Co-Simulation Between ESP-r and TRNSYS

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POLYTECHNIQUE MONTRÉAL

Outline

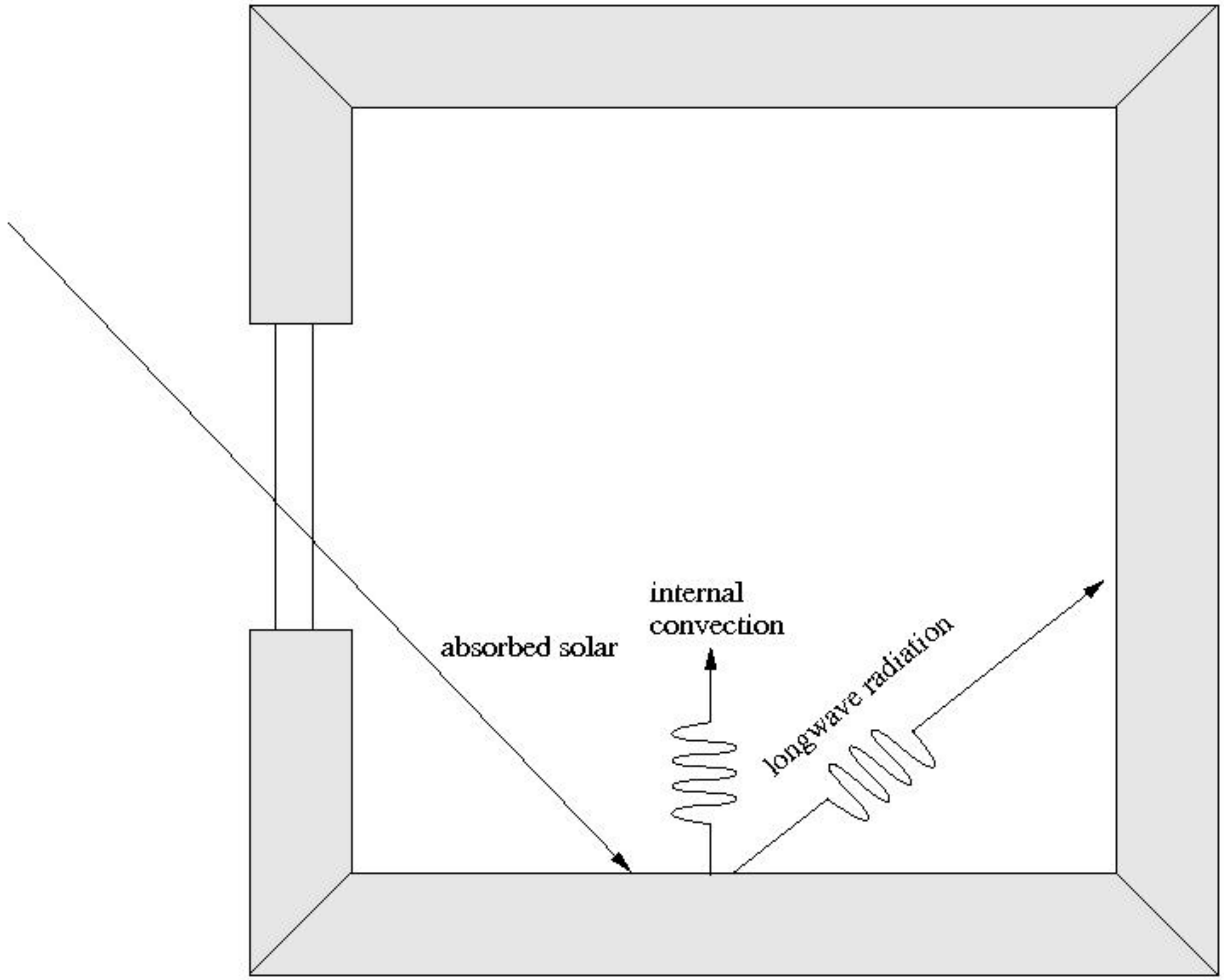
- Background: Early BPS methods.
- What is co-simulation ?
- Why co-simulate ?
- TRNSYS and ESP-r methodologies.
- The ESP-r / TRNSYS co-simulator:
  - How does it work ?
  - Is it valid ?
  - Is it stable ?
  - What is the computational burden ?
  - What can it do ?
- Configuring a co-simulation:
  - Demonstration.
  - Hands-on exercise.
- Closing:
  - Configuring a computer for co-simulation.
  - When should it be used (and not used) ?

IBM Photo Archive: IBM 7094 circa 1965

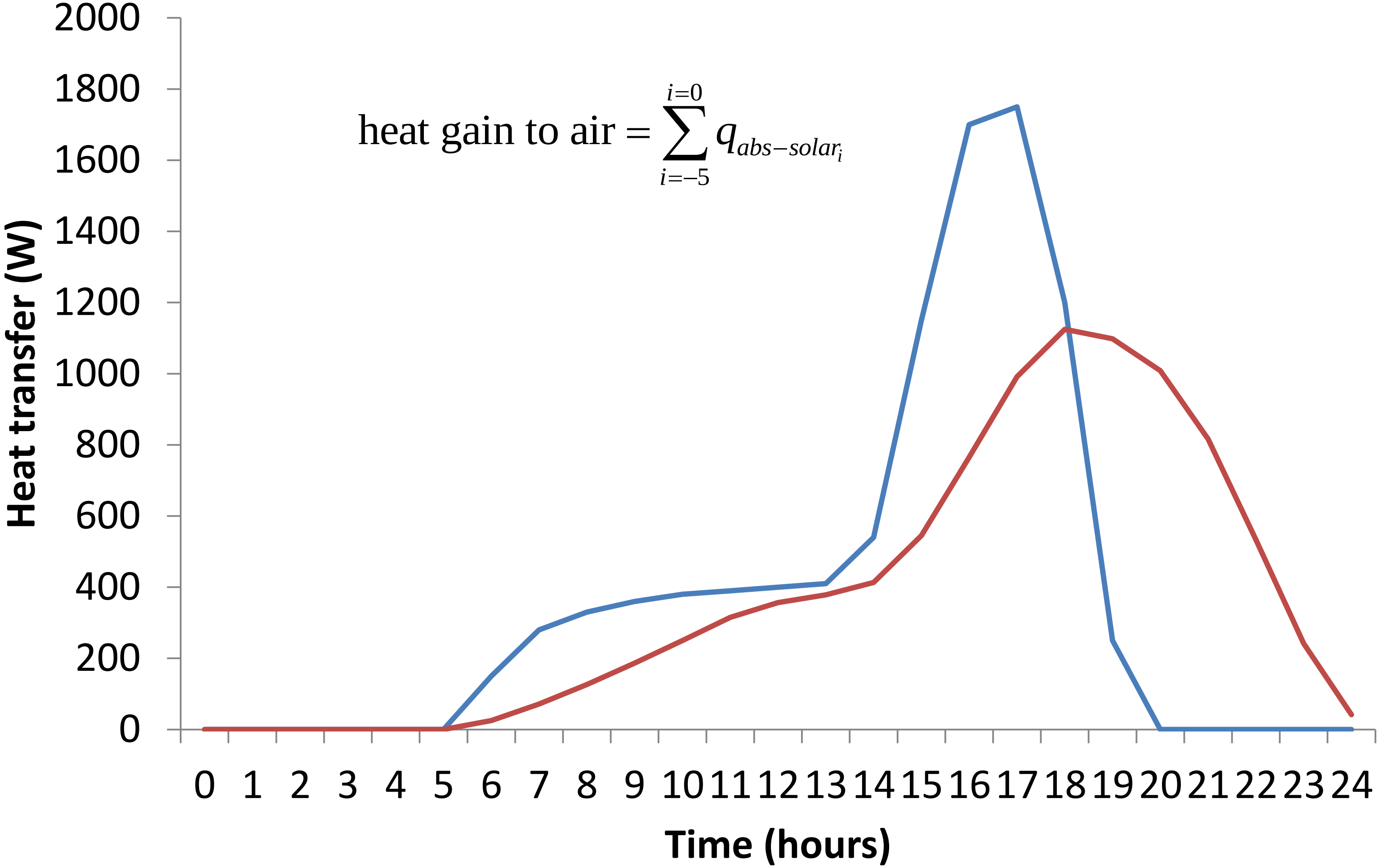
Early BPS Methods

- Late 1960's:
  - Gas Application to Total Energy (GATE).
  - Post Office program.
  - ASHRAE Task Group on Energy Requirements (TGER).

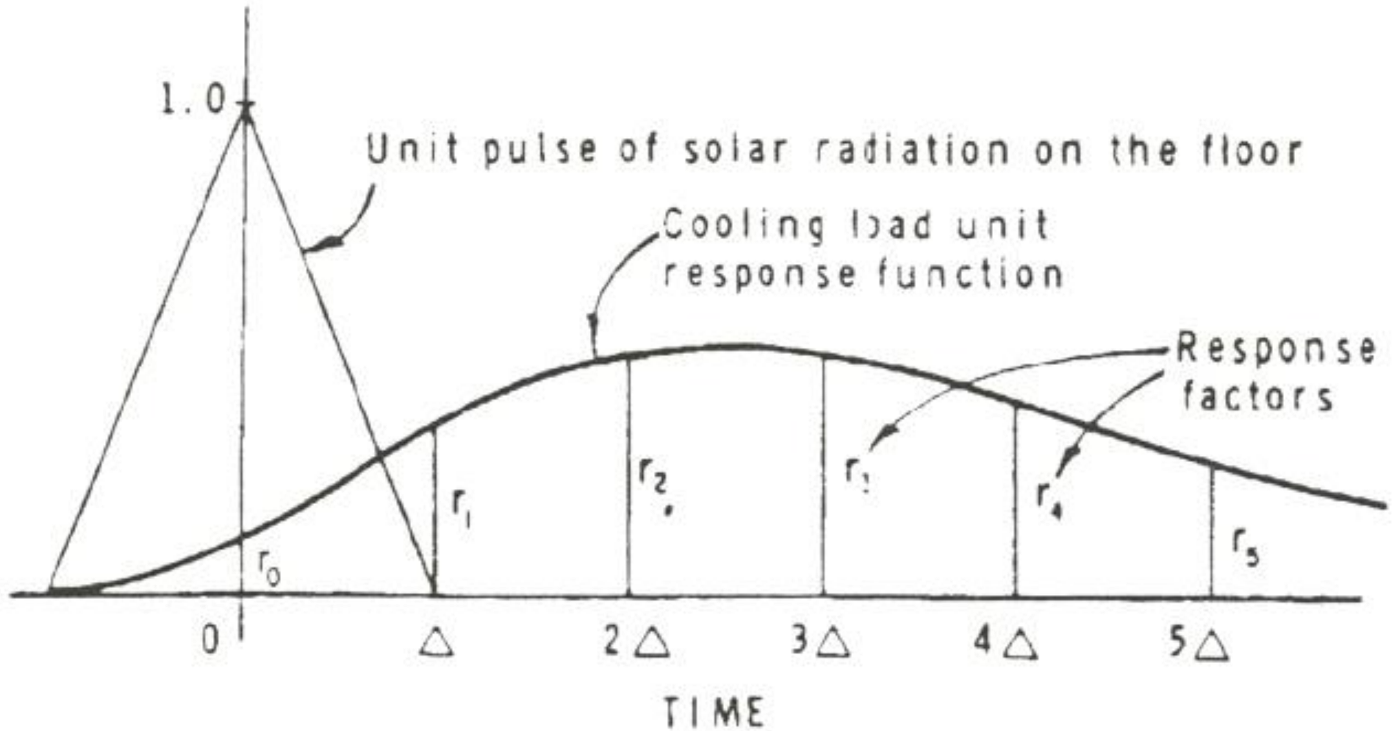
Time-Averaging Technique



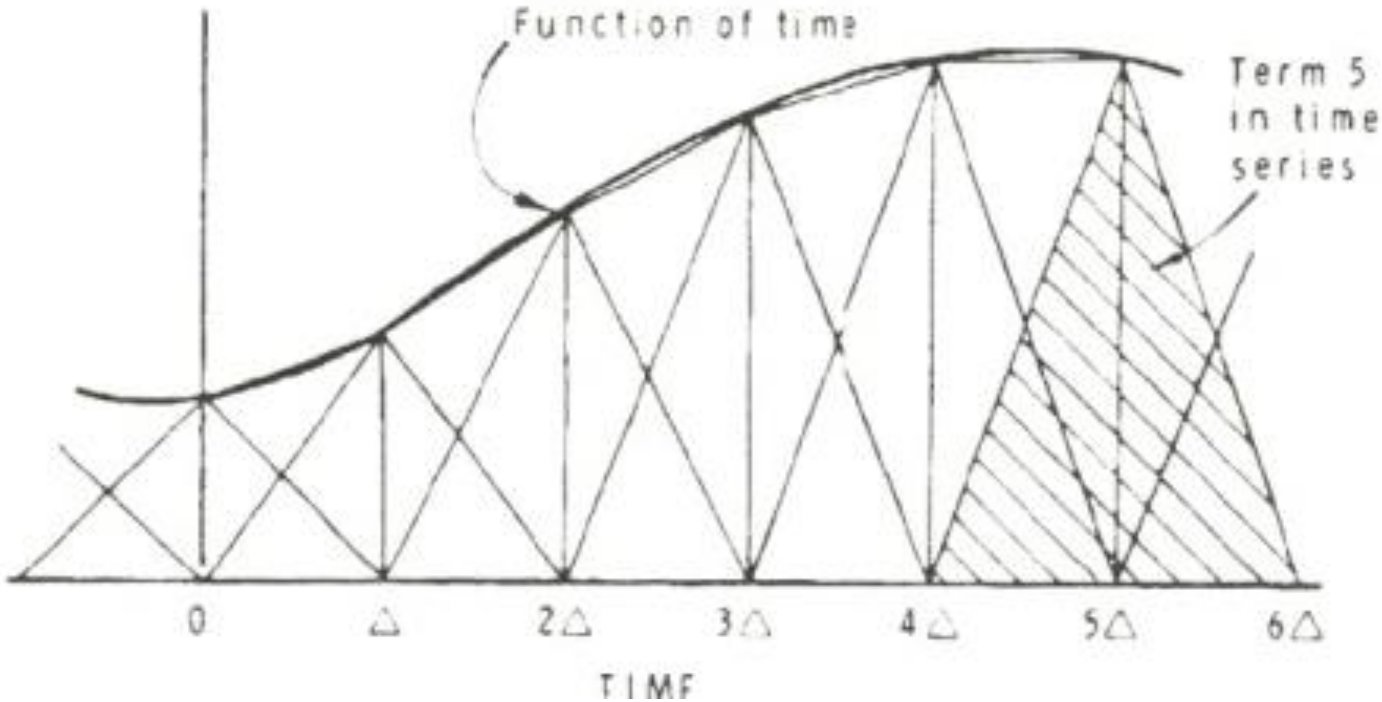
Time-Averaging Technique



Response Factor Method
(Stephenson & Mitalas, 1967)

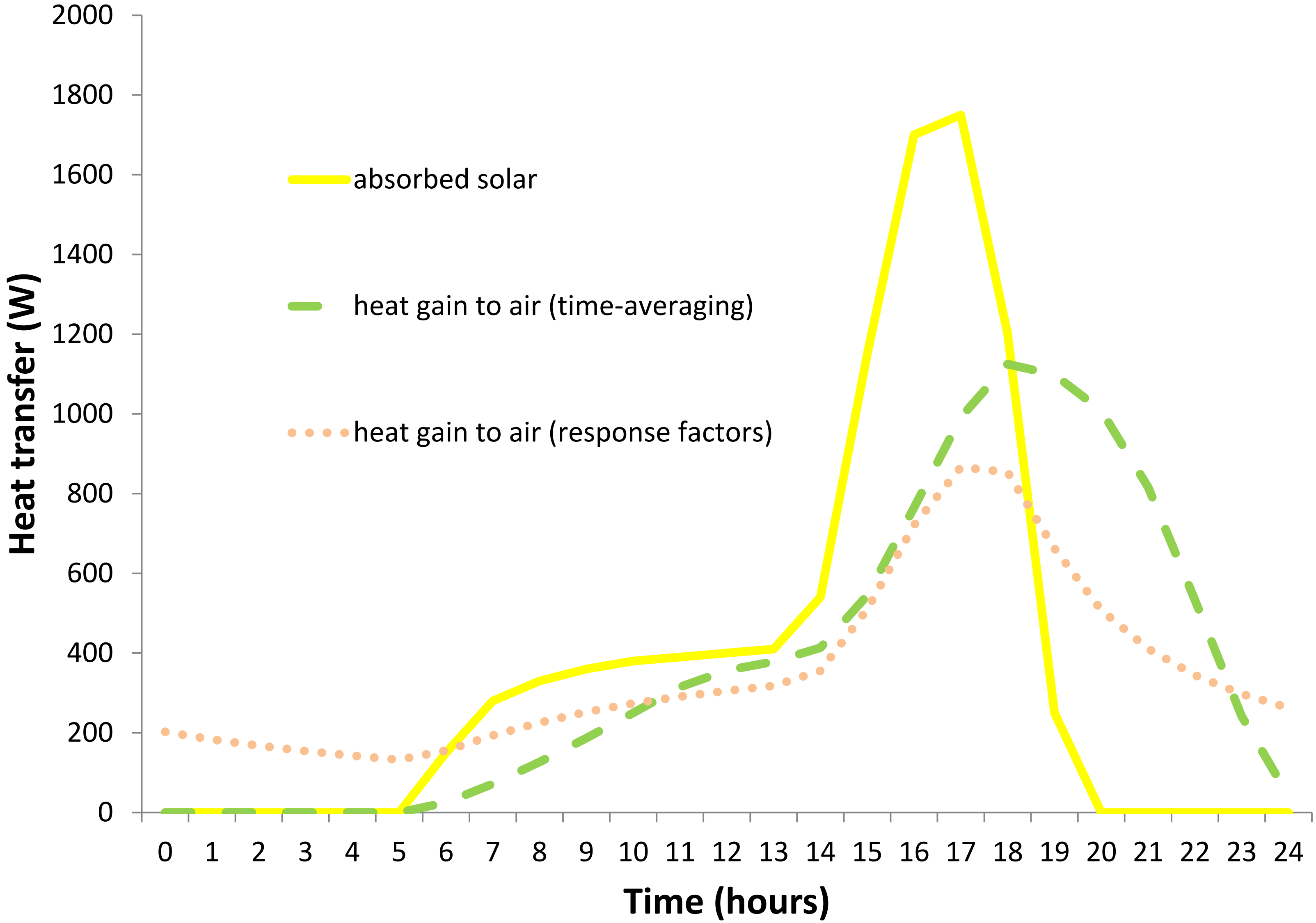


Response Factor Method (Stephenson & Mitalas, 1967)



