279.0 * ones(N)
        else if time > 4 and time < 5 then 278.0 * ones(N)
        else if time > 5 and time < 6 then 278.0 * ones(N)
        else if time > 6 and time < 7 then 279.0 * ones(N)
        else if time > 7 and time < 8 then 280.0 * ones(N)
        else if time > 8 and time < 9 then 283.0 * ones(N)
        else if time > 9 and time < 10 then 285.0 * ones(N)
        else if time > 10 and time < 11 then 287.0 * ones(N)
        else if time > 11 and time < 12 then 288.0 * ones(N)
        else if time > 12 and time < 13 then 288.0 * ones(N)
        else if time > 13 and time < 14 then 288.0 * ones(N)
        else if time > 14 and time < 15 then 288.0 * ones(N)
        else if time > 15 and time < 16 then 289.0 * ones(N)
        else if time > 16 and time < 17 then 288.0 * ones(N)
        else if time > 17 and time < 18 then 288.0 * ones(N)
        else if time > 18 and time < 19 then 288.0 * ones(N)
        else if time > 19 and time < 20 then 287.0 * ones(N)
        else if time > 20 and time < 21 then 287.0 * ones(N)
        else if time > 21 and time < 22 then 285.0 * ones(N)
        else if time > 22 and time < 23 then 284.0 * ones(N)
        else if time > 23 and time < 24 then 283.0 * ones(N)
        else if time > 24 and time < 25 then Tairi * ones(N)
        else if time > 25 and time < 26 then 280.0 * ones(N)

```

else if time > 26 and time < 27 then 280.0 * ones(N)
else if time > 27 and time < 28 then 279.0 * ones(N)
else if time > 28 and time < 29 then 278.0 * ones(N)
else if time > 29 and time < 30 then 278.0 * ones(N)
else if time > 30 and time < 31 then 279.0 * ones(N)
else if time > 31 and time < 32 then 280.0 * ones(N)
else if time > 32 and time < 33 then 283.0 * ones(N)
else if time > 33 and time < 34 then 285.0 * ones(N)
else if time > 34 and time < 35 then 287.0 * ones(N)
else if time > 35 and time < 36 then 288.0 * ones(N)
else if time > 36 and time < 37 then 288.0 * ones(N)
else if time > 37 and time < 38 then 288.0 * ones(N)
else if time > 38 and time < 39 then 288.0 * ones(N)
else if time > 39 and time < 40 then 289.0 * ones(N)
else if time > 40 and time < 41 then 288.0 * ones(N)
else if time > 41 and time < 42 then 288.0 * ones(N)
else if time > 42 and time < 43 then 288.0 * ones(N)
else if time > 43 and time < 44 then 287.0 * ones(N)
else if time > 44 and time < 45 then 287.0 * ones(N)
else if time > 45 and time < 46 then 285.0 * ones(N)
else if time > 46 and time < 47 then 284.0 * ones(N)
else if time > 47 and time < 48 then 283.0 * ones(N)
else if time > 48 and time < 49 then Tairi * ones(N)
else if time > 49 and time < 50 then 280.0 * ones(N)
else if time > 50 and time < 51 then 280.0 * ones(N)
else if time > 51 and time < 52 then 279.0 * ones(N)
else if time > 52 and time < 53 then 278.0 * ones(N)
else if time > 53 and time < 54 then 278.0 * ones(N)
else if time > 54 and time < 55 then 279.0 * ones(N)
else if time > 55 and time < 56 then 280.0 * ones(N)
else if time > 56 and time < 57 then 283.0 * ones(N)
else if time > 57 and time < 58 then 285.0 * ones(N)
else if time > 58 and time < 59 then 287.0 * ones(N)
else if time > 59 and time < 60 then 288.0 * ones(N)

else if time > 60 and time < 61 then 288.0 * ones(N)
else if time > 61 and time < 62 then 288.0 * ones(N)
else if time > 62 and time < 63 then 288.0 * ones(N)
else if time > 63 and time < 64 then 289.0 * ones(N)
else if time > 64 and time < 65 then 288.0 * ones(N)
else if time > 65 and time < 66 then 288.0 * ones(N)
else if time > 66 and time < 67 then 288.0 * ones(N)
else if time > 67 and time < 68 then 287.0 * ones(N)
else if time > 68 and time < 69 then 287.0 * ones(N)
else if time > 69 and time < 70 then 285.0 * ones(N)
else if time > 70 and time < 71 then 284.0 * ones(N)
else 283 * ones(N);

Tamb = if time < 1 then Tambi

else if time > 1 and time < 2 then 280.0
else if time > 2 and time < 3 then 280.0
else if time > 3 and time < 4 then 279.0
else if time > 4 and time < 5 then 278.0
else if time > 5 and time < 6 then 278.0
else if time > 6 and time < 7 then 279.0
else if time > 7 and time < 8 then 280.0
else if time > 8 and time < 9 then 283.0
else if time > 9 and time < 10 then 285.0
else if time > 10 and time < 11 then 287.0
else if time > 11 and time < 12 then 288.0
else if time > 12 and time < 13 then 288.0
else if time > 13 and time < 14 then 288.0
else if time > 14 and time < 15 then 288.0
else if time > 15 and time < 16 then 289.0
else if time > 16 and time < 17 then 288.0
else if time > 17 and time < 18 then 288.0
else if time > 18 and time < 19 then 288.0
else if time > 19 and time < 20 then 287.0
else if time > 20 and time < 21 then 287.0
else if time > 21 and time < 22 then 285.0

else if time > 22 and time < 23 then 284.0
else if time > 23 and time < 24 then 283.0
else if time > 24 and time < 25 then Tambi
else if time > 25 and time < 26 then 280.0
else if time > 26 and time < 27 then 280.0
else if time > 27 and time < 28 then 279.0
else if time > 28 and time < 29 then 278.0
else if time > 29 and time < 30 then 278.0
else if time > 30 and time < 31 then 279.0
else if time > 31 and time < 32 then 280.0
else if time > 32 and time < 33 then 283.0
else if time > 33 and time < 34 then 285.0
else if time > 34 and time < 35 then 287.0
else if time > 35 and time < 36 then 288.0
else if time > 36 and time < 37 then 288.0
else if time > 37 and time < 38 then 288.0
else if time > 38 and time < 39 then 288.0
else if time > 39 and time < 40 then 289.0
else if time > 40 and time < 41 then 288.0
else if time > 41 and time < 42 then 288.0
else if time > 42 and time < 43 then 288.0
else if time > 43 and time < 44 then 287.0
else if time > 44 and time < 45 then 287.0
else if time > 45 and time < 46 then 285.0
else if time > 46 and time < 47 then 284.0
else if time > 47 and time < 48 then 283.0
else if time > 48 and time < 49 then Tambi
else if time > 49 and time < 50 then 280.0
else if time > 50 and time < 51 then 280.0
else if time > 51 and time < 52 then 279.0
else if time > 52 and time < 53 then 278.0
else if time > 53 and time < 54 then 278.0
else if time > 54 and time < 55 then 279.0
else if time > 55 and time < 56 then 280.0

else if time > 56 and time < 57 then 283.0
else if time > 57 and time < 58 then 285.0
else if time > 58 and time < 59 then 287.0
else if time > 59 and time < 60 then 288.0
else if time > 60 and time < 61 then 288.0
else if time > 61 and time < 62 then 288.0
else if time > 62 and time < 63 then 288.0
else if time > 63 and time < 64 then 289.0
else if time > 64 and time < 65 then 288.0