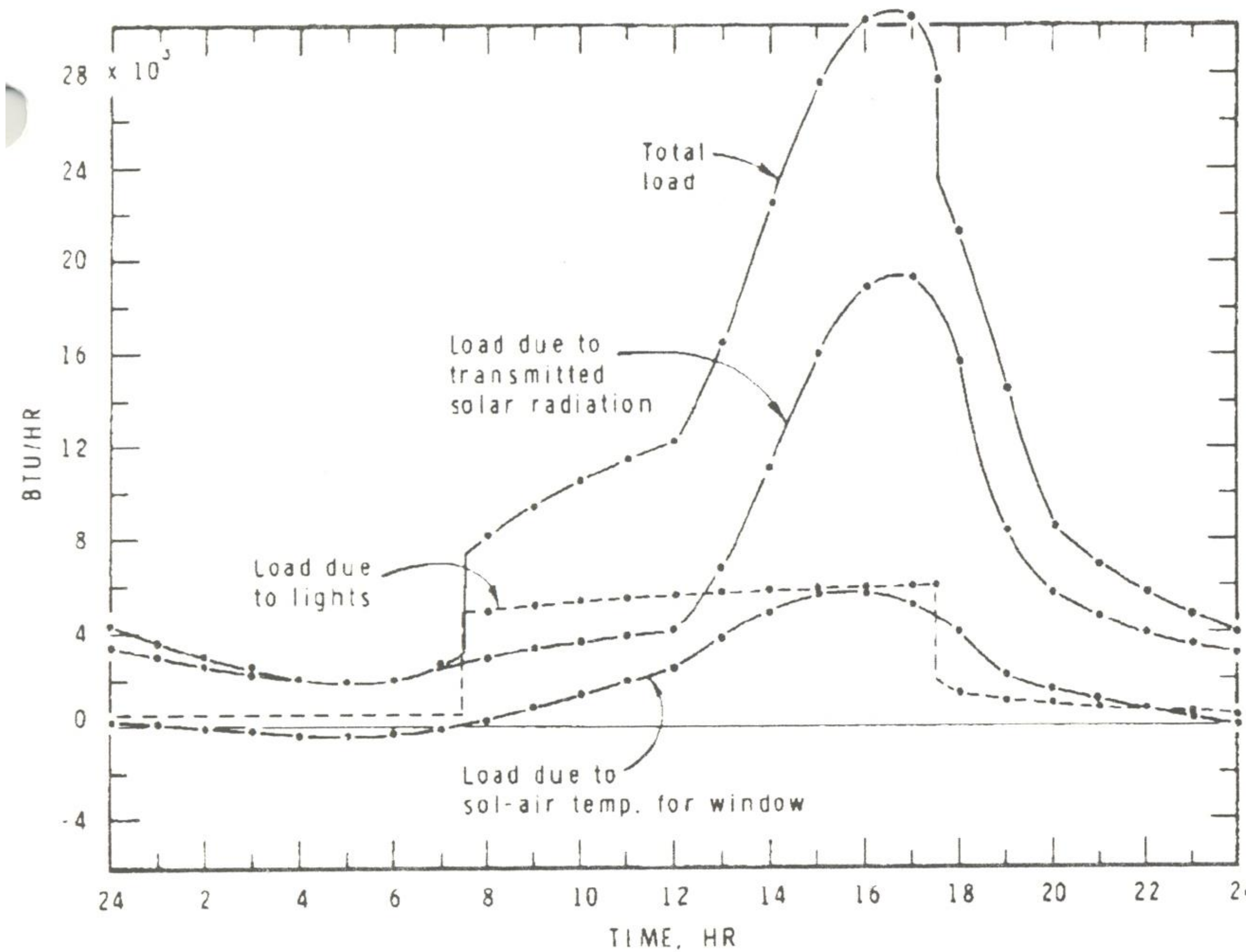
Response Factor Method (Stephenson & Mitalas, 1967)

$$q_{heat-gain-to-air,t} = \alpha_0 \cdot q_{solar-abs,t} + \alpha_1 \cdot q_{solar-abs,t-\Delta t} + \alpha_2 \cdot q_{solar-abs,t-2\Delta t} + ...$$

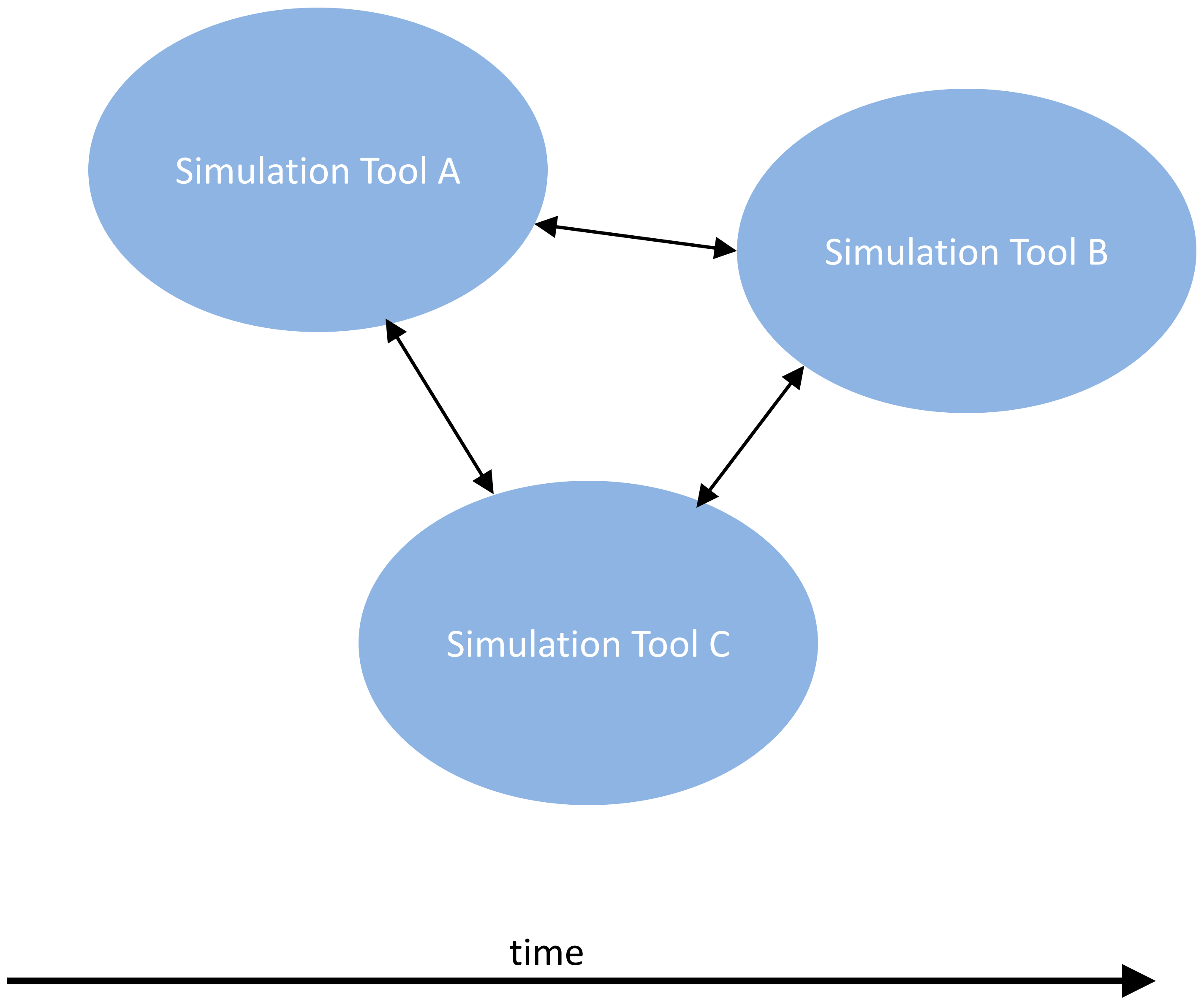


Heat transfer (W)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
absorbed solar
heat gain to air (time-averaging)
heat gain to air (response factors)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)

Principle of Superpositioning



Co-simulation

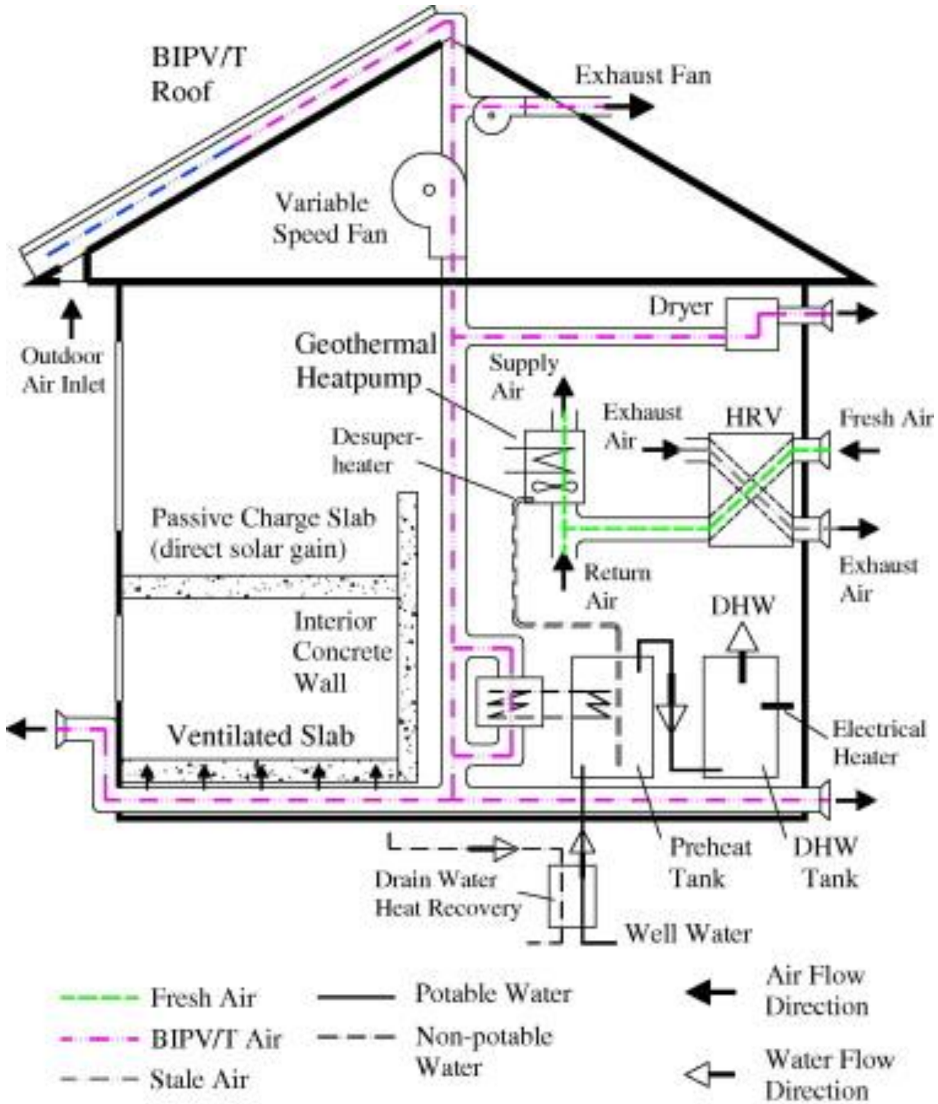

Simulation Tool A
Simulation Tool B
Simulation Tool C
time

"Internal" Coupling (≠ Co-Simulation)

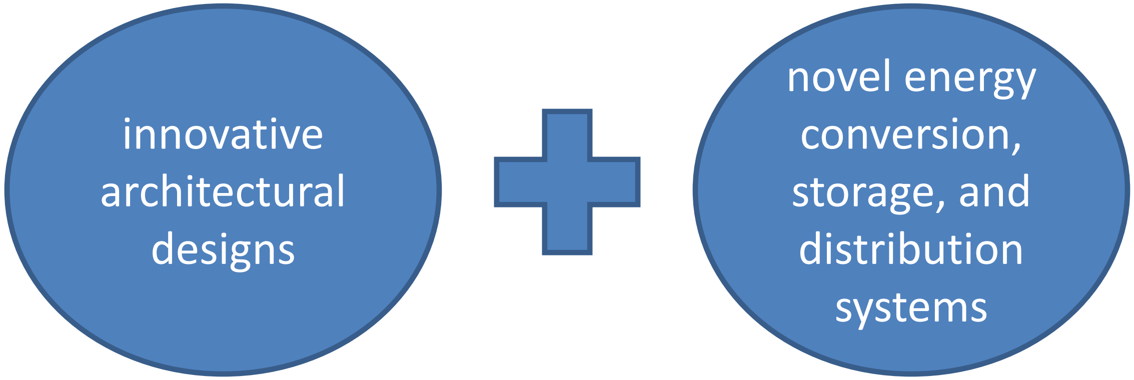
- Single executable:
  - Tool's source code incorporated into host program.
- BPS examples:
  - COMIS $\rightarrow$ TRNSYS (Dorer and Weber 1999).
  - COMIS $\rightarrow$ EnergyPlus (Huang et al. 1999).
  - TRNSYS Type 1 solar collector $\rightarrow$ ESP-r (Aasem 1993).
  - ESP-r micro-cogen models $\rightarrow$ TRNSYS (Weber 2007).
  - "TRNSYS wrapper" for TRNSYS types $\rightarrow$ ESP-r (Wang and Beausoleil-Morrison 2009).

“External” Coupling (Co-Simulation)

- Separate programs linked at run-time:
  - March together through time.
  - Usually one tool is master, the other slave.
- Examples:
  - Radiance $\rightarrow$ ESP-r (Janak 1997).
  - Fluent $\rightarrow$ ESP-r (Djunaedy 2005).
  - TRNSYS $\rightarrow$ EnergyPlus (Trčka et al. 2009).
- BCVTB (Wetter 2010):
  - Avoids master-slave paradigm.
  - Middleware manages data exchange via internet.
  - Each simulation tool acts as a client.
  - BUT, precludes iteration within time-step.

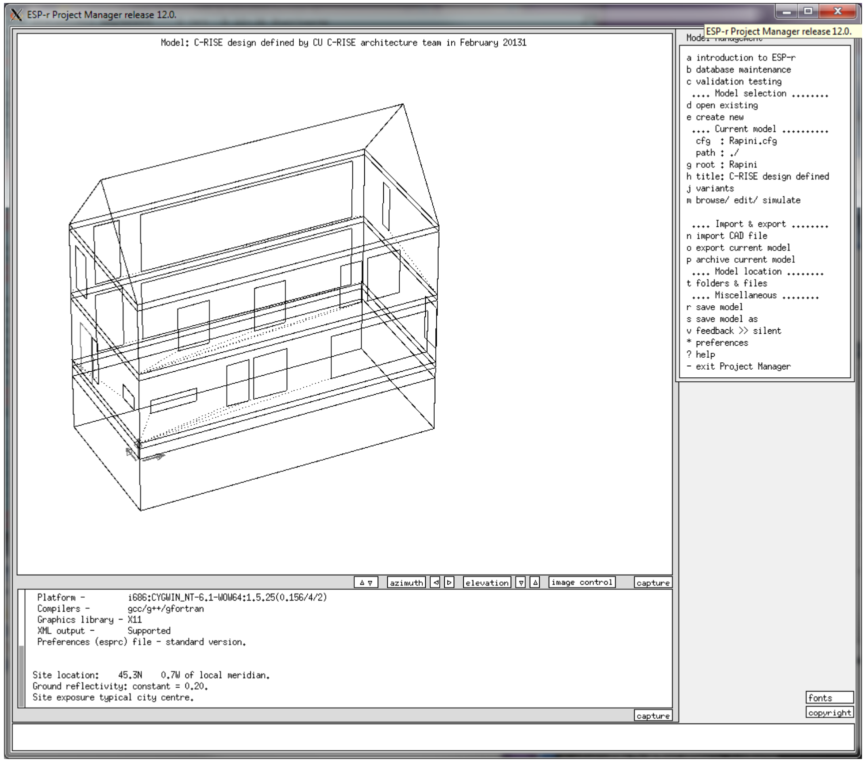


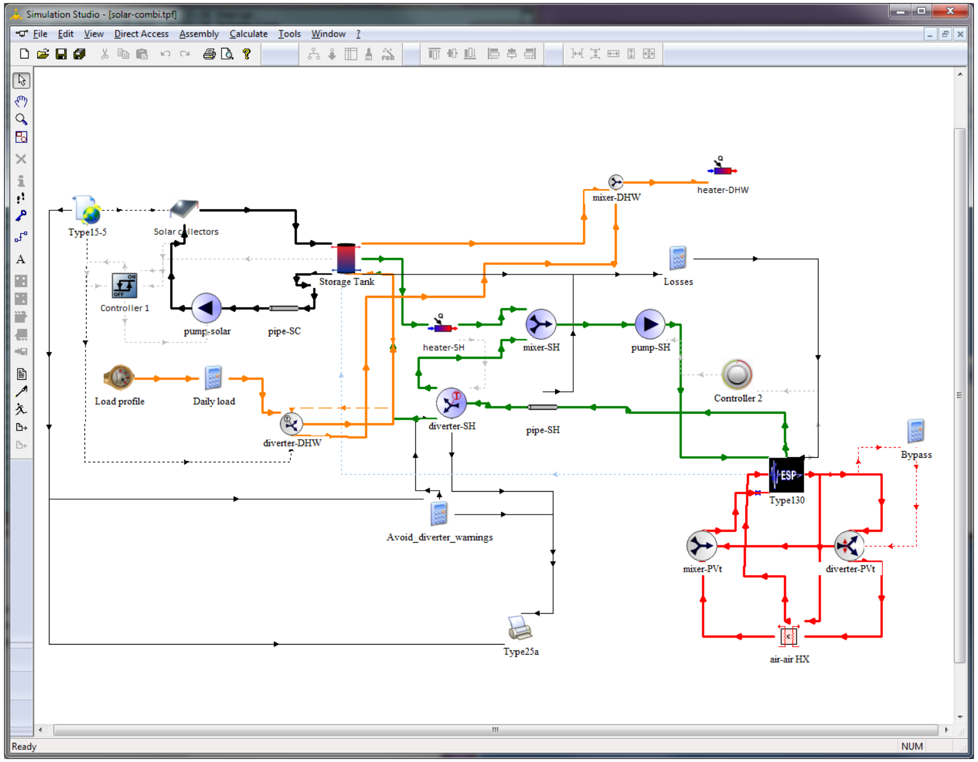
Source: Yuxiang Chen, A.K. Athienitis, Khaled Galal (2010), "Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept", Solar Energy (84) 11 1892-1907.