else if time > 65 and time < 66 then 288.0
else if time > 66 and time < 67 then 288.0
else if time > 67 and time < 68 then 287.0
else if time > 68 and time < 69 then 287.0
else if time > 69 and time < 70 then 285.0
else if time > 70 and time < 71 then 284.0
else 283;

Tcloud = if time < 1 then Tcloudi * ones(N)

else if time > 1 and time < 2 then 270.0 * ones(N)
else if time > 2 and time < 3 then 270.0 * ones(N)
else if time > 3 and time < 4 then 269.0 * ones(N)
else if time > 4 and time < 5 then 268.0 * ones(N)
else if time > 5 and time < 6 then 268.0 * ones(N)
else if time > 6 and time < 7 then 269.0 * ones(N)
else if time > 7 and time < 8 then 270.0 * ones(N)
else if time > 8 and time < 9 then 273.0 * ones(N)
else if time > 9 and time < 10 then 275.0 * ones(N)
else if time > 10 and time < 11 then 277.0 * ones(N)
else if time > 11 and time < 12 then 278.0 * ones(N)
else if time > 12 and time < 13 then 278.0 * ones(N)
else if time > 13 and time < 14 then 278.0 * ones(N)
else if time > 14 and time < 15 then 278.0 * ones(N)
else if time > 15 and time < 16 then 279.0 * ones(N)
else if time > 16 and time < 17 then 278.0 * ones(N)
else if time > 17 and time < 18 then 278.0 * ones(N)

else if time > 18 and time < 19 then 278.0 * ones(N)
else if time > 19 and time < 20 then 277.0 * ones(N)
else if time > 20 and time < 21 then 277.0 * ones(N)
else if time > 21 and time < 22 then 275.0 * ones(N)
else if time > 22 and time < 23 then 274.0 * ones(N)
else if time > 23 and time < 24 then 273.0 * ones(N)
else if time > 24 and time < 25 then Tcloudi * ones(N)
else if time > 25 and time < 26 then 270.0 * ones(N)
else if time > 26 and time < 27 then 270.0 * ones(N)
else if time > 27 and time < 28 then 269.0 * ones(N)
else if time > 28 and time < 29 then 268.0 * ones(N)
else if time > 29 and time < 30 then 268.0 * ones(N)
else if time > 30 and time < 31 then 269.0 * ones(N)
else if time > 31 and time < 32 then 270.0 * ones(N)
else if time > 32 and time < 33 then 273.0 * ones(N)
else if time > 33 and time < 34 then 275.0 * ones(N)
else if time > 34 and time < 35 then 277.0 * ones(N)
else if time > 35 and time < 36 then 278.0 * ones(N)
else if time > 36 and time < 37 then 278.0 * ones(N)
else if time > 37 and time < 38 then 278.0 * ones(N)
else if time > 38 and time < 39 then 278.0 * ones(N)
else if time > 39 and time < 40 then 279.0 * ones(N)
else if time > 40 and time < 41 then 278.0 * ones(N)
else if time > 41 and time < 42 then 278.0 * ones(N)
else if time > 42 and time < 43 then 278.0 * ones(N)
else if time > 43 and time < 44 then 277.0 * ones(N)
else if time > 44 and time < 45 then 277.0 * ones(N)
else if time > 45 and time < 46 then 275.0 * ones(N)
else if time > 46 and time < 47 then 274.0 * ones(N)
else if time > 47 and time < 48 then 273.0 * ones(N)
else if time > 48 and time < 49 then Tcloudi * ones(N)
else if time > 49 and time < 50 then 270.0 * ones(N)
else if time > 50 and time < 51 then 270.0 * ones(N)
else if time > 51 and time < 52 then 269.0 * ones(N)

else if time > 52 and time < 53 then 268.0 * ones(N)
 else if time > 53 and time < 54 then 268.0 * ones(N)
 else if time > 54 and time < 55 then 269.0 * ones(N)
 else if time > 55 and time < 56 then 270.0 * ones(N)
 else if time > 56 and time < 57 then 273.0 * ones(N)
 else if time > 57 and time < 58 then 275.0 * ones(N)
 else if time > 58 and time < 59 then 277.0 * ones(N)
 else if time > 59 and time < 60 then 278.0 * ones(N)
 else if time > 60 and time < 61 then 278.0 * ones(N)
 else if time > 61 and time < 62 then 278.0 * ones(N)
 else if time > 62 and time < 63 then 278.0 * ones(N)
 else if time > 63 and time < 64 then 279.0 * ones(N)
 else if time > 64 and time < 65 then 278.0 * ones(N)
 else if time > 65 and time < 66 then 278.0 * ones(N)
 else if time > 66 and time < 67 then 278.0 * ones(N)
 else if time > 67 and time < 68 then 277.0 * ones(N)
 else if time > 68 and time < 69 then 277.0 * ones(N)
 else if time > 69 and time < 70 then 275.0 * ones(N)
 else if time > 70 and time < 71 then 274.0 * ones(N)
 else 273 * ones(N);

Ic = if time < 6 then Ici * ones(N)

else if time > 6 and time < 7 then 70.0 * ones(N)
 else if time > 7 and time < 8 then 100.0 * ones(N)
 else if time > 8 and time < 9 then 120.0 * ones(N)
 else if time > 9 and time < 10 then 80.0 * ones(N)
 else if time > 10 and time < 11 then 80.0 * ones(N)
 else if time > 11 and time < 12 then 80.0 * ones(N)
 else if time > 12 and time < 13 then 80.0 * ones(N)
 else if time > 13 and time < 14 then 80.0 * ones(N)
 else if time > 14 and time < 15 then 200.0 * ones(N)
 else if time > 15 and time < 16 then 200.0 * ones(N)
 else if time > 16 and time < 17 then 80.0 * ones(N)
 else if time > 17 and time < 18 then 200.0 * ones(N)
 else if time > 18 and time < 19 then 170.0 * ones(N)

else if time > 19 and time < 20 then 80.0 * ones(N)
else if time > 20 and time < 21 then 100.0 * ones(N)
else if time > 21 and time < 30 then Ici * ones(N)
else if time > 30 and time < 31 then 70.0 * ones(N)
else if time > 31 and time < 32 then 100.0 * ones(N)
else if time > 32 and time < 33 then 120.0 * ones(N)
else if time > 33 and time < 34 then 80.0 * ones(N)
else if time > 34 and time < 35 then 80.0 * ones(N)
else if time > 35 and time < 36 then 80.0 * ones(N)
else if time > 36 and time < 37 then 80.0 * ones(N)
else if time > 37 and time < 38 then 80.0 * ones(N)
else if time > 38 and time < 39 then 200.0 * ones(N)
else if time > 39 and time < 40 then 200.0 * ones(N)
else if time > 40 and time < 41 then 80.0 * ones(N)
else if time > 41 and time < 42 then 200.0 * ones(N)
else if time > 42 and time < 43 then 170.0 * ones(N)
else if time > 43 and time < 44 then 80.0 * ones(N)
else if time > 44 and time < 45 then 100.0 * ones(N)
else if time > 45 and time < 54 then Ici * ones(N)
else if time > 54 and time < 55 then 70.0 * ones(N)
else if time > 55 and time < 56 then 100.0 * ones(N)
else if time > 56 and time < 57 then 120.0 * ones(N)
else if time > 57 and time < 58 then 80.0 * ones(N)
else if time > 58 and time < 59 then 80.0 * ones(N)
else if time > 59 and time < 60 then 80.0 * ones(N)
else if time > 60 and time < 61 then 80.0 * ones(N)
else if time > 61 and time < 62 then 80.0 * ones(N)
else if time > 62 and time < 63 then 200.0 * ones(N)
else if time > 63 and time < 64 then 200.0 * ones(N)
else if time > 64 and time < 65 then 80.0 * ones(N)
else if time > 65 and time < 66 then 200.0 * ones(N)
else if time > 66 and time < 67 then 170.0 * ones(N)
else if time > 67 and time < 68 then 80.0 * ones(N)
else if time > 68 and time < 69 then 100.0 * ones(N)