Integrated building designs require integrated modelling approaches.

No single BPS tool offers sufficient capabilities and flexibility.



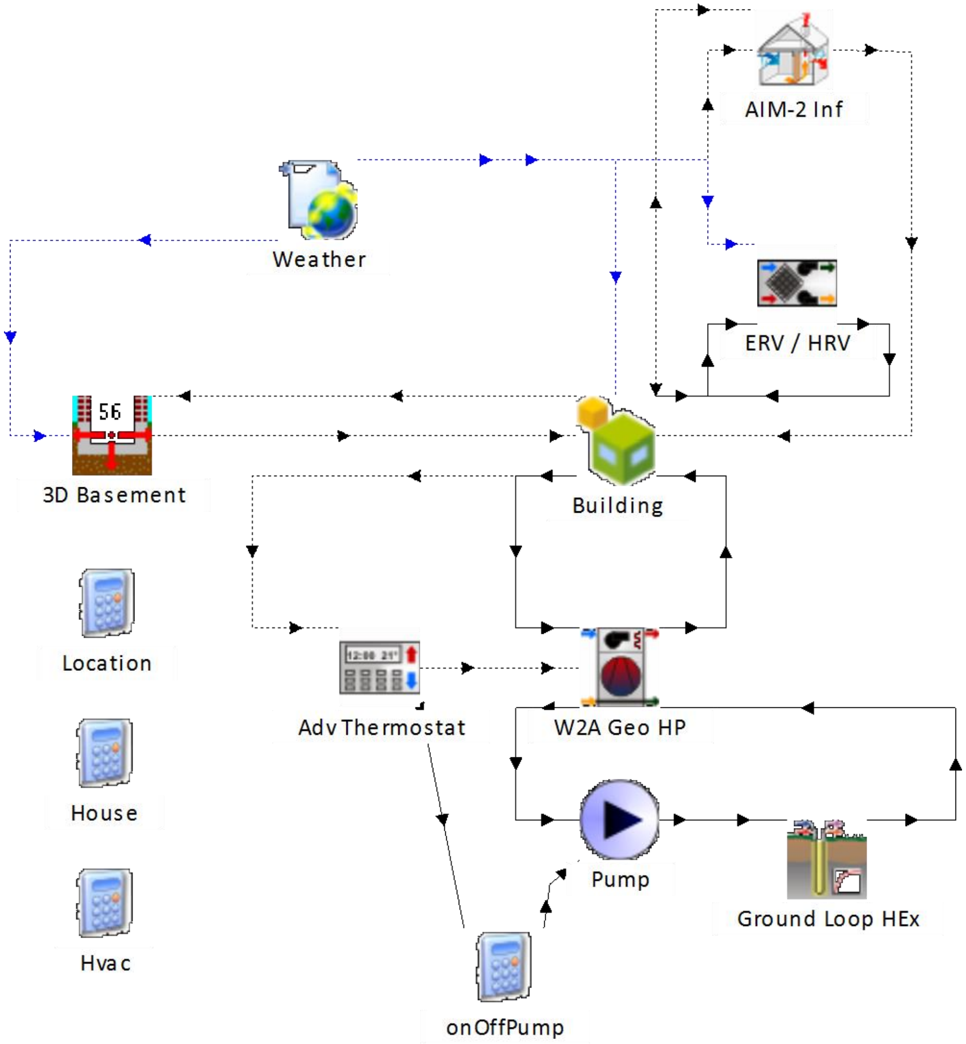


ESP-r and TRNSYS Solution Methodologies

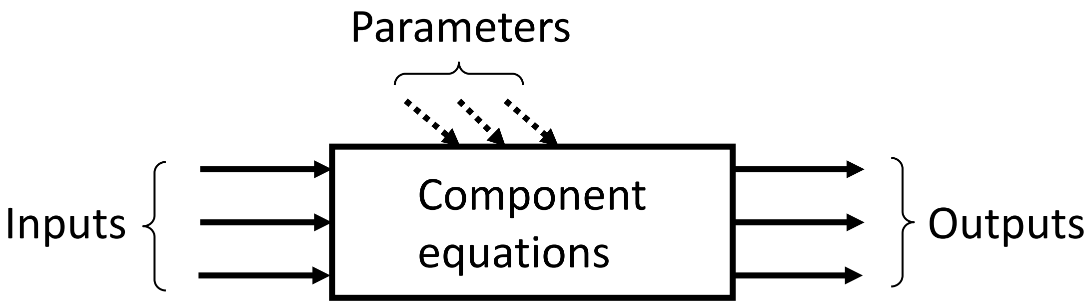
TRNSYS Methodologies

- TRNSYS methodologies
  - The TRNSYS philosophy
  - Kernel, solver and Types
  - Successive substitution and oscillations
  - Conclusions

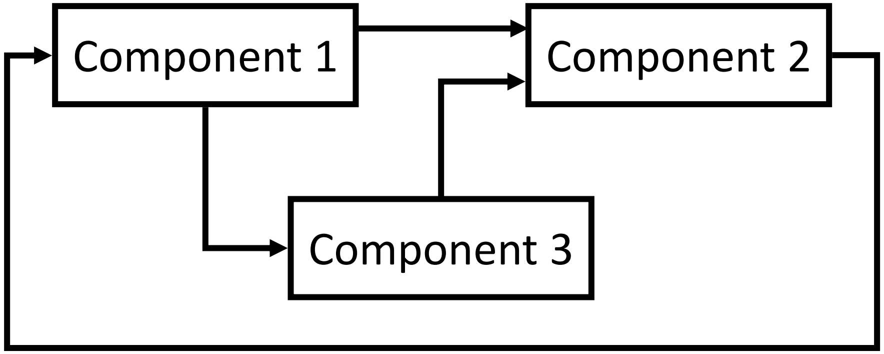
TRNSYS philosophy



TRNSYS philosophy

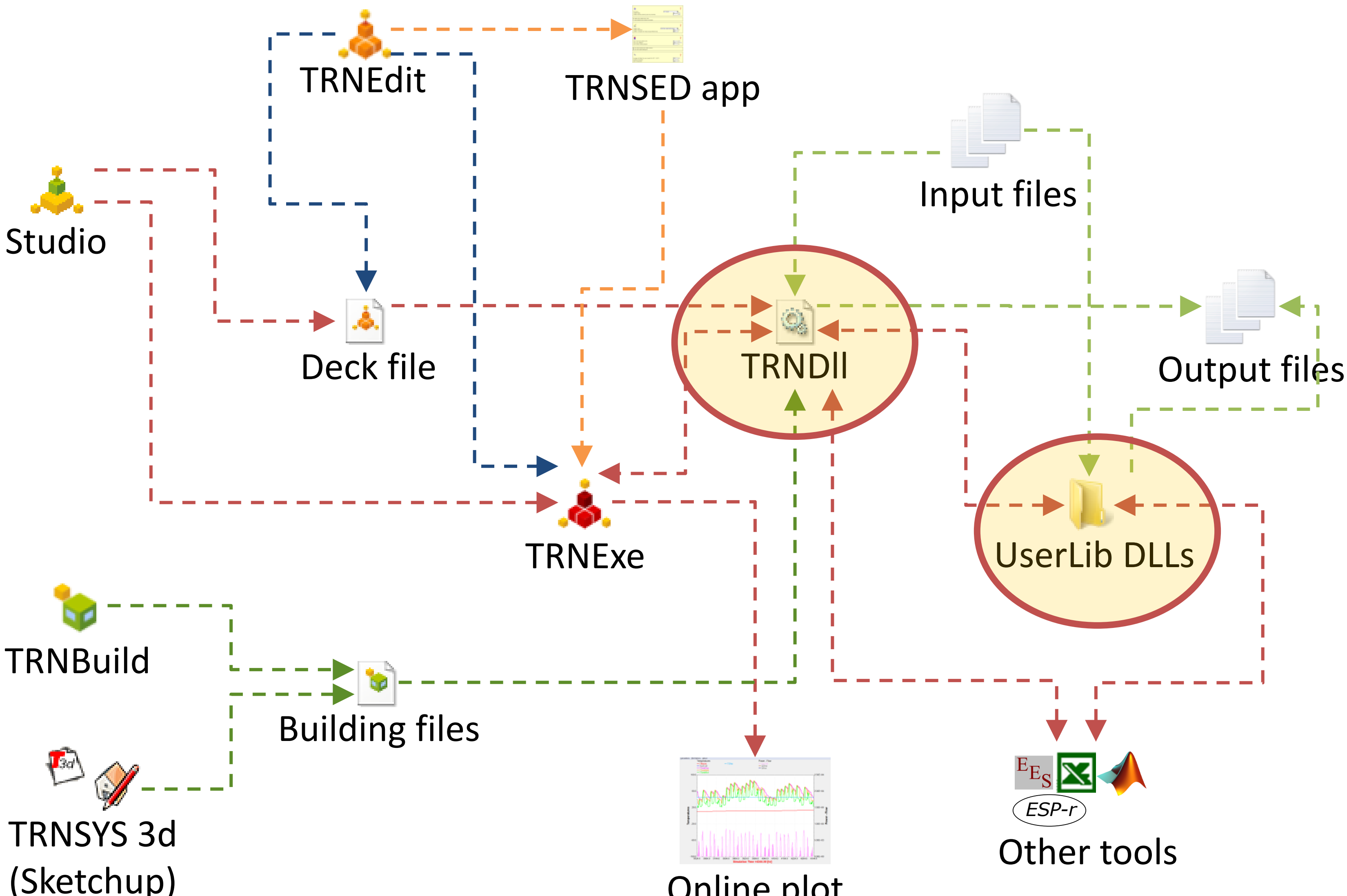


Components solve their own equations (inputs → outputs)



Main solver links components outputs to inputs and solves the algebraic / differential system

Where is this happening?

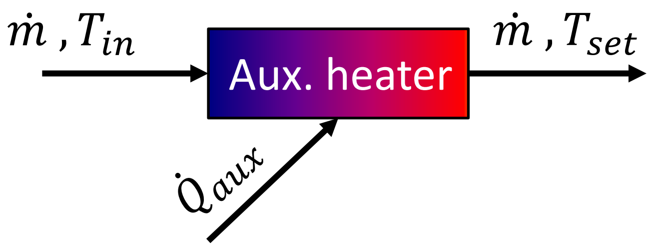


What's in a component?

Example: auxiliary heater

Equation(s)

$\dot{m}\, c_p\, (T_{set} - T_{in}) = \dot{Q}_{aux}$

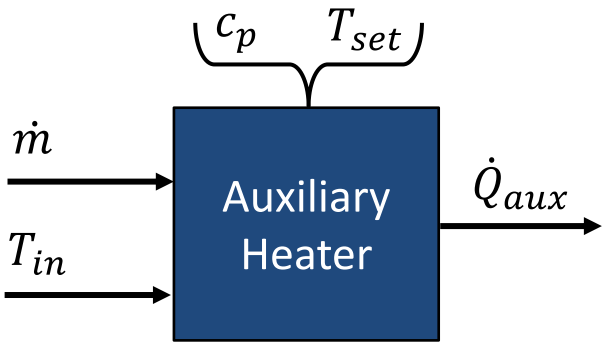


Black-box description (option 2)