```

else Ici * ones(N);
Qelec = if time < 8 then 0.0
      else if time > 8 and time < 21 then 0.0
      else if time > 21 and time < 36 then Qelec
      else if time > 36 and time < 45 then 0.0
      else if time > 45 and time < 60 then Qelec
      else if time > 60 and time < 69 then 0.0
      else Qelec;
mti = if time < 6.0 then mtii
     else if time > 6.0 and time < 7.0 then 0.0
     else if time > 7.0 and time < 8.0 then 0.0
     else if time > 8.0 and time < 11.0 then 0.03333333
     else if time > 11.0 and time < 12.0 then 0.05475
     else if time > 12.0 and time < 13.0 then 0.05475
     else if time > 13.0 and time < 16.0 then 0.0715
     else if time > 16.0 and time < 17.0 then 0.042
     else if time > 17.0 and time < 18.0 then mtii
     else if time > 18.0 and time < 21.0 then 0.035
     else if time > 21.0 and time < 30.0 then mtii
     else if time > 30.0 and time < 31.0 then 0.0
     else if time > 31.0 and time < 32.0 then 0.0
     else if time > 32.0 and time < 35.0 then 0.033333333
     else if time > 35.0 and time < 36.0 then 0.05475
     else if time > 36.0 and time < 37.0 then 0.05475
     else if time > 37.0 and time < 40.0 then 0.0715
     else if time > 40.0 and time < 41.0 then 0.042
     else if time > 41.0 and time < 42.0 then mtii
     else if time > 42.0 and time < 45.0 then 0.035
     else if time > 45.0 and time < 54.0 then mtii
     else if time > 54.0 and time < 55.0 then 0.0
     else if time > 55.0 and time < 56.0 then 0.0
     else if time > 56.0 and time < 59.0 then 0.03333333
     else if time > 59.0 and time < 60.0 then 0.05475
     else if time > 60.0 and time < 61.0 then 0.05475

```

else if time > 61.0 and time < 64.0 then 0.0715
else if time > 64.0 and time < 65.0 then 0.042
else if time > 65.0 and time < 66.0 then mtii
else if time > 66.0 and time < 69.0 then 0.035
else mtii;

mto = if time < 6.0 then mtoi

else if time > 6.0 and time < 7.0 then 0.195
else if time > 7.0 and time < 8.0 then mtoi
else if time > 8.0 and time < 11.0 then mtoi
else if time > 11.0 and time < 12.0 then 0.042
else if time > 12.0 and time < 13.0 then 0.042
else if time > 13.0 and time < 16.0 then mtoi
else if time > 16.0 and time < 17.0 then 0.042
else if time > 17.0 and time < 18.0 then mtoi
else if time > 18.0 and time < 21.0 then mtoi
else if time > 21.0 and time < 30.0 then mtoi
else if time > 30.0 and time < 31.0 then 0.195
else if time > 31.0 and time < 32.0 then mtoi
else if time > 32.0 and time < 35.0 then mtoi
else if time > 35.0 and time < 36.0 then 0.042
else if time > 36.0 and time < 37.0 then 0.042
else if time > 37.0 and time < 40.0 then mtoi
else if time > 40.0 and time < 41.0 then 0.042
else if time > 41.0 and time < 42.0 then mtoi
else if time > 42.0 and time < 45.0 then mtoi
else if time > 42.0 and time < 54.0 then mtoi
else if time > 54.0 and time < 55.0 then 0.195
else if time > 55.0 and time < 56.0 then mtoi
else if time > 56.0 and time < 59.0 then mtoi
else if time > 59.0 and time < 60.0 then 0.042
else if time > 60.0 and time < 61.0 then 0.042
else if time > 61.0 and time < 64.0 then mtoi
else if time > 64.0 and time < 65.0 then 0.042
else if time > 65.0 and time < 66.0 then mtoi

```
else if time > 66.0 and time < 69.0 then mtoi  
else mtoi;  
end solarcloudyfinal;
```

Totally cloudy day:

model solartotallycloudyfinal

// Constants

constant Real PI = 3.141592654 "pi, -";

constant Real sbc = 0.0000000567 "Stefan Boltzmann constant, W/m²/K⁴";

constant Real emissa = 0.01 "Emissivity of the absorber pipe,-";

constant Real emisse = 0.92 "Emissivity of the glass envelope,-";

constant Real densw = 1000.0 "Density of water, kg/m³";

constant Real densa = 8900.0 "Density of absorber pipe, kg/m³";

constant Real dense = 2700.0 "Density of glass envelope, kg/m³";

constant Real densair = 1.2 "Density of air, kg/m³";

constant Real hcair = 1033 "Heat capacity of air, J/kg/K";

constant Real hcw = 4180.0 "Heat capacity of water, J/kg/K";

constant Real hca = 389.0 "Heat capacity of absorber pipe, J/kg/K";

constant Real hce = 833 "Heat capacity of glass envelope, J/kg/K";

// Parameters

parameter Real rc = 0.025 "Radius of the solar collector and the coil, m";

parameter Real Dc = 0.05 "Diameter of the collector";

parameter Real rai = 0.025 "Inner radius of the absorber pipe, m";

parameter Real rao = 0.03 "Outer radius of the absorber pipe, m";

parameter Real rei = 0.045 "Inner radius of the glass envelope, m";

parameter Real reo = 0.05 "Outer radius of the glass envelope, m";

parameter Real rr = 0.03 "Inner radius of the underfloor pipe, m";

parameter Real rt = 0.565 "Diameter of the tank, m";

parameter Real Dt = 1.13 "Diameter of the tank, m";

parameter Real Dr = 0.06 "Diameter of the underfloor pipe, m";

parameter Real Ht = 0.9 "Total height of the tank, m";

parameter Real he = 1.27 "Individual coefficient of natural convection from the envelope to the air, W/m²/K";

parameter Real hr = 5.0 "Natural convection coefficient from the underfloor pipe to the air of the house, W/m²/K";

parameter Real hcn = 4.0 "Natural convection coefficient from the wall of the house to the ambient air, W/m²/K";

parameter Real hcnt = 1.71 "Individual coefficient of heat transmission by natural convection between the tank and iar of the house, W/m²/K";

```

parameter Real L = 112.5 "Length of the collector pipe, m";
parameter Real Lcoil = 29 "Lenght of the coil pipe, m";
parameter Real Lr = 200 "Length of the underfloor pipe, m";
parameter Real Vair = 384 "Air volume in the house, m3";
parameter Integer N = 10 "Number of control volumes";
parameter Real dx = L / N "Length of each control volume in the collector, m";
parameter Real dy = Lcoil / N "Length of each control volume in the coil, m";
parameter Real dz = Lr / N "Length of each control volume in the underfloor pipe, m";
parameter Real sigma = sbc / (1 / emissa + (1 - emisse) / emisse * rao / rei) "Radiation
coefficient";
parameter Real Ac = PI / 4 * Dc ^ 2 "Cross sectional area of the collector, m2";
parameter Real At = PI / 4 * Dt ^ 2 "Cross sectional area of the tank, m2";
parameter Real Ar = PI / 4 * Dr ^ 2 "Cross sectional area of the radiation pipe, m2";
parameter Real Alost = 272 "Area of lost in the house, m2";
parameter Real Pc = 2 * PI * rc "Perimeter of the collector, m";
parameter Real Aa = PI * (rao ^ 2 - rai ^ 2) "Cross sectional area of the absorber pipe, m2";
parameter Real Pai = 2 * PI * rai "Inner perimeter of the absorber pipe, m";
parameter Real Pao = 2 * PI * rao "Outer perimeter of the absorber pipe, m";
parameter Real Peo = 2 * PI * reo "Outer perimeter of the glass envelope, m";
parameter Real Pr = 2 * PI * rr "Inner perimeter of the underfloor pipe, m";
parameter Real Ae = PI * (reo ^ 2 - rei ^ 2) "Cross sectional area of the glass envelope, m2";
parameter Real mair = Vair * densair "Mass of air in the house";
parameter Real Twall = 287 "Temperature of the wall fo the house";
// Initial state parameters
parameter Real Tc1i = 278 "Initial temperature of the water that flows inside the collector,
K";
parameter Real Tc2i = 278 "Initial temperature of the water that flow inside the coil, K";
parameter Real Tai = 278 "Initial temperature of the absorber pipe, K";
parameter Real Tei = 278 "Initial temperature of the glass envelope, K";
parameter Real Tti = 278 "Initial temperature of the tank, K";
parameter Real hwti = 0.9 "Initial value of the height of water inside the tank, m";
parameter Real Tri = 278 "Initial temperature of the underfloor pipe, K";
parameter Real Thoui = 288 "Initial temperature of the house, K";
// Input parameters

```

```

parameter Real Twi = 278 "Value of the inlet temperature of water to the tank, K";
parameter Real Tairi = 280 "Value of the ambient air, K";
parameter Real Tambi = 280 "Value of the ambient air, K";
parameter Real Tcloudi = 270 "Value of the temperature of the clouds, K";
parameter Real Ici = 0.0 "Total energy provided by the sun, W";
parameter Real Qelec = 2000.0 "Total heat provided by the electricity system, W";
parameter Real vwci = 2.5 "Velocity of water inside the collector and coil pipe, m/s";
parameter Real mtii = 0.025 "Inlet mass flow to the tank, kg/s";
parameter Real mtoi = 0.025 "Outlet mass flow from the tank, kg/s";
parameter Real Qri = 0.0 "Heat transferred by the underfloor pipe, W";
parameter Real vwri = 0.005 "Velocity of the water that flows inside the underfloor pipe,
m/s";

```

```
// Variables
```

```

Real Qc2t "Heat provided by the coil, W";
Real mwt "Mass of water inside the tank, kg";
Real mc "Mass flow inside the collector";
Real mr "Mass flow inside the radiation pipe, kg/s";
Real hc "Forced convective heat transfer coefficient inside the collector pipe";
Real Qlost "lost of heat from the house to the ambient air, W";
Real a "Heat transferred by the underfloor pipe, W";

```

```
// Declaring N state variables in an array, setting initial (start) values
```

```

Real Tc1[N](each start = Tc1i) "Temperature in collector conduit, K";
Real Tc2[N](each start = Tc2i) "Temperature in conduit in heat exchanger through tank, K";
Real Ta[N](each start = Tai) "Temperature in absorber, K";
Real Te[N](each start = Tei) "Temperature in *envelope*??, K";
Real Tt(start = Tti) "Temperature in tank, K";
Real hwt(start = hwti) "Level/height of tank, m";
Real Tr[N](each start = Tri) "Temperature of the underfloor pipe, K";
Real Thou(start = Thoui) "Temperature in the house, K";

```