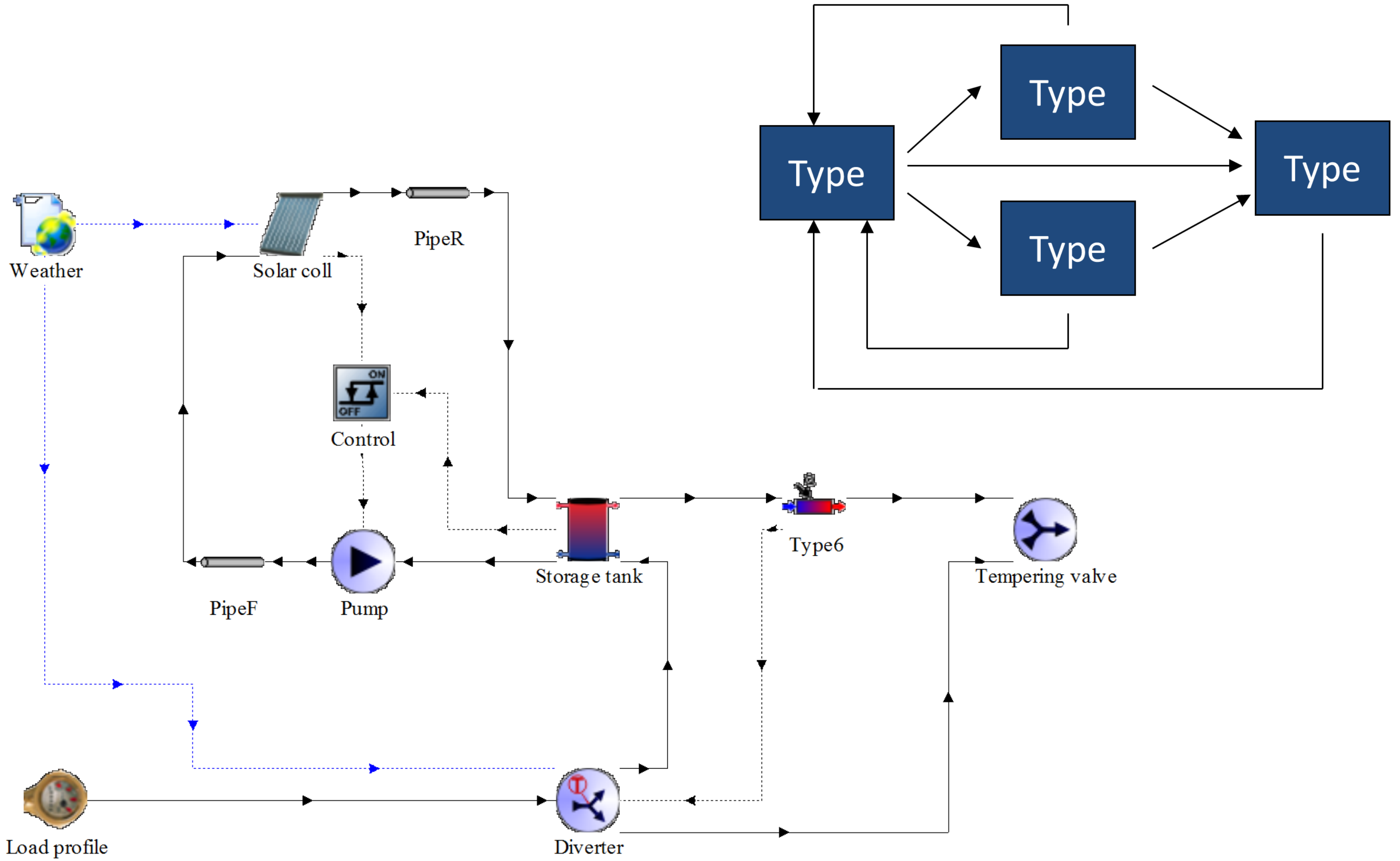
Parameters: c_p , T_{set}

Inputs: $\dot{m}$, T_{in}

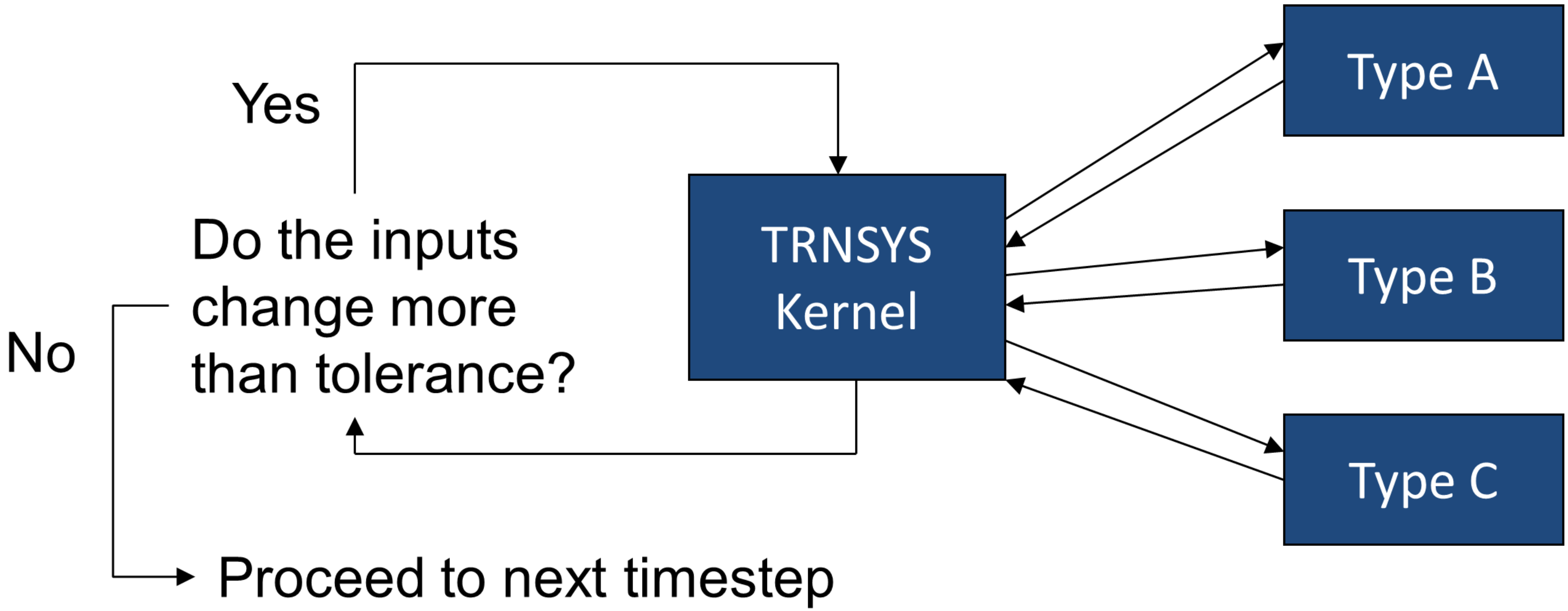
Outputs: $\dot{Q}_{aux}$



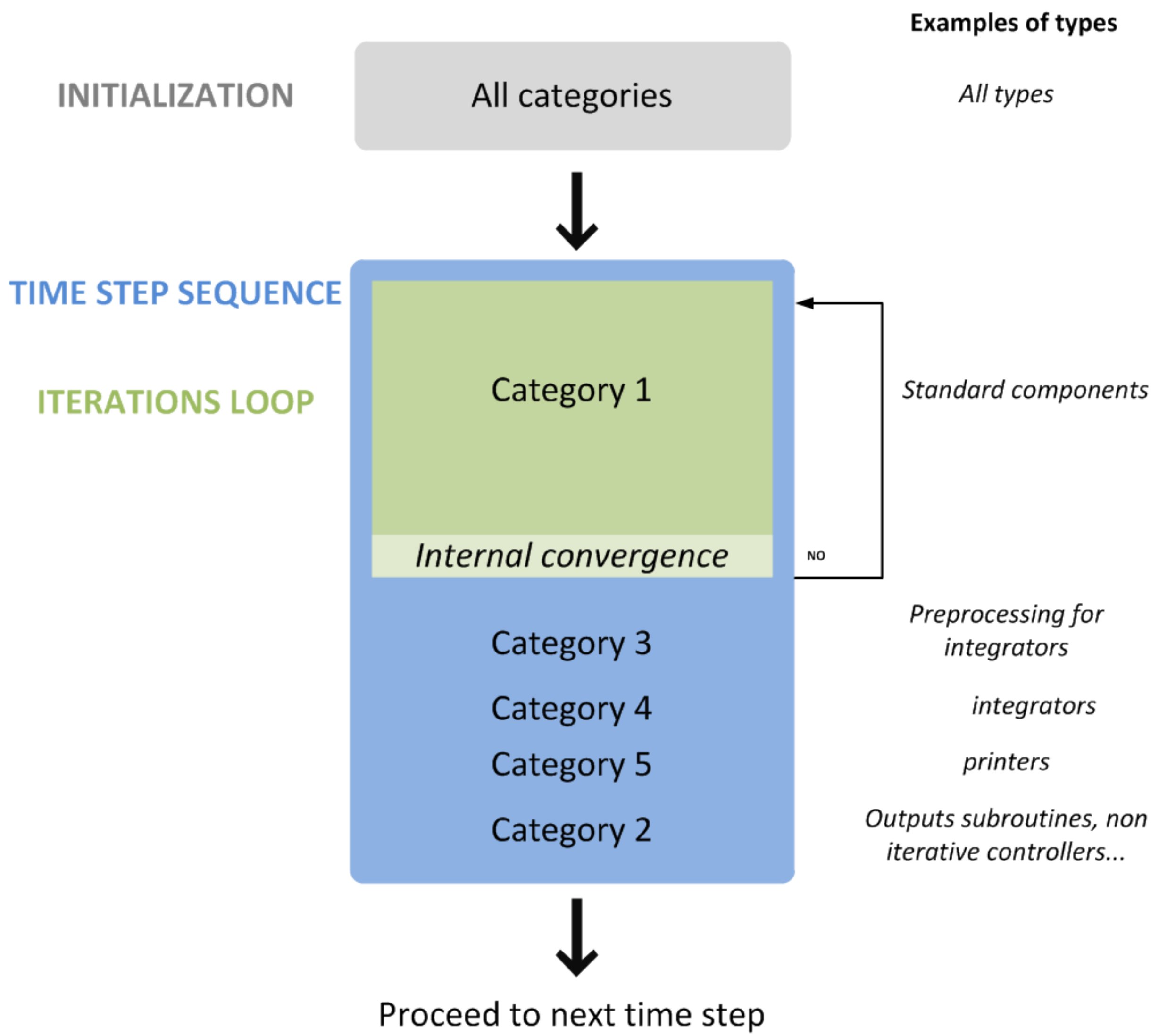
TRNSYS system = network of Types



TRNSYS solution methodology



How the kernel calls TRNSYS Types



Calling sequence for a standard Type

1. Version signing call

- Set type version

2. Initialization call

- Array sizing, memory allocation, file opening, parameter checking, ...

3. First call of a time step

- Perform initializations for time step for this type
- Get stored variable from previous time step
- Do standard call actions

4. Standard iteration call

- Get input values
- Perform calculations
- Set output values

5. Post convergence call

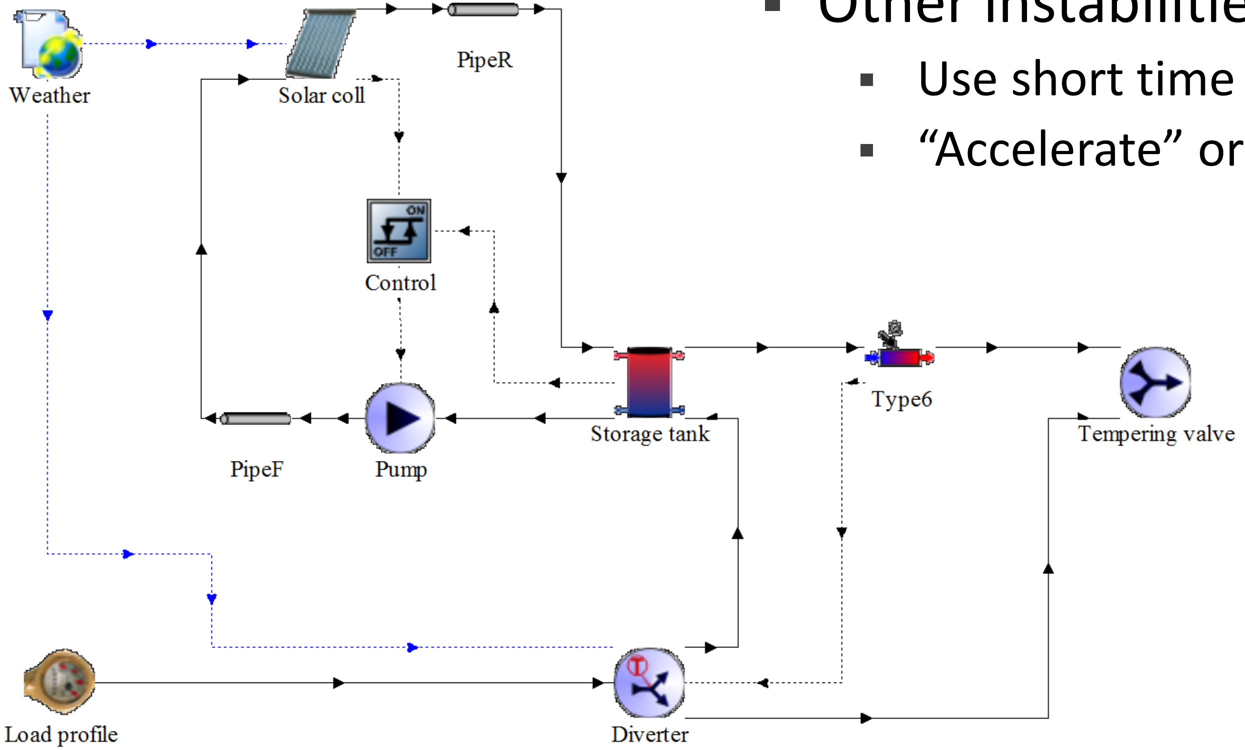
- Printing, integrating...
- Increment/reset counters, update stored variables

6. Last call of the simulation

- Close external data files
- Calculate summary information...

Successive substitution and oscillations…

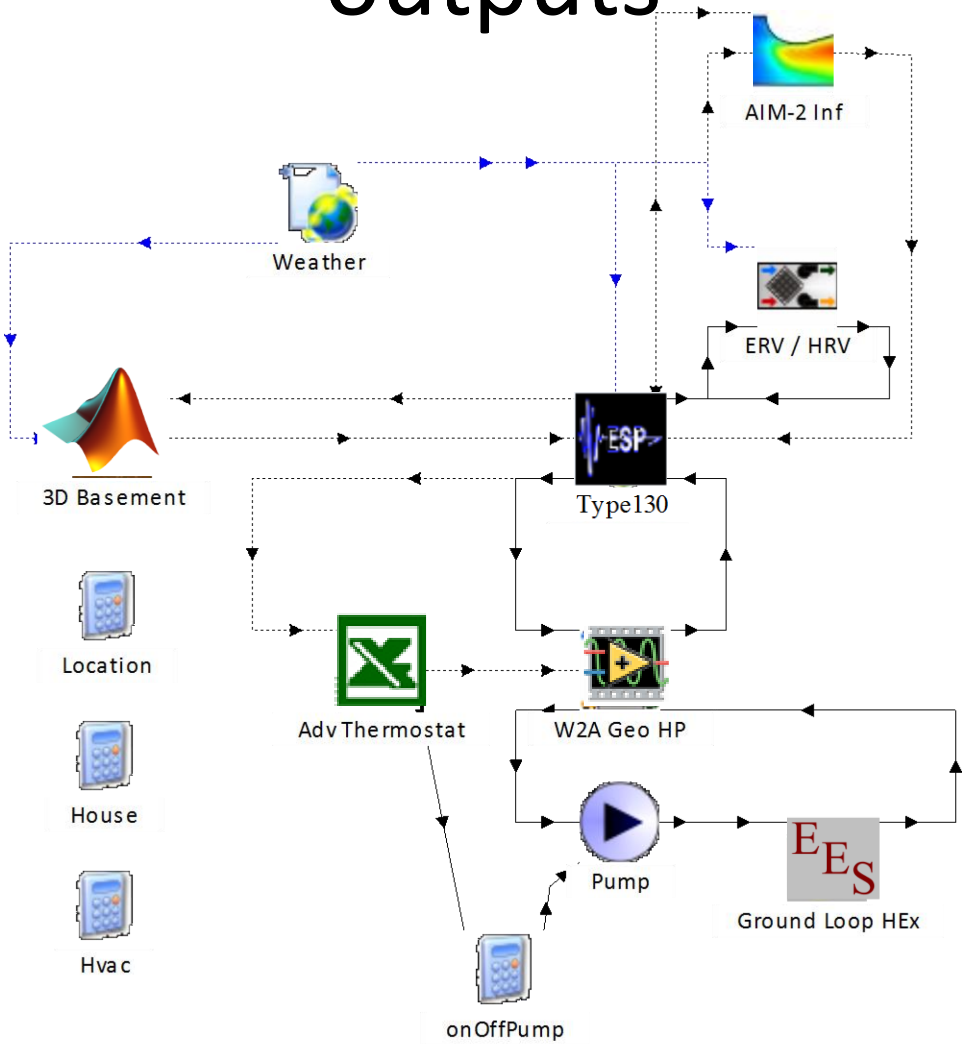
- Controllers (on/off cycles)
  - → NStick or replace (PLR approach)
- Algebraic loops (no mass)
  - → Add pipes/ storage
- Other instabilities
  - Use short time step
  - “Accelerate” or relaxation



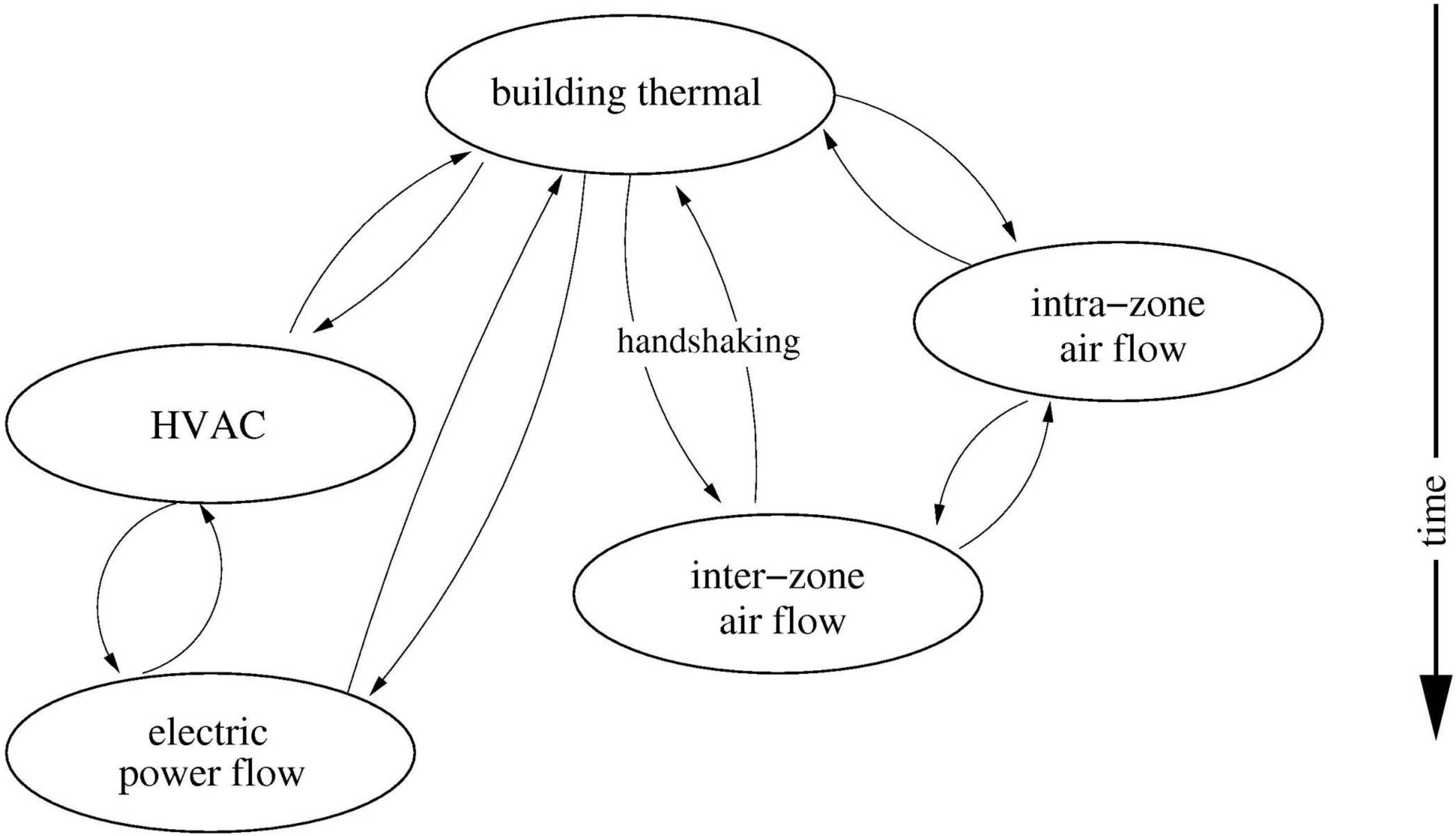
Conclusions

- TRNSYS components are input/output relationships
  - Instantaneous or differential equations
- Solver calls them successively until convergence is reached
- Convergence is not guaranteed
  - Several methods are possible to improve convergence
  - Significant limitation of TRNSYS, and its most powerful feature at the same time
    - TRNSYS makes no assumption on components (except that they will converge…)
    - No predefined “domains” or preferential solving order. The solver attempts to reach overall convergence
- Good or bad?
  - Compare writing a solar collector model in ESP-r vs. in TRNSYS
  - Compare solving a complex non-linear problem in EES or another equation-based program
  - One advantage: flexibility of programming / language / environment