```
// Declaring input variables
```

```

Real Tw "Value of the inlet temperature of water to the tank, K";
Real Tair[N] "Value of the ambient air, K";
Real Tamb "Temperature of the ambient air, K";
Real Tcloud[N] "Value of the temperature of the clouds, K";

```

Real Ic[N] "Total energy provided by the sun, W";

Real Qelec "Total heat provided by the electricity system, W";

Real vwc "Velocity of water inside the collector and coil pipe, m/s";

Real mti "Inlet mass flow to the tank, kg/s";

Real mto "Outlet mass flow from the tank, kg/s";

Real Qr "Heat transferred by the underfloor pipe, W";

Real vwr "Velocity of the water that flows inside the underfloor pipe";

equation

// Heat input to tank

$$Qc2t = (hwt * 5 * hc * (\text{sum}(Tc2) - N * Tt));$$

//Heat transferred by underfloor pipe

$$a = 2 * PI * rr * Lr * hr * (\text{sum}(Tr) - N * Thou);$$

// Lost of heat to the ambient air

$$Qlost = Alost * hcn * (Twall - Tamb);$$

// Coefficients of heat transfer

$$hc = 4280 * (0.00488 * ((303 + 363) / 2) - 1) * (vwc ^ 0.8) / (Dc ^ 0.2);$$

// Mass of water inside the tank

$$mwt = At * hwt * densw;$$

// Mass flow inside the collector

$$mc = vwc * Ac * densw;$$

//Mass flow inside the underfloor pipe

$$mr = vwr * Ar * densw;$$

// Differential equations

$$\text{der}(Tc1[1]) = (mc / densw / Ac / dx * (Tc2[N] - Tc1[1]) + (hc * Pc) / densw / Ac / hcw * (Ta[1] - Tc1[1])) * 3600;$$

$$\text{der}(Tc1[2:\text{end}]) = (mc / densw / Ac / dx * (Tc1[1:\text{end} - 1] - Tc1[2:\text{end}]) + (hc * Pc) / densw / Ac / hcw * (Ta[2:\text{end}] - Tc1[2:\text{end}])) * 3600;$$

$$\text{der}(Tc2[1]) = (mc / densw / Ac / dy * (Tc1[N] - Tc2[1]) - (hc * Pc) / densw / Ac / hcw * (Tc2[1] - Tt)) * 3600;$$

$$\text{der}(Tc2[2:\text{end}]) = (mc / densw / Ac / dy * (Tc2[1:\text{end} - 1] - Tc2[2:\text{end}]) - (hc * Pc) / densw / Ac / hcw * (Tc2[2:\text{end}] - Tt * \text{ones}(N - 1))) * 3600;$$

$$\text{der}(Ta) = ((Ic * 2 * rao) / densa / hca / Aa - (\text{sigma} * Pao) / densa / hca / Aa * (Ta .^ 4 - Te .^ 4) - (hc * Pai) / densa / hca / Aa * (Ta - Tc1)) * 3600;$$

$$\text{der}(Te) = ((\text{sigma} * Pao) / dense / hce / Ae * (Ta .^ 4 - Te .^ 4) - (\text{sbc} * \text{emisse} * Peo) / dense / hce / Ae * (Te .^ 4 - Tcloud .^ 4) - (he * Peo) / dense / hce / Ae * (Te - Tair)) * 3600;$$

der(Tt) = (mti / mwt * (Tw - Tt) + Qc2t / mwt / hcw + hwt / Ht * Qelec / mwt / hcw - 2 * PI
* rt * hwt * hcnt / mwt / hcw * (Tt - Thou)) * 3600;

der(hwt) = ((mti - mto) / densw / At) * 3600;

der(Tr[1]) = (mr / densw / Ar / dz * (Tt - Tr[1]) - (hr * Pr) / densw / Ar / hcw * (Tr[1] -
Thou)) * 3600;

der(Tr[2:end]) = (mr / densw / Ar / dz * (Tr[1:end - 1] - Tr[2:end]) - (hr * Pr) / densw / Ar /
hcw * (Tr[2:end] - Thou * ones(N - 1))) * 3600;

der(Thou) = (Qr / mair / hcair - Qlost / mair / hcair) * 3600;

// Inlet values

vwr = if time < 6 then 0.0

else vwri;

Qr = a;

vwc = if time < 6 then 0.1

else if time > 6 and time < 9 then vwci

else if time > 9 and time < 21 then vwci

else if time > 21 and time < 31 then 0.1

else if time > 31 and time < 45 then vwci

else if time > 45 and time < 55 then 0.1

else if time > 55 and time < 69 then vwci

else 0.1;

Tw = if time < 9 then Twi

else if time > 9 and time < 21 then 280.0

else if time > 21 and time < 33 then Twi

else if time > 33 and time < 45 then 280.0

else if time > 45 and time < 57 then Twi

else if time > 57 and time < 69 then 280.0

else Twi;

Tair = if time < 1 then Tairi * ones(N)

else if time > 1 and time < 2 then 280.0 * ones(N)

else if time > 2 and time < 3 then 280.0 * ones(N)

else if time > 3 and time < 4 then 279.0 * ones(N)

else if time > 4 and time < 5 then 278.0 * ones(N)

else if time > 5 and time < 6 then 278.0 * ones(N)

else if time > 6 and time < 7 then 279.0 * ones(N)

else if time > 7 and time < 8 then 280.0 * ones(N)
else if time > 8 and time < 9 then 283.0 * ones(N)
else if time > 9 and time < 10 then 285.0 * ones(N)
else if time > 10 and time < 11 then 287.0 * ones(N)
else if time > 11 and time < 12 then 288.0 * ones(N)
else if time > 12 and time < 13 then 288.0 * ones(N)
else if time > 13 and time < 14 then 288.0 * ones(N)
else if time > 14 and time < 15 then 288.0 * ones(N)
else if time > 15 and time < 16 then 289.0 * ones(N)
else if time > 16 and time < 17 then 288.0 * ones(N)
else if time > 17 and time < 18 then 288.0 * ones(N)
else if time > 18 and time < 19 then 288.0 * ones(N)
else if time > 19 and time < 20 then 287.0 * ones(N)
else if time > 20 and time < 21 then 287.0 * ones(N)
else if time > 21 and time < 22 then 285.0 * ones(N)
else if time > 22 and time < 23 then 284.0 * ones(N)
else if time > 23 and time < 24 then 283.0 * ones(N)
else if time > 24 and time < 25 then Tairi * ones(N)
else if time > 25 and time < 26 then 280.0 * ones(N)
else if time > 26 and time < 27 then 280.0 * ones(N)
else if time > 27 and time < 28 then 279.0 * ones(N)
else if time > 28 and time < 29 then 278.0 * ones(N)
else if time > 29 and time < 30 then 278.0 * ones(N)
else if time > 30 and time < 31 then 279.0 * ones(N)
else if time > 31 and time < 32 then 280.0 * ones(N)
else if time > 32 and time < 33 then 283.0 * ones(N)
else if time > 33 and time < 34 then 285.0 * ones(N)
else if time > 34 and time < 35 then 287.0 * ones(N)
else if time > 35 and time < 36 then 288.0 * ones(N)
else if time > 36 and time < 37 then 288.0 * ones(N)
else if time > 37 and time < 38 then 288.0 * ones(N)
else if time > 38 and time < 39 then 288.0 * ones(N)
else if time > 39 and time < 40 then 289.0 * ones(N)
else if time > 40 and time < 41 then 288.0 * ones(N)

else if time > 41 and time < 42 then 288.0 * ones(N)
else if time > 42 and time < 43 then 288.0 * ones(N)
else if time > 43 and time < 44 then 287.0 * ones(N)
else if time > 44 and time < 45 then 287.0 * ones(N)
else if time > 45 and time < 46 then 285.0 * ones(N)
else if time > 46 and time < 47 then 284.0 * ones(N)
else if time > 47 and time < 48 then 283.0 * ones(N)
else if time > 48 and time < 49 then Tairi * ones(N)
else if time > 49 and time < 50 then 280.0 * ones(N)
else if time > 50 and time < 51 then 280.0 * ones(N)
else if time > 51 and time < 52 then 279.0 * ones(N)
else if time > 52 and time < 53 then 278.0 * ones(N)
else if time > 53 and time < 54 then 278.0 * ones(N)
else if time > 54 and time < 55 then 279.0 * ones(N)
else if time > 55 and time < 56 then 280.0 * ones(N)
else if time > 56 and time < 57 then 283.0 * ones(N)
else if time > 57 and time < 58 then 285.0 * ones(N)
else if time > 58 and time < 59 then 287.0 * ones(N)
else if time > 59 and time < 60 then 288.0 * ones(N)
else if time > 60 and time < 61 then 288.0 * ones(N)
else if time > 61 and time < 62 then 288.0 * ones(N)
else if time > 62 and time < 63 then 288.0 * ones(N)
else if time > 63 and time < 64 then 289.0 * ones(N)
else if time > 64 and time < 65 then 288.0 * ones(N)
else if time > 65 and time < 66 then 288.0 * ones(N)
else if time > 66 and time < 67 then 288.0 * ones(N)
else if time > 67 and time < 68 then 287.0 * ones(N)
else if time > 68 and time < 69 then 287.0 * ones(N)
else if time > 69 and time < 70 then 285.0 * ones(N)
else if time > 70 and time < 71 then 284.0 * ones(N)
else 283 * ones(N);

Tamb = if time < 1 then Tambi

else if time > 1 and time < 2 then 280.0

else if time > 2 and time < 3 then 280.0

else if time > 3 and time < 4 then 279.0
else if time > 4 and time < 5 then 278.0
else if time > 5 and time < 6 then 278.0
else if time > 6 and time < 7 then 279.0
else if time > 7 and time < 8 then 280.0
else if time > 8 and time < 9 then 283.0
else if time > 9 and time < 10 then 285.0
else if time > 10 and time < 11 then 287.0
else if time > 11 and time < 12 then 288.0
else if time > 12 and time < 13 then 288.0
else if time > 13 and time < 14 then 288.0
else if time > 14 and time < 15 then 288.0
else if time > 15 and time < 16 then 289.0
else if time > 16 and time < 17 then 288.0
else if time > 17 and time < 18 then 288.0
else if time > 18 and time < 19 then 288.0
else if time > 19 and time < 20 then 287.0
else if time > 20 and time < 21 then 287.0
else if time > 21 and time < 22 then 285.0
else if time > 22 and time < 23 then 284.0
else if time > 23 and time < 24 then 283.0
else if time > 24 and time < 25 then Tambi
else if time > 25 and time < 26 then 280.0
else if time > 26 and time < 27 then 280.0
else if time > 27 and time < 28 then 279.0
else if time > 28 and time < 29 then 278.0
else if time > 29 and time < 30 then 278.0
else if time > 30 and time < 31 then 279.0
else if time > 31 and time < 32 then 280.0
else if time > 32 and time < 33 then 283.0
else if time > 33 and time < 34 then 285.0
else if time > 34 and time < 35 then 287.0
else if time > 35 and time < 36 then 288.0
else if time > 36 and time < 37 then 288.0

else if time > 37 and time < 38 then 288.0
else if time > 38 and time < 39 then 288.0
else if time > 39 and time < 40 then 289.0
else if time > 40 and time < 41 then 288.0
else if time > 41 and time < 42 then 288.0
else if time > 42 and time < 43 then 288.0
else if time > 43 and time < 44 then 287.0
else if time > 44 and time < 45 then 287.0
else if time > 45 and time < 46 then 285.0
else if time > 46 and time < 47 then 284.0
else if time > 47 and time < 48 then 283.0
else if time > 48 and time < 49 then Tambi
else if time > 49 and time < 50 then 280.0
else if time > 50 and time < 51 then 280.0
else if time > 51 and time < 52 then 279.0
else if time > 52 and time < 53 then 278.0
else if time > 53 and time < 54 then 278.0
else if time > 54 and time < 55 then 279.0
else if time > 55 and time < 56 then 280.0
else if time > 56 and time < 57 then 283.0
else if time > 57 and time < 58 then 285.0
else if time > 58 and time < 59 then 287.0
else if time > 59 and time < 60 then 288.0
else if time > 60 and time < 61 then 288.0
else if time > 61 and time < 62 then 288.0
else if time > 62 and time < 63 then 288.0
else if time > 63 and time < 64 then 289.0
else if time > 64 and time < 65 then 288.0
else if time > 65 and time < 66 then 288.0
else if time > 66 and time < 67 then 288.0
else if time > 67 and time < 68 then 287.0
else if time > 68 and time < 69 then 287.0
else if time > 69 and time < 70 then 285.0
else if time > 70 and time < 71 then 284.0

else 283;

Tcloud = if time < 1 then Tcloudi * ones(N)

else if time > 1 and time < 2 then 270.0 * ones(N)

else if time > 2 and time < 3 then 270.0 * ones(N)

else if time > 3 and time < 4 then 269.0 * ones(N)

else if time > 4 and time < 5 then 268.0 * ones(N)

else if time > 5 and time < 6 then 268.0 * ones(N)

else if time > 6 and time < 7 then 269.0 * ones(N)

else if time > 7 and time < 8 then 270.0 * ones(N)

else if time > 8 and time < 9 then 273.0 * ones(N)

else if time > 9 and time < 10 then 275.0 * ones(N)

else if time > 10 and time < 11 then 277.0 * ones(N)

else if time > 11 and time < 12 then 278.0 * ones(N)

else if time > 12 and time < 13 then 278.0 * ones(N)

else if time > 13 and time < 14 then 278.0 * ones(N)

else if time > 14 and time < 15 then 278.0 * ones(N)

else if time > 15 and time < 16 then 279.0 * ones(N)

else if time > 16 and time < 17 then 278.0 * ones(N)

else if time > 17 and time < 18 then 278.0 * ones(N)

else if time > 18 and time < 19 then 278.0 * ones(N)

else if time > 19 and time < 20 then 277.0 * ones(N)

else if time > 20 and time < 21 then 277.0 * ones(N)

else if time > 21 and time < 22 then 275.0 * ones(N)

else if time > 22 and time < 23 then 274.0 * ones(N)

else if time > 23 and time < 24 then 273.0 * ones(N)

else if time > 24 and time < 25 then Tcloudi * ones(N)

else if time > 25 and time < 26 then 270.0 * ones(N)

else if time > 26 and time < 27 then 270.0 * ones(N)

else if time > 27 and time < 28 then 269.0 * ones(N)

else if time > 28 and time < 29 then 268.0 * ones(N)

else if time > 29 and time < 30 then 268.0 * ones(N)

else if time > 30 and time < 31 then 269.0 * ones(N)

else if time > 31 and time < 32 then 270.0 * ones(N)

else if time > 32 and time < 33 then 273.0 * ones(N)

else if time > 33 and time < 34 then 275.0 * ones(N)
else if time > 34 and time < 35 then 277.0 * ones(N)
else if time > 35 and time < 36 then 278.0 * ones(N)
else if time > 36 and time < 37 then 278.0 * ones(N)
else if time > 37 and time < 38 then 278.0 * ones(N)
else if time > 38 and time < 39 then 278.0 * ones(N)
else if time > 39 and time < 40 then 279.0 * ones(N)
else if time > 40 and time < 41 then 278.0 * ones(N)
else if time > 41 and time < 42 then 278.0 * ones(N)
else if time > 42 and time < 43 then 278.0 * ones(N)
else if time > 43 and time < 44 then 277.0 * ones(N)
else if time > 44 and time < 45 then 277.0 * ones(N)
else if time > 45 and time < 46 then 275.0 * ones(N)
else if time > 46 and time < 47 then 274.0 * ones(N)
else if time > 47 and time < 48 then 273.0 * ones(N)
else if time > 48 and time < 49 then Tcloudi * ones(N)
else if time > 49 and time < 50 then 270.0 * ones(N)
else if time > 50 and time < 51 then 270.0 * ones(N)
else if time > 51 and time < 52 then 269.0 * ones(N)
else if time > 52 and time < 53 then 268.0 * ones(N)
else if time > 53 and time < 54 then 268.0 * ones(N)
else if time > 54 and time < 55 then 269.0 * ones(N)
else if time > 55 and time < 56 then 270.0 * ones(N)
else if time > 56 and time < 57 then 273.0 * ones(N)
else if time > 57 and time < 58 then 275.0 * ones(N)
else if time > 58 and time < 59 then 277.0 * ones(N)
else if time > 59 and time < 60 then 278.0 * ones(N)
else if time > 60 and time < 61 then 278.0 * ones(N)
else if time > 61 and time < 62 then 278.0 * ones(N)
else if time > 62 and time < 63 then 278.0 * ones(N)
else if time > 63 and time < 64 then 279.0 * ones(N)
else if time > 64 and time < 65 then 278.0 * ones(N)
else if time > 65 and time < 66 then 278.0 * ones(N)
else if time > 66 and time < 67 then 278.0 * ones(N)

else if time > 67 and time < 68 then 277.0 * ones(N)
else if time > 68 and time < 69 then 277.0 * ones(N)
else if time > 69 and time < 70 then 275.0 * ones(N)
else if time > 70 and time < 71 then 274.0 * ones(N)
else 273 * ones(N);

Ic = if time < 6 then Ici * ones(N)

else if time > 6 and time < 7 then 70.0 * ones(N)
else if time > 7 and time < 8 then 100.0 * ones(N)
else if time > 8 and time < 9 then 120.0 * ones(N)
else if time > 9 and time < 10 then 150.0 * ones(N)
else if time > 10 and time < 11 then 170.0 * ones(N)
else if time > 11 and time < 12 then 200.0 * ones(N)
else if time > 12 and time < 13 then 200.0 * ones(N)
else if time > 13 and time < 14 then 200.0 * ones(N)
else if time > 14 and time < 15 then 200.0 * ones(N)
else if time > 15 and time < 16 then 200.0 * ones(N)
else if time > 16 and time < 17 then 200.0 * ones(N)
else if time > 17 and time < 18 then 200.0 * ones(N)
else if time > 18 and time < 19 then 170.0 * ones(N)
else if time > 19 and time < 20 then 150.0 * ones(N)
else if time > 20 and time < 21 then 100.0 * ones(N)
else if time > 21 and time < 31 then Ici * ones(N)
else if time > 31 and time < 32 then 50.0 * ones(N)
else if time > 32 and time < 33 then 50.0 * ones(N)
else if time > 33 and time < 34 then 70.0 * ones(N)
else if time > 34 and time < 35 then 80.0 * ones(N)
else if time > 35 and time < 36 then 80.0 * ones(N)
else if time > 36 and time < 37 then 80.0 * ones(N)
else if time > 37 and time < 38 then 80.0 * ones(N)
else if time > 38 and time < 39 then 80.0 * ones(N)
else if time > 39 and time < 40 then 80.0 * ones(N)
else if time > 40 and time < 41 then 80.0 * ones(N)
else if time > 41 and time < 42 then 80.0 * ones(N)
else if time > 42 and time < 43 then 70.0 * ones(N)