TRNSYS provides inputs and expects outputs

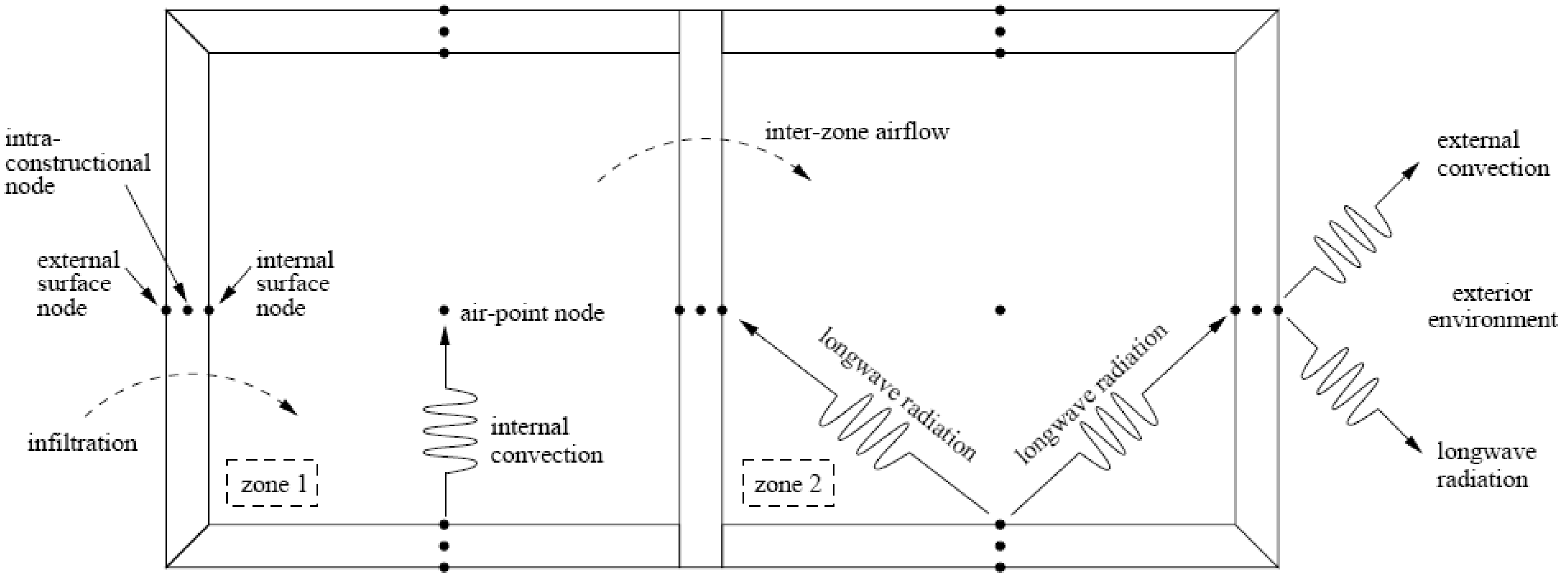


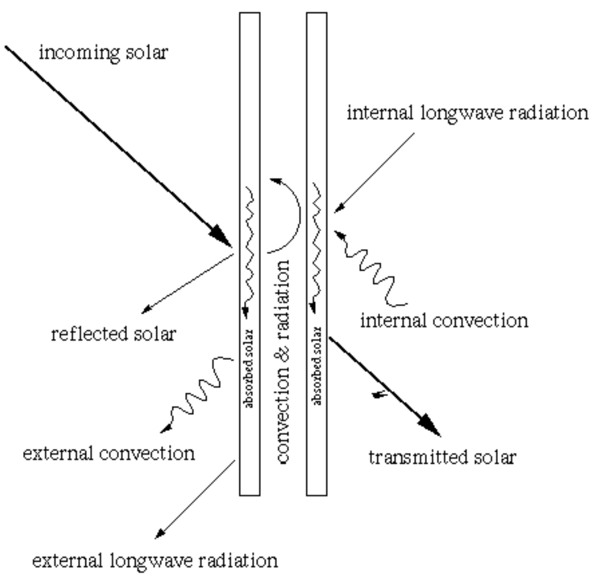
ESP-r's partitioned solution approach



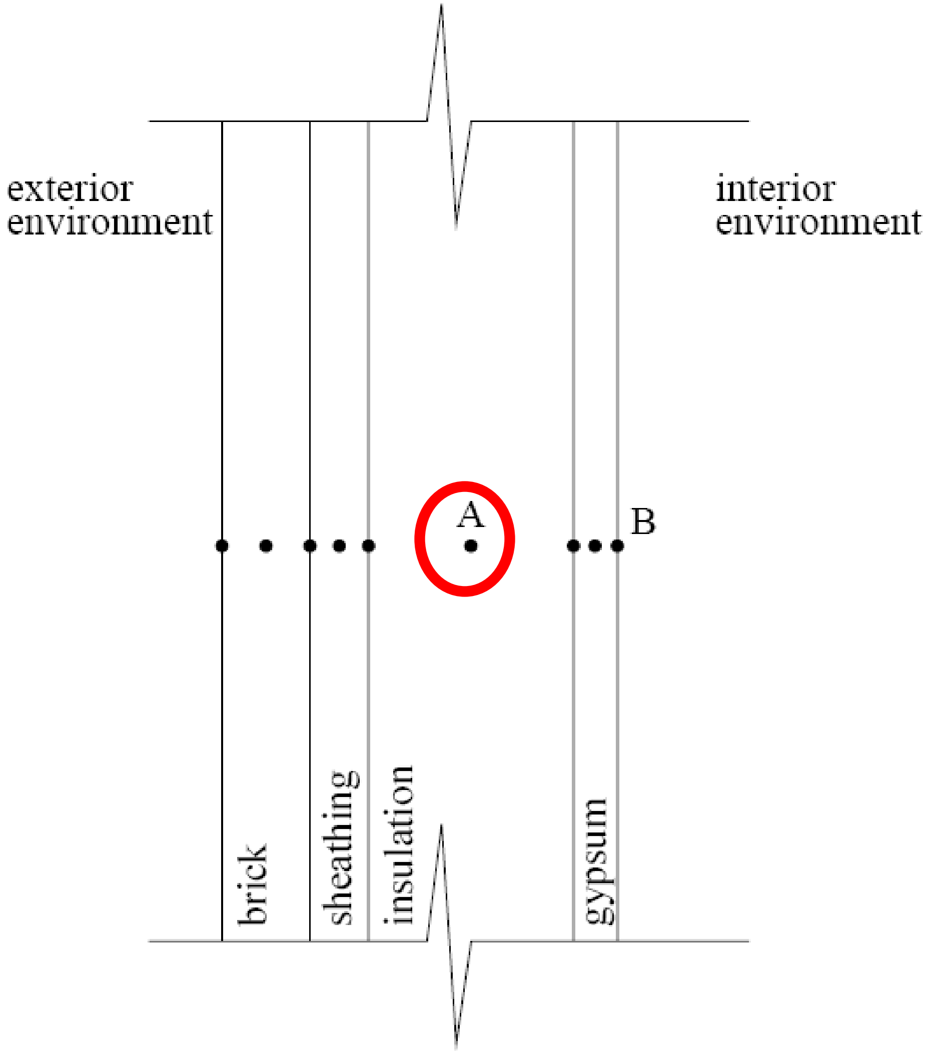
Building Thermal Domain

Relevant Heat and Mass Transfer Processes

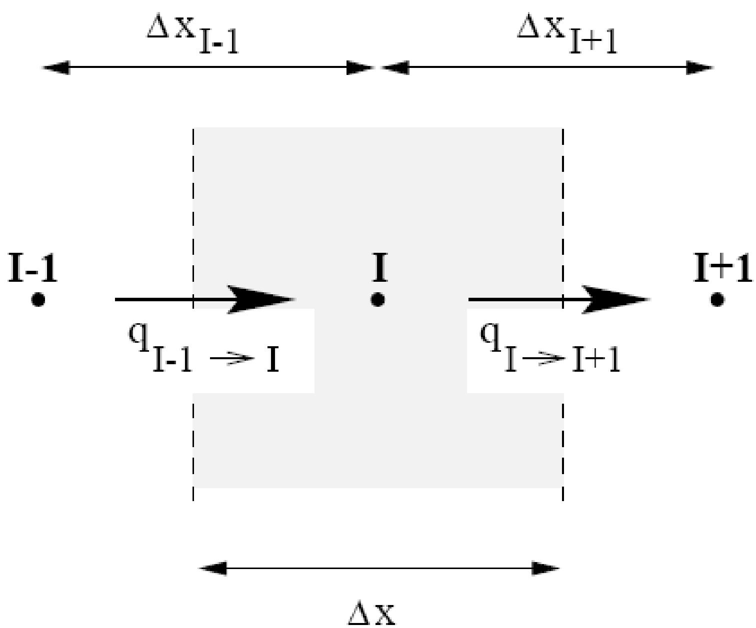




Discretize Envelope into Control Volumes (CV)



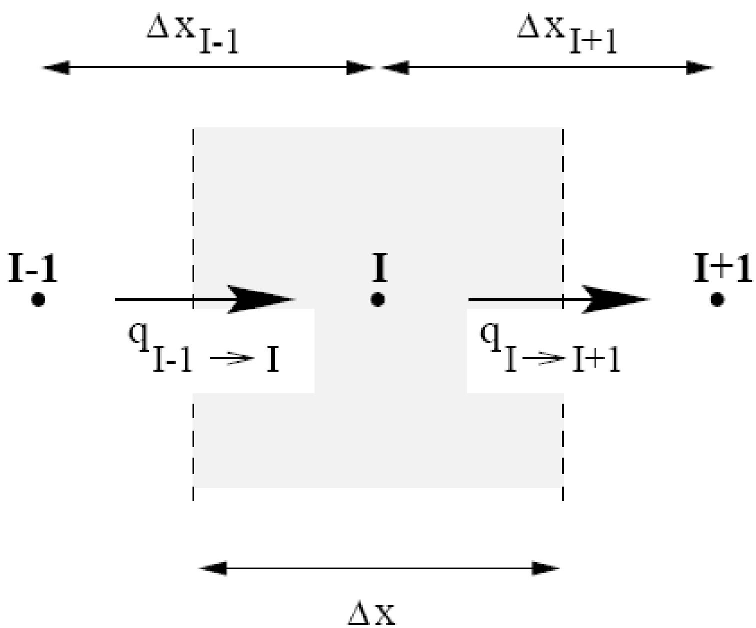
Form Heat Balances for Each CV: Intra-Constructional CV's



$$\begin{Bmatrix} \text{storage of} \\ \text{heat in CV} \end{Bmatrix} = \begin{Bmatrix} \text{net conduction} \\ \text{into CV} \end{Bmatrix} + \begin{Bmatrix} \text{source of heat} \\ \text{within CV} \end{Bmatrix}$$

$$\rho c_p \frac{\partial T}{\partial t} = -\frac{\partial q''_x}{\partial x} + q'''_{plant}$$

Integration Over Space and FD by Taylor Series Expansion



$$\int_{\Delta V} \rho c_p \frac{\partial T}{\partial t}\, dV = -\int_{\Delta V} \frac{\partial q''_x}{\partial x}\, dV + \int_{\Delta V} q'''_{plant}\, dV$$

$$(\rho c_p \Delta x \Delta y \Delta z)_I \frac{T_I^{t+\Delta t} - T_I^t}{\Delta t} = q_{I-1\to I} - q_{I\to I+1} + q_{plant}$$

$$q_{I-1\to I} \approx \frac{k_{I-1}\Delta y \Delta z}{\Delta x_{I-1}} (T_{I-1}^t - T_I^t)$$

$$q_{I\to I+1} \approx \frac{k_{I+1}\Delta y \Delta z}{\Delta x_{I+1}} (T_I^t - T_{I+1}^t)$$

Fully <u>explicit</u> form of discretized approximation:

$$\frac{(\rho c_p \Delta x \Delta y \Delta z)_I}{\Delta t}(T_I^{t+\Delta t} - T_I^t) = \frac{k_{I-1}\Delta y \Delta z}{\Delta x_{I-1}}(T_{I-1}^t - T_I^t) - \frac{k_{I+1}\Delta y \Delta z}{\Delta x_{I+1}}(T_I^t - T_{I+1}^t) + q_{plant}^t$$

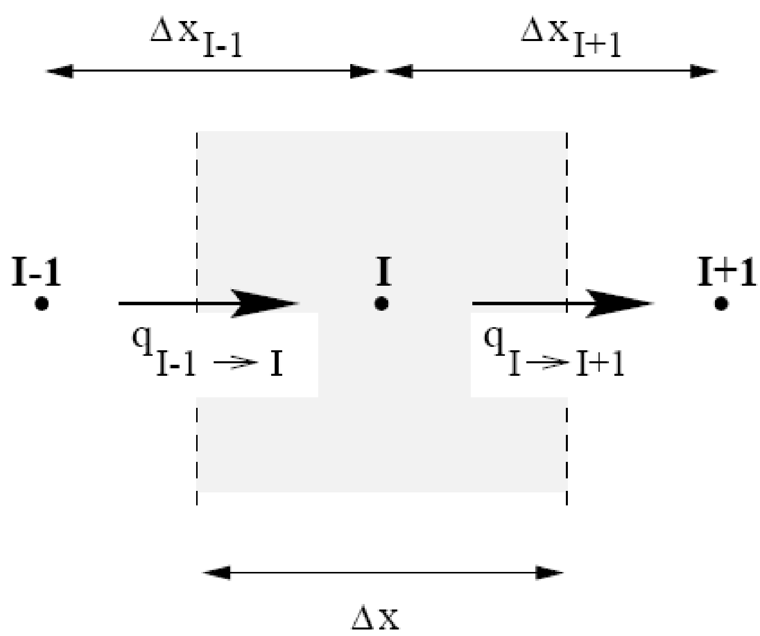
Fully <u>implicit</u> form of discretized approximation:

$$\frac{(\rho c_p \Delta x \Delta y \Delta z)_I}{\Delta t}(T_I^{t+\Delta t} - T_I^t) = \frac{k_{I-1}\Delta y \Delta z}{\Delta x_{I-1}}(T_{I-1}^{t+\Delta t} - T_I^{t+\Delta t}) - \frac{k_{I+1}\Delta y \Delta z}{\Delta x_{I+1}}(T_I^{t+\Delta t} - T_{I+1}^{t+\Delta t}) + q_{plant}^{t+\Delta t}$$

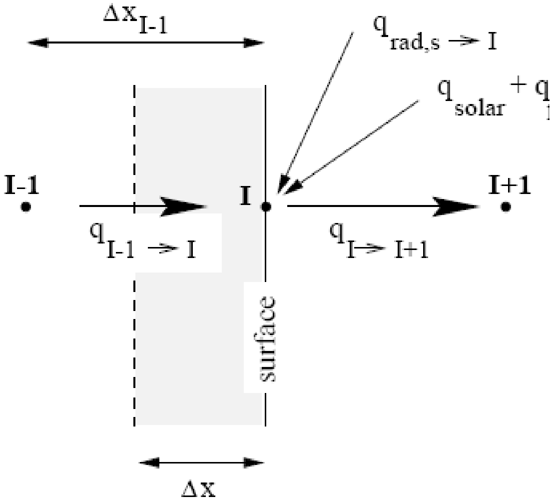
Crank-Nicholson difference formulation for intra-constructional CV's:

$$\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}+\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}+\frac{k_{I+1}}{\Delta x\Delta x_{I+1}}\right]T_I^{t+\Delta t}-\left[\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}\right]T_{I-1}^{t+\Delta t}-\left[\frac{k_{I+1}}{\Delta x\Delta x_{I+1}}\right]T_{I+1}^{t+\Delta t}-\frac{q_{plant}^{t+\Delta t}}{\Delta x\Delta y\Delta z}$$

$$=\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}-\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}-\frac{k_{I+1}}{\Delta x\Delta x_{I+1}}\right]T_I^{t}+\left[\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}\right]T_{I-1}^{t}+\left[\frac{k_{I+1}}{\Delta x\Delta x_{I+1}}\right]T_{I+1}^{t}+\frac{q_{plant}^{t}}{\Delta x\Delta y\Delta z}$$



Crank-Nicholson difference formulation for internal surface CV's:



$$\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}+\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}+\frac{h_{c,I}^{t+\Delta t}}{\Delta x}+\frac{\sum_{s=1}^{N}h_{r,s\to I}^{t+\Delta t}}{\Delta x}\right]T_I^{t+\Delta t}-\left[\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}\right]T_{I-1}^{t+\Delta t}$$

$$-\left[\frac{h_{c,I}^{t+\Delta t}}{\Delta x}\right]T_{I+1}^{t+\Delta t}-\frac{\sum_{s=1}^{N}h_{r,s\to I}^{t+\Delta t}T_s^{t+\Delta t}}{\Delta x}-\frac{q_{solar,I}^{t+\Delta t}}{\Delta x\Delta y\Delta z}-\frac{q_{cas-rad,I}^{t+\Delta t}}{\Delta x\Delta y\Delta z}-\frac{q_{plant,I}^{t+\Delta t}}{\Delta x\Delta y\Delta z}$$

$$=\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}-\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}-\frac{h_{c,I}^{t}}{\Delta x}-\frac{\sum_{s=1}^{N}h_{r,s\to I}^{t}}{\Delta x}\right]T_I^{t}+\left[\frac{k_{I-1}}{\Delta x\Delta x_{I-1}}\right]T_{I-1}^{t}$$

$$+\left[\frac{h_{c,I}^{t}}{\Delta x}\right]T_{I+1}^{t}+\frac{\sum_{s=1}^{N}h_{r,s\to I}^{t}T_s^{t}}{\Delta x}+\frac{q_{solar,I}^{t}}{\Delta x\Delta y\Delta z}+\frac{q_{cas-rad,I}^{t}}{\Delta x\Delta y\Delta z}+\frac{q_{plant,I}^{t}}{\Delta x\Delta y\Delta z}$$

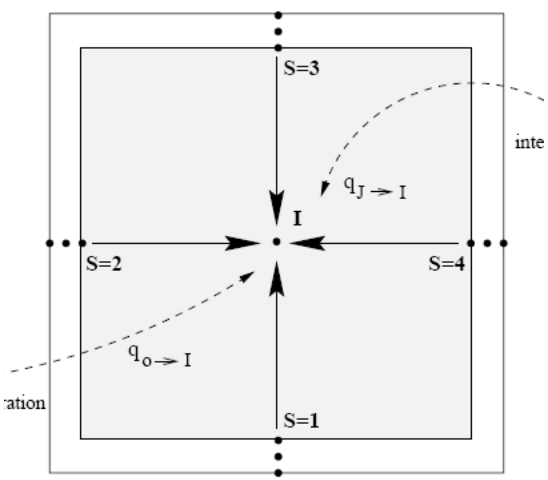
Crank-Nicholson difference formulation for zone air CV's:

$$\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}+\frac{\sum_{s=1}^{N} h_{c,s}^{t+\Delta t}A_s}{VOL_{room}}+\frac{\sum_{J=1}^{M}\dot m_{J\to I}^{t+\Delta t}c_p}{VOL_{room}}+\frac{\dot m_{o\to I}^{t+\Delta t}c_p}{VOL_{room}}\right]T_I^{t+\Delta t}-\left[\frac{\sum_{s=1}^{N} h_{c,s}^{t+\Delta t}A_s T_s^{t+\Delta t}}{VOL_{room}}\right]$$

$$-\left[\frac{\sum_{J=1}^{M}\dot m_{J\to I}^{t+\Delta t}c_p T_J^{t+\Delta t}}{VOL_{room}}\right]-\left[\frac{\dot m_{o\to I}^{t+\Delta t}c_p T_o^{t+\Delta t}}{VOL_{room}}\right]-\frac{q_{cas-conv,I}^{t+\Delta t}}{VOL_{room}}-\frac{q_{plant,I}^{t+\Delta t}}{VOL_{room}}$$