```

else if time > 43 and time < 44 then 70.0 * ones(N)
else if time > 44 and time < 45 then 50.0 * ones(N)
else if time > 45 and time < 55 then Ici * ones(N)
else if time > 55 and time < 56 then 50.0 * ones(N)
else if time > 56 and time < 57 then 50.0 * ones(N)
else if time > 57 and time < 58 then 70.0 * ones(N)
else if time > 58 and time < 59 then 80.0 * ones(N)
else if time > 59 and time < 60 then 80.0 * ones(N)
else if time > 60 and time < 61 then 80.0 * ones(N)
else if time > 61 and time < 62 then 80.0 * ones(N)
else if time > 62 and time < 63 then 80.0 * ones(N)
else if time > 63 and time < 64 then 80.0 * ones(N)
else if time > 64 and time < 65 then 80.0 * ones(N)
else if time > 65 and time < 66 then 80.0 * ones(N)
else if time > 66 and time < 67 then 70.0 * ones(N)
else if time > 67 and time < 68 then 70.0 * ones(N)
else if time > 68 and time < 69 then 50.0 * ones(N)
else Ici * ones(N);
Qelec = if time < 8 then 0.0
      else if time > 8 and time < 21 then Qelec
      else if time > 21 and time < 36 then Qelec
      else if time > 36 and time < 45 then Qelec
      else if time > 45 and time < 60 then Qelec
      else if time > 60 and time < 69 then Qelec
      else Qelec;
mti = if time < 6.0 then mtii
      else if time > 6.0 and time < 7.0 then 0.0
      else if time > 7.0 and time < 8.0 then 0.0
      else if time > 8.0 and time < 11.0 then 0.03333333
      else if time > 11.0 and time < 12.0 then 0.05475
      else if time > 12.0 and time < 13.0 then 0.05475
      else if time > 13.0 and time < 16.0 then 0.045
      else if time > 16.0 and time < 17.0 then 0.045
      else if time > 17.0 and time < 18.0 then 0.056

```

```

else if time > 18.0 and time < 21.0 then 0.05015
else if time > 21.0 and time < 30.0 then mtii
else if time > 30.0 and time < 31.0 then 0.0
else if time > 31.0 and time < 32.0 then 0.0
else if time > 32.0 and time < 35.0 then 0.033333333
else if time > 35.0 and time < 36.0 then 0.05475
else if time > 36.0 and time < 37.0 then 0.05475
else if time > 37.0 and time < 40.0 then 0.045
else if time > 40.0 and time < 41.0 then 0.045
else if time > 41.0 and time < 42.0 then 0.056
else if time > 42.0 and time < 45.0 then 0.05015
else if time > 45.0 and time < 54.0 then mtii
else if time > 54.0 and time < 55.0 then 0.0
else if time > 55.0 and time < 56.0 then 0.0
else if time > 56.0 and time < 59.0 then 0.033333333
else if time > 59.0 and time < 60.0 then 0.05475
else if time > 60.0 and time < 61.0 then 0.05475
else if time > 61.0 and time < 64.0 then 0.045
else if time > 64.0 and time < 65.0 then 0.045
else if time > 65.0 and time < 66.0 then 0.056
else if time > 66.0 and time < 69.0 then 0.05015
else mtii;

```

mto = if time < 6.0 then mtoi

```

else if time > 6.0 and time < 7.0 then 0.195
else if time > 7.0 and time < 8.0 then mtoi
else if time > 8.0 and time < 11.0 then mtoi
else if time > 11.0 and time < 12.0 then 0.042
else if time > 12.0 and time < 13.0 then 0.042
else if time > 13.0 and time < 16.0 then mtoi
else if time > 16.0 and time < 17.0 then 0.042
else if time > 17.0 and time < 18.0 then mtoi
else if time > 18.0 and time < 21.0 then mtoi
else if time > 21.0 and time < 30.0 then mtoi
else if time > 30.0 and time < 31.0 then 0.195

```