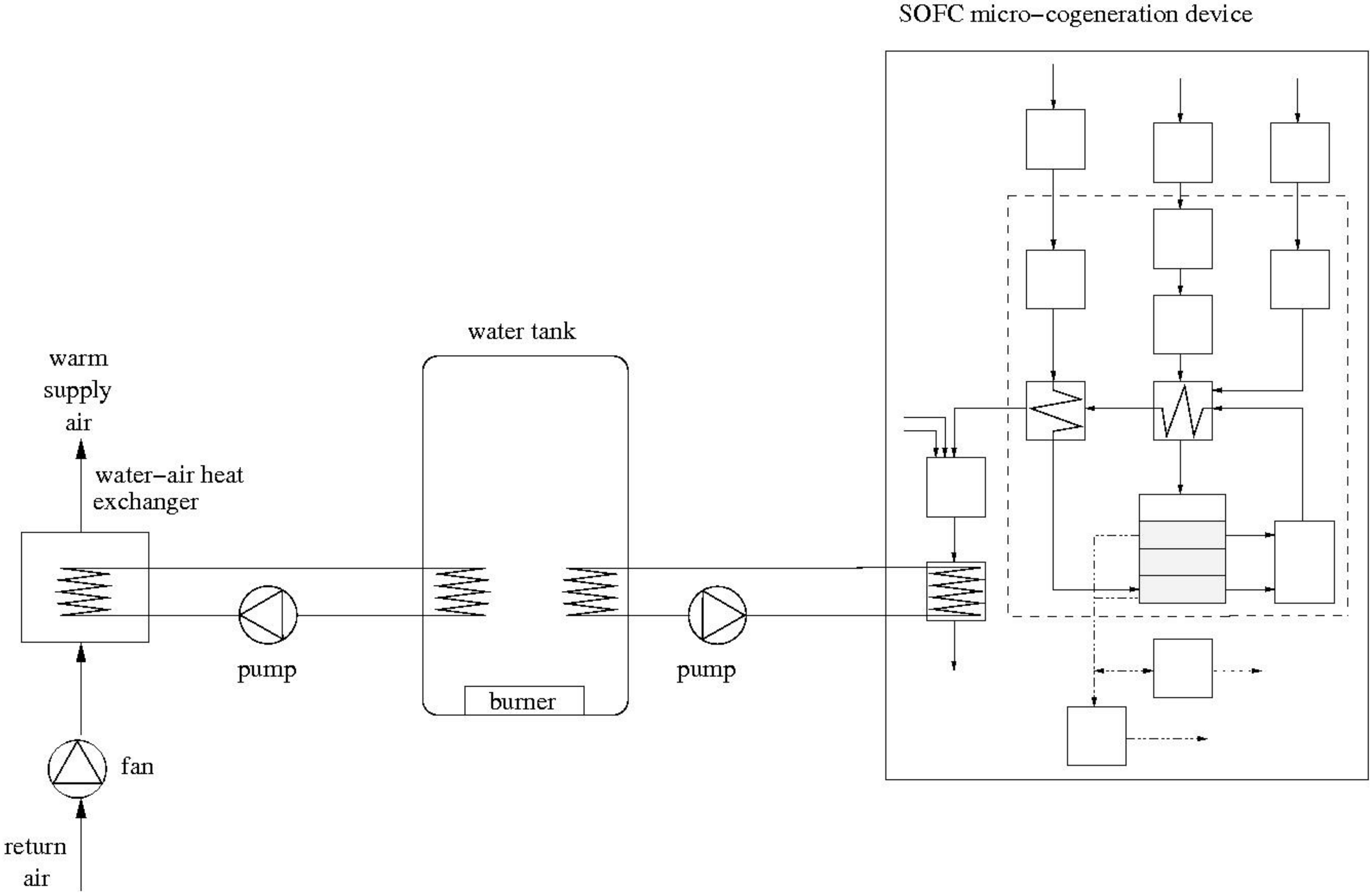
$$=\left[\frac{2\cdot(\rho c_p)_I}{\Delta t}-\frac{\sum_{s=1}^{N} h_{c,s}^{t}A_s}{VOL_{room}}-\frac{\sum_{J=1}^{M}\dot m_{J\to I}^{t}c_p}{VOL_{room}}-\frac{\dot m_{o\to I}^{t}c_p}{VOL_{room}}\right]T_I^{t}+\left[\frac{\sum_{s=1}^{N} h_{c,s}^{t}A_s T_s^{t}}{VOL_{room}}\right]$$

$$+\left[\frac{\sum_{J=1}^{M}\dot m_{J\to I}^{t}c_p T_J^{t}}{VOL_{room}}\right]+\left[\frac{\dot m_{o\to I}^{t}c_p T_o^{t}}{VOL_{room}}\right]+\frac{q_{cas-conv,I}^{t}}{VOL_{room}}+\frac{q_{plant,I}^{t}}{VOL_{room}}$$

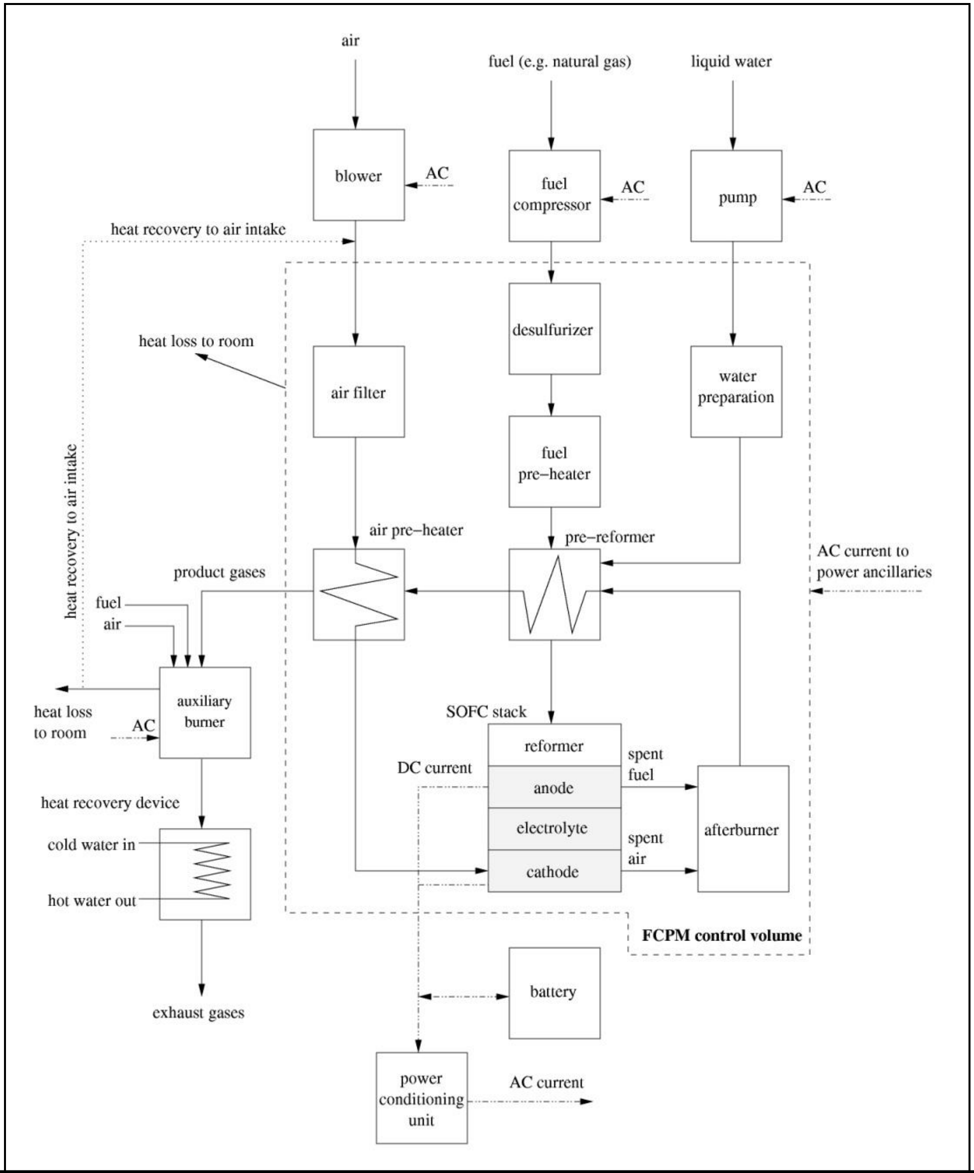


$$
\left[\begin{array}{cccccccccccccccccccc}
a_{1,1} & a_{1,2} & & & & & & & & & & & & & & & & & & \\
a_{2,1} & a_{2,2} & a_{2,3} & & & & & & & & & & & & & & & & & a_{2,20} \\
 & a_{3,2} & a_{3,3} & & & a_{3,6} & & & a_{3,9} & & & a_{3,12} & & & a_{3,15} & & & a_{3,18} & a_{3,19} & \\
 & & & a_{4,4} & a_{4,5} & & & & & & & & & & & & & & & \\
 & & & a_{5,4} & a_{5,5} & a_{5,6} & & & & & & & & & & & & & & \\
 & & a_{6,3} & & a_{6,5} & a_{6,6} & & & a_{6,9} & & & a_{6,12} & & & a_{6,15} & & & a_{6,18} & a_{6,19} & \\
 & & & & & & a_{7,7} & a_{7,8} & & & & & & & & & & & & \\
 & & & & & & a_{8,7} & a_{8,8} & a_{8,9} & & & & & & & & & & & \\
 & & a_{9,3} & & & a_{9,6} & & a_{9,8} & a_{9,9} & & & a_{9,12} & & & a_{9,15} & & & a_{9,18} & a_{9,19} & \\
 & & & & & & & & & a_{10,10} & a_{10,11} & & & & & & & & & \\
 & & & & & & & & & a_{11,10} & a_{11,11} & a_{11,12} & & & & & & & & \\
 & & a_{12,3} & & & a_{12,6} & & & a_{12,6} & & a_{12,11} & a_{12,12} & & & a_{12,15} & & & a_{12,18} & a_{12,19} & \\
 & & & & & & & & & & & & a_{13,13} & a_{13,14} & & & & & & \\
 & & & & & & & & & & & & a_{14,13} & a_{14,14} & a_{14,15} & & & & & \\
 & & a_{15,3} & & & a_{15,6} & & & a_{15,9} & & & a_{15,12} & & a_{15,14} & a_{15,15} & & & a_{15,18} & a_{15,19} & \\
 & & & & & & & & & & & & & & & a_{16,16} & a_{16,17} & & & \\
 & & & & & & & & & & & & & & & a_{17,16} & a_{17,17} & a_{17,18} & & \\
 & & a_{18,3} & & & a_{18,6} & & & a_{18,9} & & & a_{18,12} & & & a_{18,15} & & a_{18,17} & a_{18,18} & a_{18,19} & \\
 & & a_{19,3} & & & a_{19,6} & & & a_{19,9} & & & a_{19,12} & & & a_{19,15} & & & a_{19,18} & a_{19,19} &
\end{array}\right]
\times
\begin{bmatrix} T_{A,1} \\ T_{A,2} \\ T_{A,s} \\ T_{B,1} \\ T_{B,2} \\ T_{B,s} \\ T_{C,1} \\ T_{C,2} \\ T_{C,s} \\ T_{D,1} \\ T_{D,2} \\ T_{D,s} \\ T_{E,1} \\ T_{E,2} \\ T_{E,s} \\ T_{F,1} \\ T_{F,2} \\ T_{F,s} \\ T_a \\ q_{plant} \end{bmatrix}
=
\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \\ z_9 \\ z_{10} \\ z_{11} \\ z_{12} \\ z_{13} \\ z_{14} \\ z_{15} \\ z_{16} \\ z_{17} \\ z_{18} \\ z_{19} \end{bmatrix}
$$

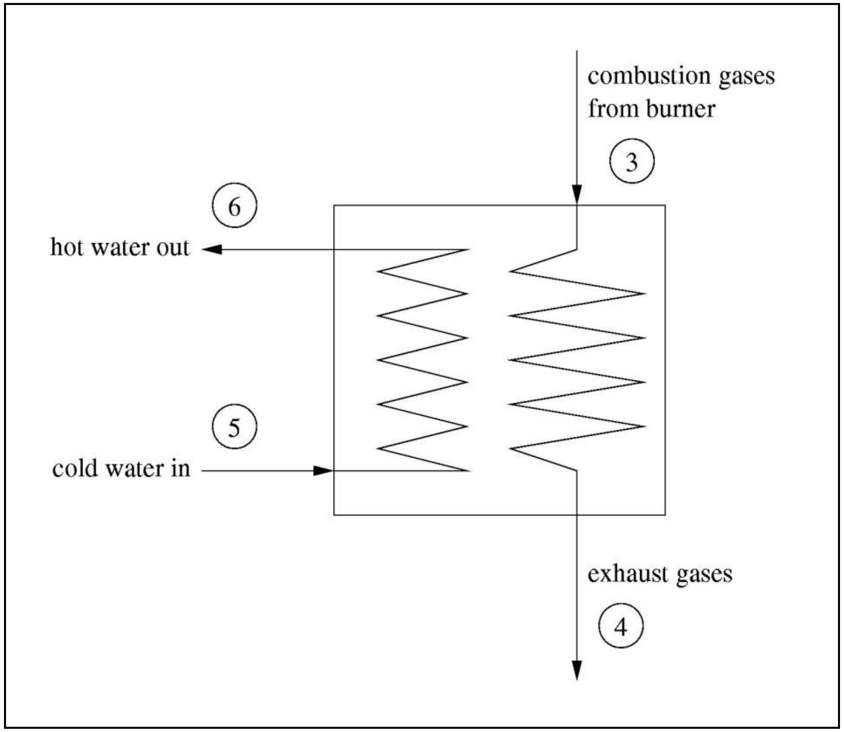
Plant Network



Plant Component



CV Energy Balances

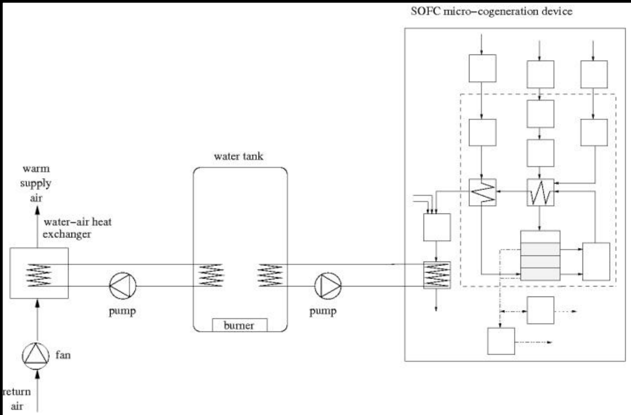


$$q_{HX} = (UA)_{eff} \cdot \frac{(T_3 - T_6) - (T_4 - T_5)}{\ln\left(\frac{T_3 - T_6}{T_4 - T_5}\right)}$$

$$T_4 = \left\{ \frac{1 - \frac{(\dot{N}\hat{c}_P)_3}{(\dot{N}\hat{c}_P)_5}}{e^{\left[(UA)_{eff} \cdot \left(\frac{1}{(\dot{N}\hat{c}_P)_3} - \frac{1}{(\dot{N}\hat{c}_P)_5}\right)\right]} - \frac{(\dot{N}\hat{c}_P)_3}{(\dot{N}\hat{c}_P)_5}} \right\} \cdot T_3 + \left\{ \frac{e^{\left[(UA)_{eff} \cdot \left(\frac{1}{(\dot{N}\hat{c}_P)_3} - \frac{1}{(\dot{N}\hat{c}_P)_5}\right)\right]} - 1}{e^{\left[(UA)_{eff} \cdot \left(\frac{1}{(\dot{N}\hat{c}_P)_3} - \frac{1}{(\dot{N}\hat{c}_P)_5}\right)\right]} - \frac{(\dot{N}\hat{c}_P)_3}{(\dot{N}\hat{c}_P)_5}} \right\} \cdot T_5$$

Energy balance for control volume representing gas contained in heat exchanger:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \end{bmatrix} \times \begin{bmatrix} T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} z_1 \end{bmatrix}$$