```
else if time > 31.0 and time < 32.0 then mtoi
else if time > 32.0 and time < 35.0 then mtoi
else if time > 35.0 and time < 36.0 then 0.042
else if time > 36.0 and time < 37.0 then 0.042
else if time > 37.0 and time < 40.0 then mtoi
else if time > 40.0 and time < 41.0 then 0.042
else if time > 41.0 and time < 42.0 then mtoi
else if time > 42.0 and time < 45.0 then mtoi
else if time > 42.0 and time < 54.0 then mtoi
else if time > 54.0 and time < 55.0 then 0.195
else if time > 55.0 and time < 56.0 then mtoi
else if time > 56.0 and time < 59.0 then mtoi
else if time > 59.0 and time < 60.0 then 0.042
else if time > 60.0 and time < 61.0 then 0.042
else if time > 61.0 and time < 64.0 then mtoi
else if time > 64.0 and time < 65.0 then 0.042
else if time > 65.0 and time < 66.0 then mtoi
else if time > 66.0 and time < 69.0 then mtoi
else mtoi;
end solartotallycloudyfinal;
```

Appendix 4: Different results

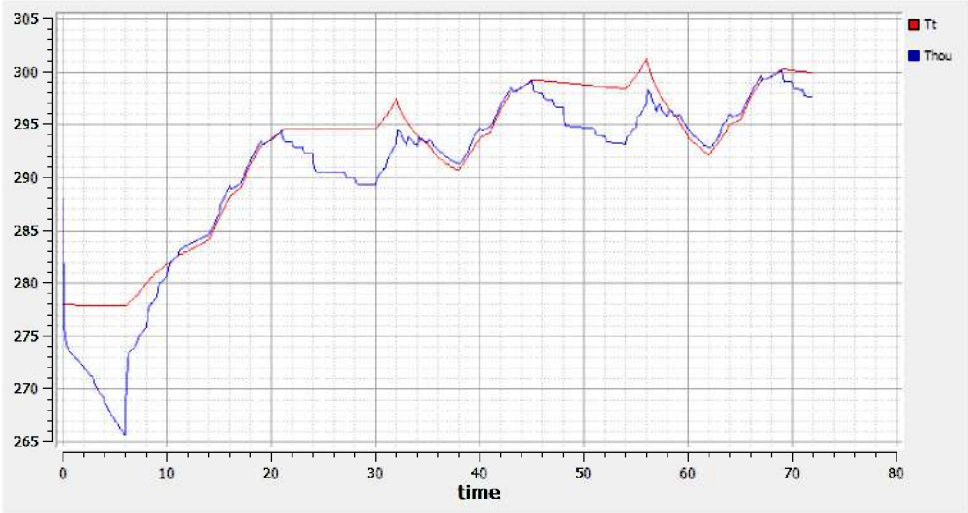


Fig 4.26: Outputs in a partly cloudy day: T_t , T_{hou} at $v_{wr} = 2.0$

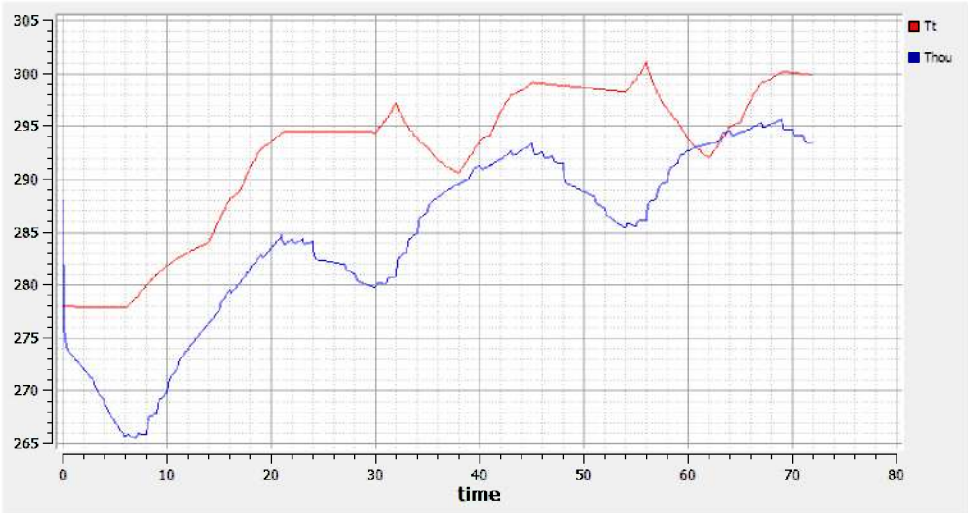


Fig 4.27: Outputs in a partly cloudy day: T_t , T_{hou} at $v_{wr} = 0.005$

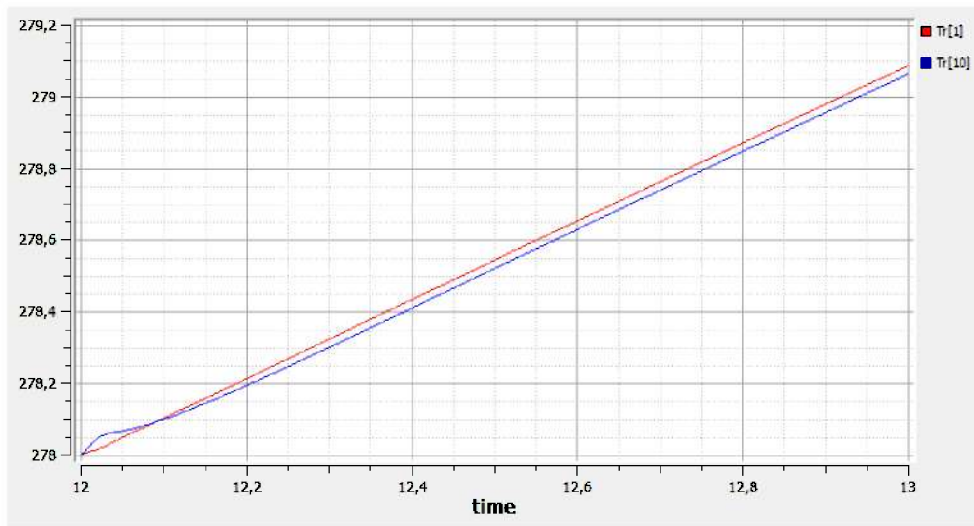


Fig 4.28: Outputs in a partly cloudy day: $T_r[1]$, $T_r[10]$ at $v_{wr} = 2.0$

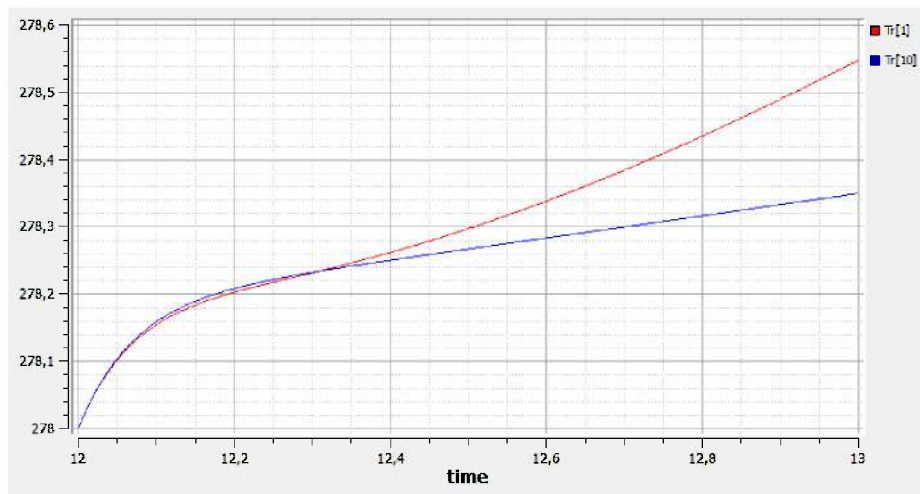


Fig 4.29: Outputs in a partly cloudy day: $T_r[1]$, $T_r[10]$ at $v_{wr} = 0.005$

..