SOFC

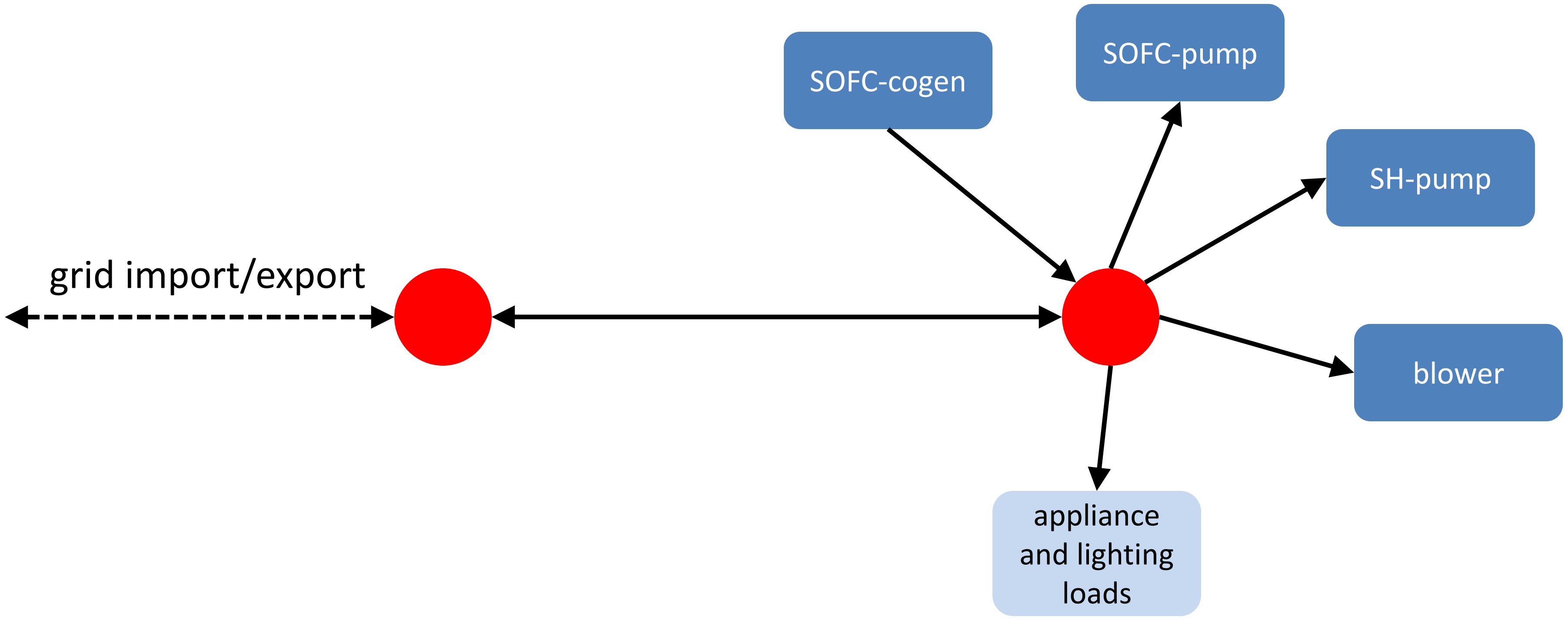
tank

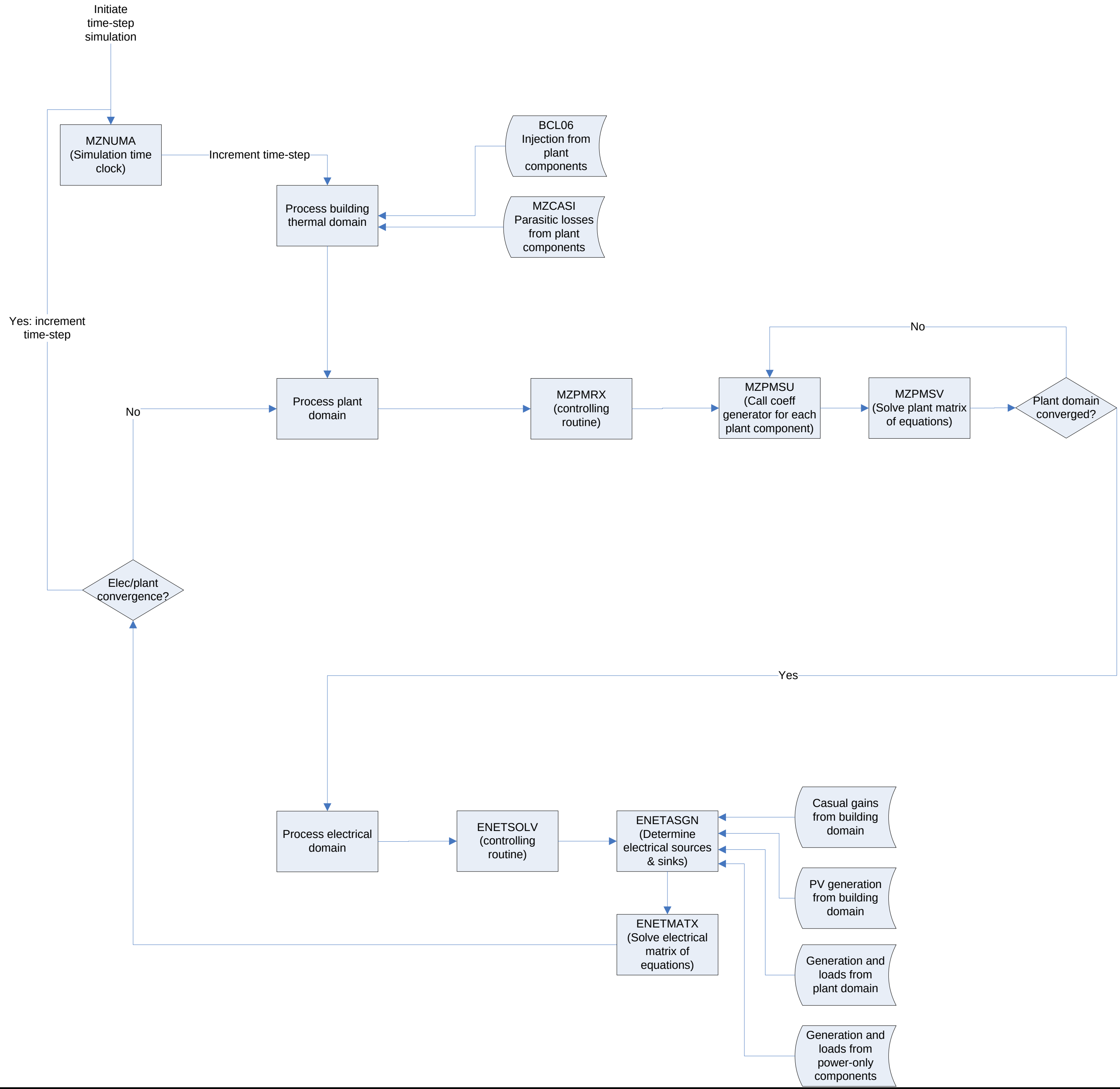
SH-pump

water-air HX

$$
\begin{bmatrix}
a_{1,1} \\
& a_{2,2} \\
&& a_{3,3} \\
&&& a_{4,4} \\
&&& a_{5,4} & a_{5,5} \\
&&&& a_{6,5} & a_{6,6} & a_{6,7} &&&&& && a_{6,14} \\
&&&& a_{7,5} && a_{7,7} \\
&&&&& & a_{8,7} & a_{8,8} \\
&&&&& && a_{9,8} & a_{9,9} \\
&&&&& &&&& a_{10,10} \\
&&&&& &&&&& a_{11,11} \\
&&&&& &&&&& & a_{12,12} \\
&&&&& &&&&& && a_{13,13} \\
&&&&& &&&&& &&& a_{14,14} &&&& a_{14,18} \\
&&&&& a_{15,6} &&&&& &&&& a_{15,15} &&&&& &&&& a_{15,24} \\
&&&&& &&&&& &&&&& a_{16,16} \\
&&&&& &&&&& &&&&& a_{17,16} & a_{17,17} \\
&&&&& &&&&& &&&&& && a_{18,18} & a_{18,19} \\
&&&&& &&&&& &&&& a_{19,15} &&&& a_{19,19} \\
&&&&& &&&&& &&&&& &&&& a_{20,20} & a_{20,21} \\
&&&&& &&&&& &&&& a_{21,15} &&&&& & a_{21,21} \\
&&&&& &&&&& &&&&& &&&&& & a_{22,22} & a_{22,23} & a_{22,24} \\
&&&&& &&&&& &&&&& &&&&& & a_{23,22} & a_{23,23} && a_{23,25} \\
&&&&& &&&&& &&&&& &&&& a_{24,20} && a_{24,22} && a_{24,24} \\
&&&&& &&&&& &&&&& &&&&& &&&& a_{25,25}
\end{bmatrix}
\times
\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \\ T_{10} \\ T_{11} \\ T_{12} \\ T_{13} \\ T_{14} \\ T_{15} \\ T_{16} \\ T_{17} \\ T_{18} \\ T_{19} \\ T_{20} \\ T_{21} \\ T_{22} \\ T_{23} \\ T_{24} \\ T_{25} \end{bmatrix}
=
\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \\ z_9 \\ z_{10} \\ z_{11} \\ z_{12} \\ z_{13} \\ z_{14} \\ z_{15} \\ z_{16} \\ z_{17} \\ z_{18} \\ z_{19} \\ z_{20} \\ z_{21} \\ z_{22} \\ z_{23} \\ z_{24} \\ z_{25} \end{bmatrix}
$$

Electrical Domain





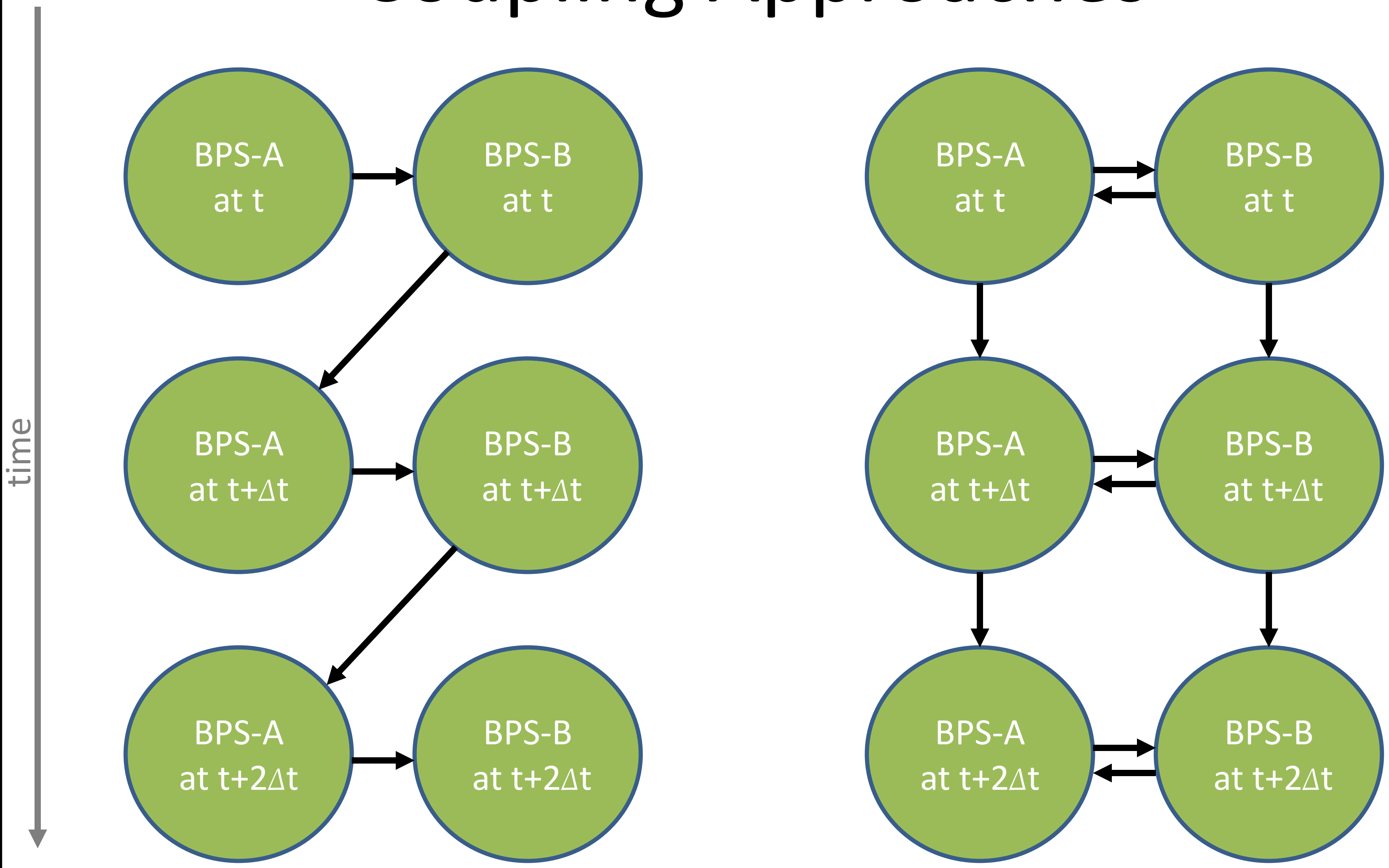
Initiate time-step simulation
MZNUMA (Simulation time clock)
Increment time-step
Process building thermal domain
BCL06 Injection from plant components
MZCASI Parasitic losses from plant components
Yes: increment time-step
No
Process plant domain
MZPMRX (controlling routine)
MZPMSU (Call coeff generator for each plant component)
MZPMSV (Solve plant matrix of equations)
Plant domain converged?
No
Elec/plant convergence?
Yes
Process electrical domain
ENETSOLV (controlling routine)
ENETASGN (Determine electrical sources & sinks)
Casual gains from building domain
PV generation from building domain
Generation and loads from plant domain
Generation and loads from power-only components
ENETMATX (Solve electrical matrix of equations)

ESP-r & TRNSYS Co-Simulation

Design Approach

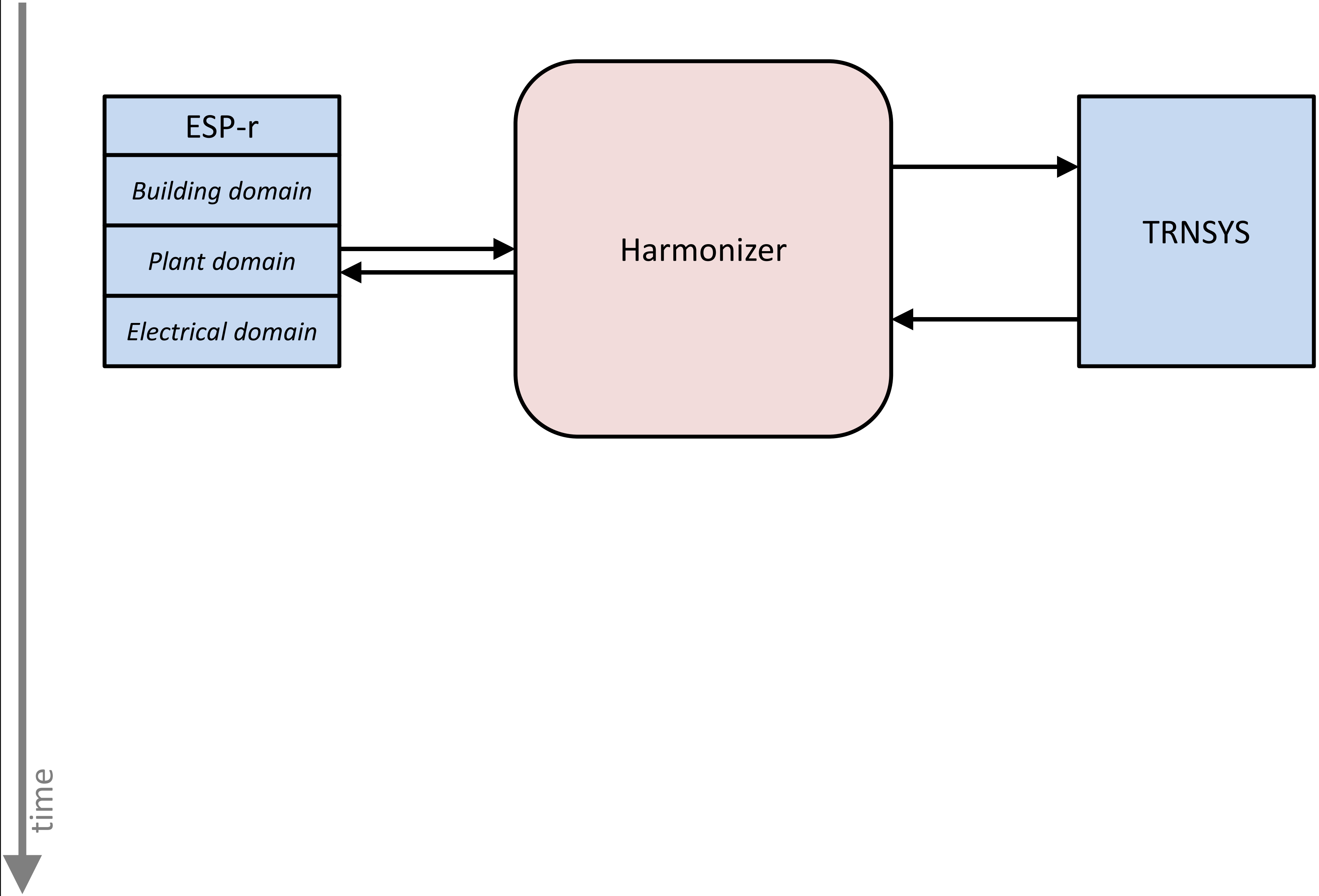
- Middleware:
  - Called the *Harmonizer*.
  - Controls coupling between ESP-r and TRNSYS.
  - Determines convergence.
  - Manages marching through time.
  - Ensures synchronization.
- ESP-r and TRNSYS:
  - Encapsulated as shared libraries (DLL's).
  - Simulations proceed as separate threads.
  - Communicate through Harmonizer.

Coupling Approaches

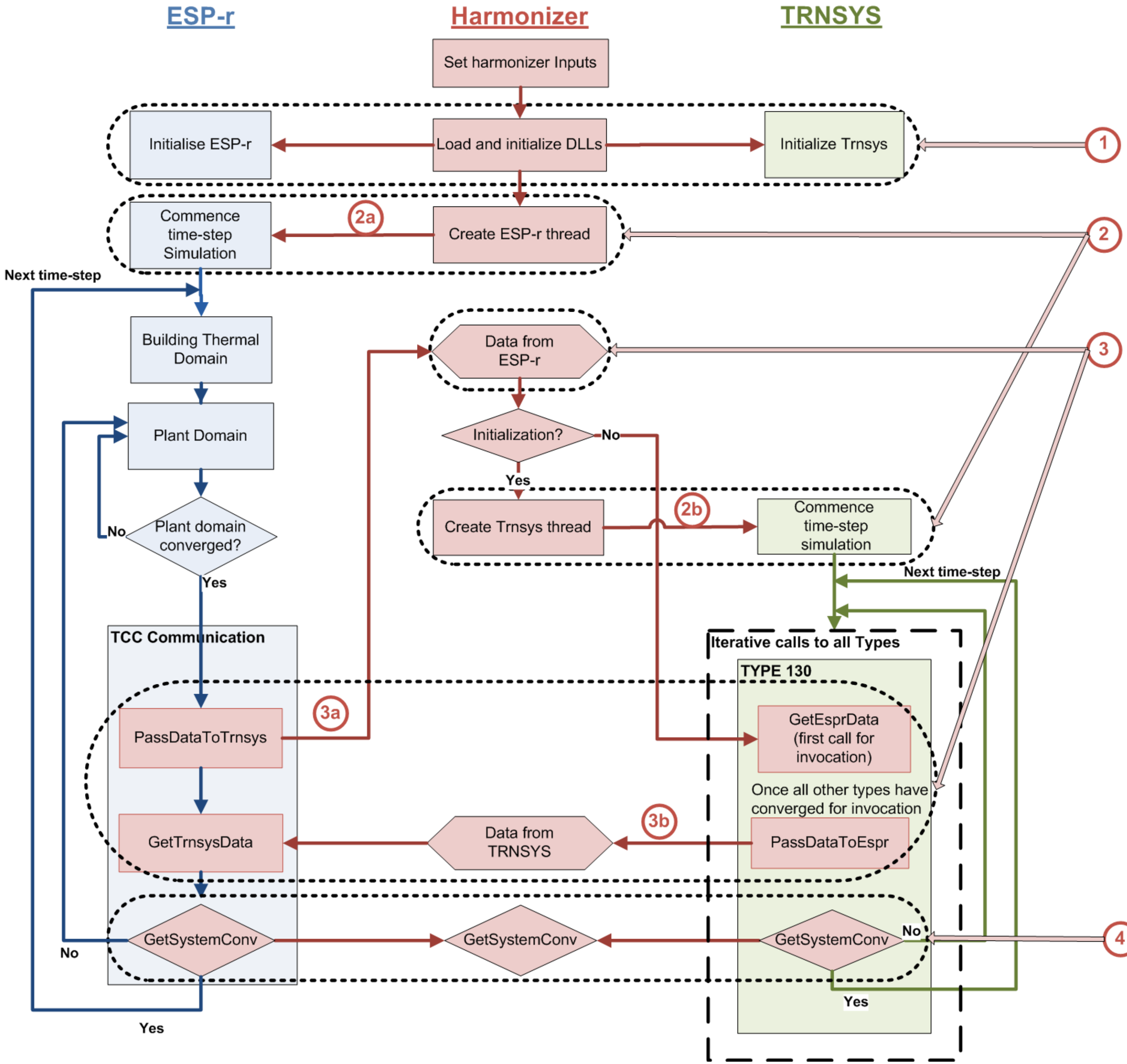


loose coupling (aka ping-pong)

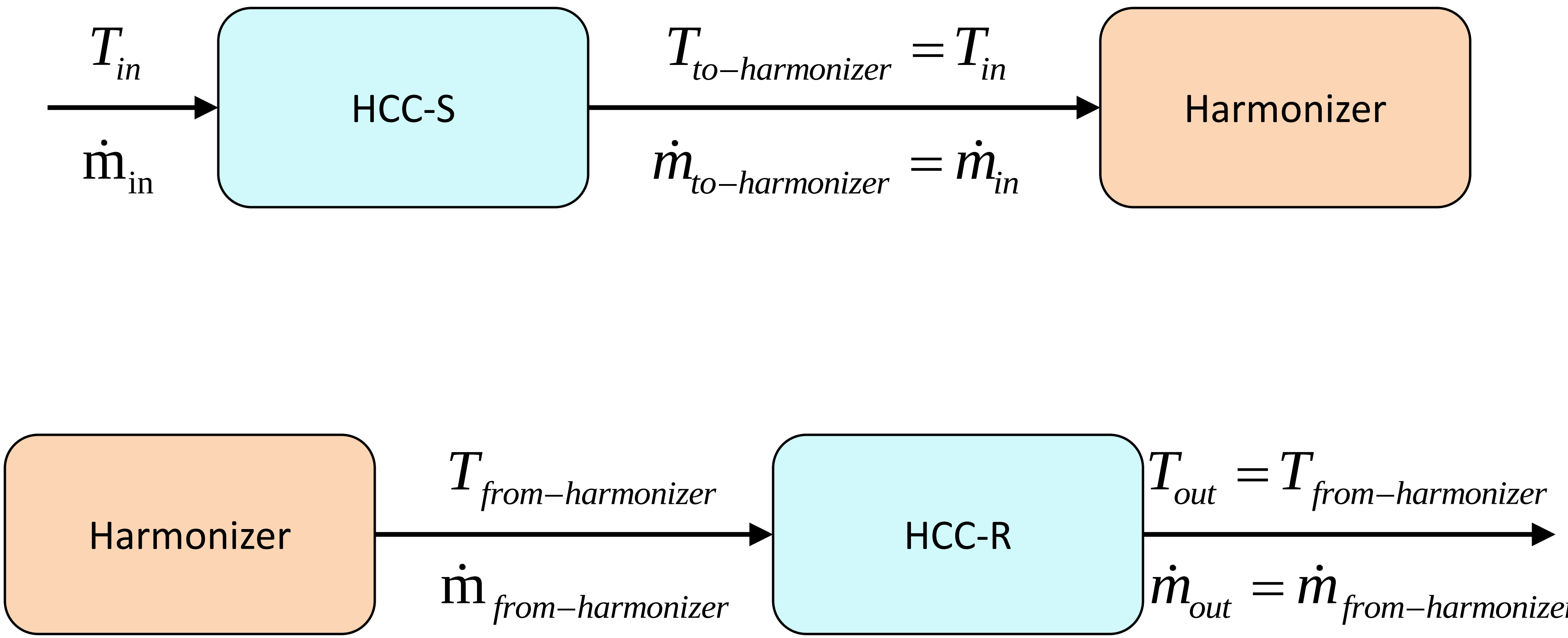
strong coupling (aka onion)

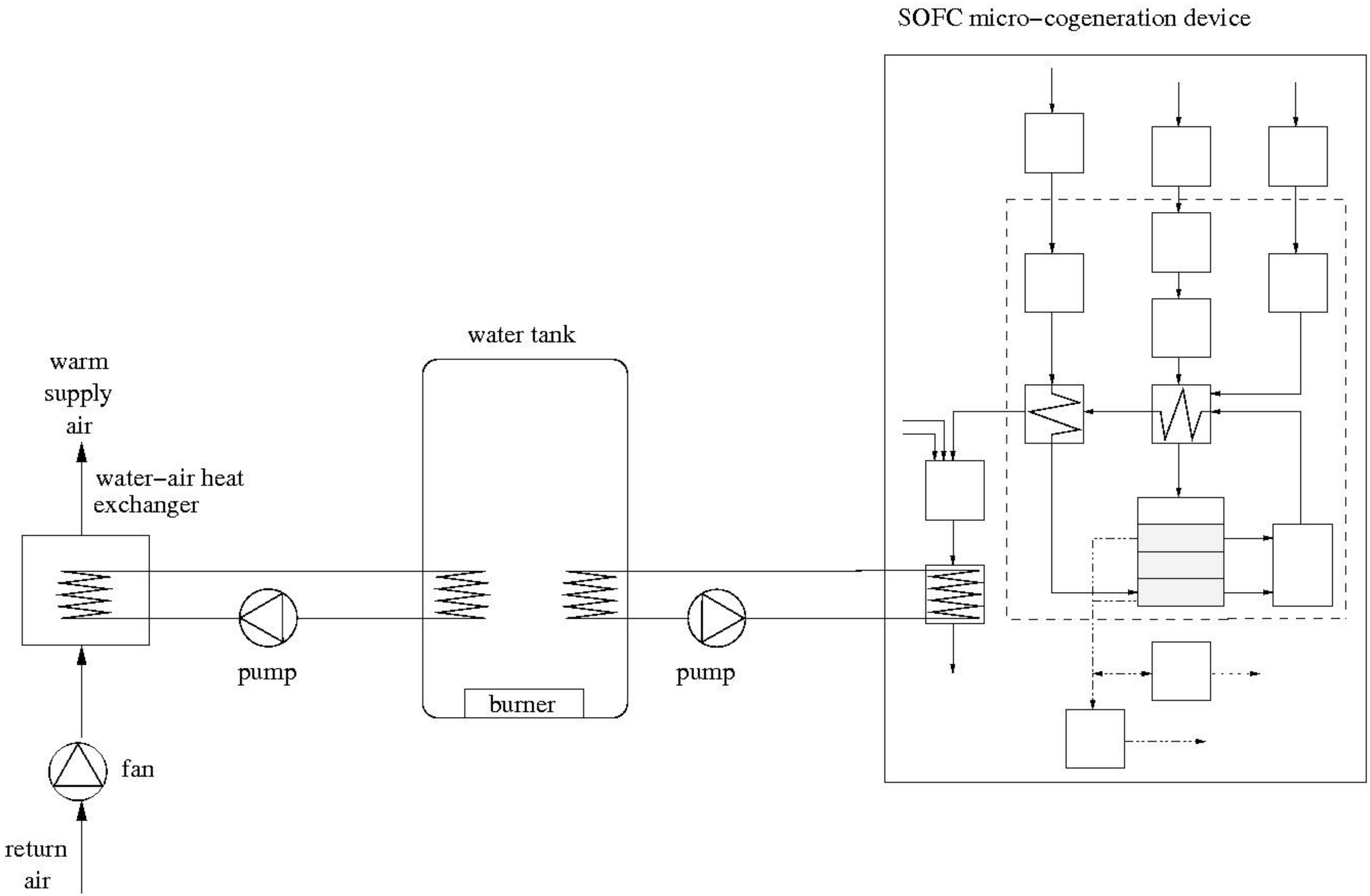


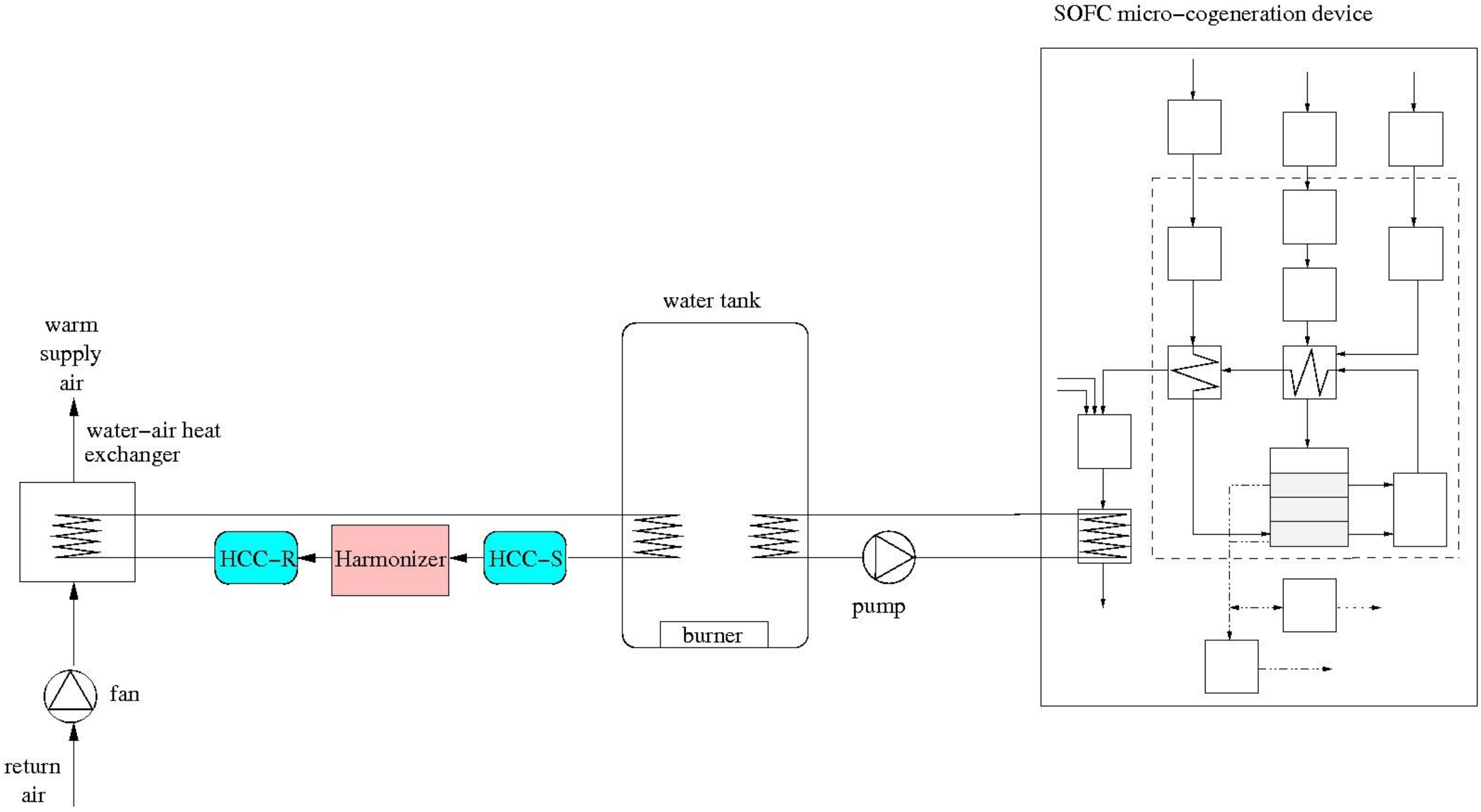
ESP-r
Building domain
Plant domain
Electrical domain
Harmonizer
TRNSYS
time

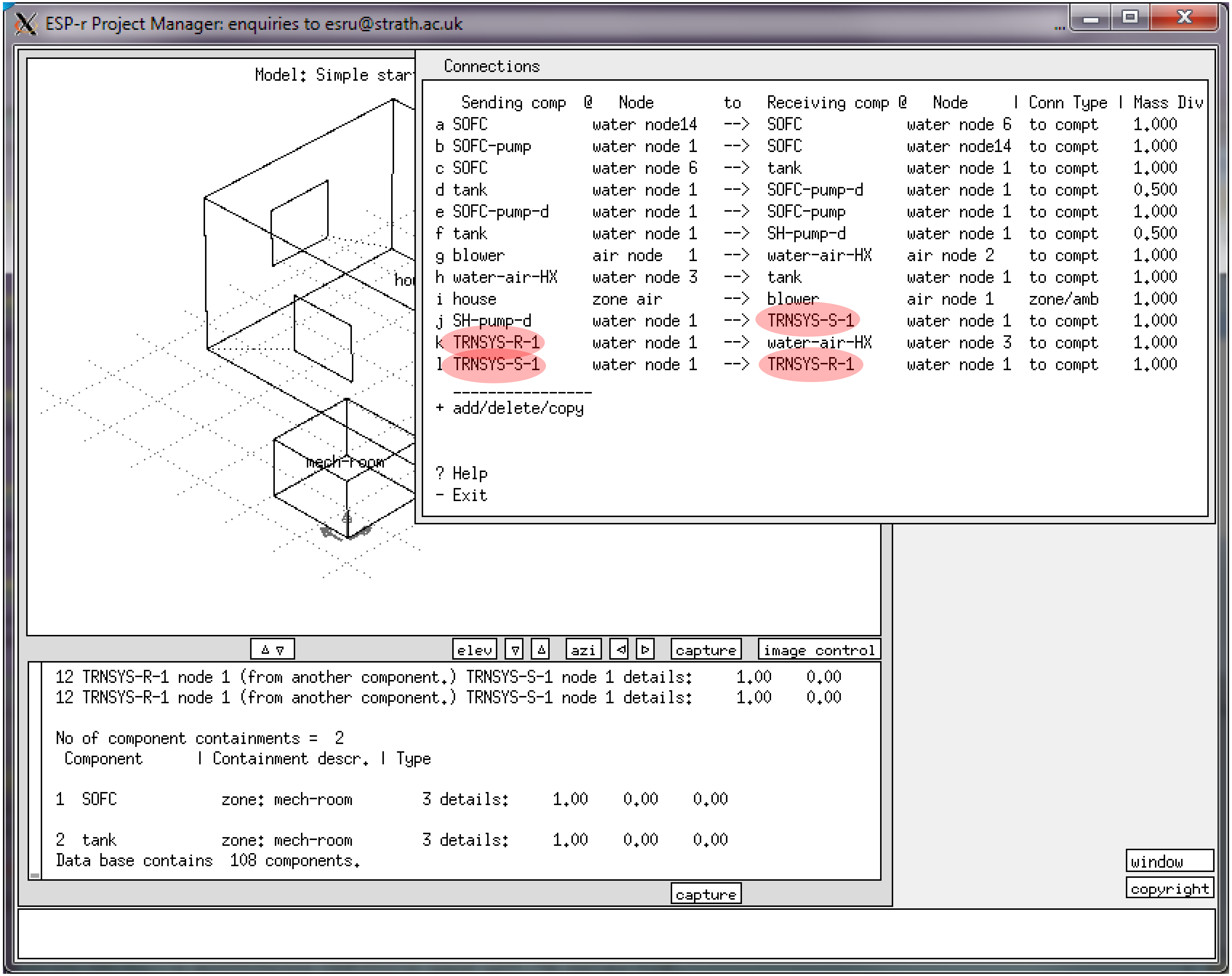

ESP-r
Harmonizer
TRNSYS
Set harmonizer Inputs
Initialise ESP-r
Load and initialize DLLs
Initialize Trnsys
1
Commence time-step Simulation
2a
Create ESP-r thread
2
Next time-step
Building Thermal Domain
Data from ESP-r
3
Plant Domain
Initialization?
No
Yes
No
Plant domain converged?
Create Trnsys thread
2b
Commence time-step simulation
Yes
Next time-step
TCC Communication
Iterative calls to all Types
TYPE 130
PassDataToTrnsys
3a
GetEsprData (first call for invocation)
Once all other types have converged for invocation
GetTrnsysData
Data from TRNSYS
3b
PassDataToEspr
GetSystemConv
GetSystemConv
GetSystemConv
No
4
No
Yes
Yes

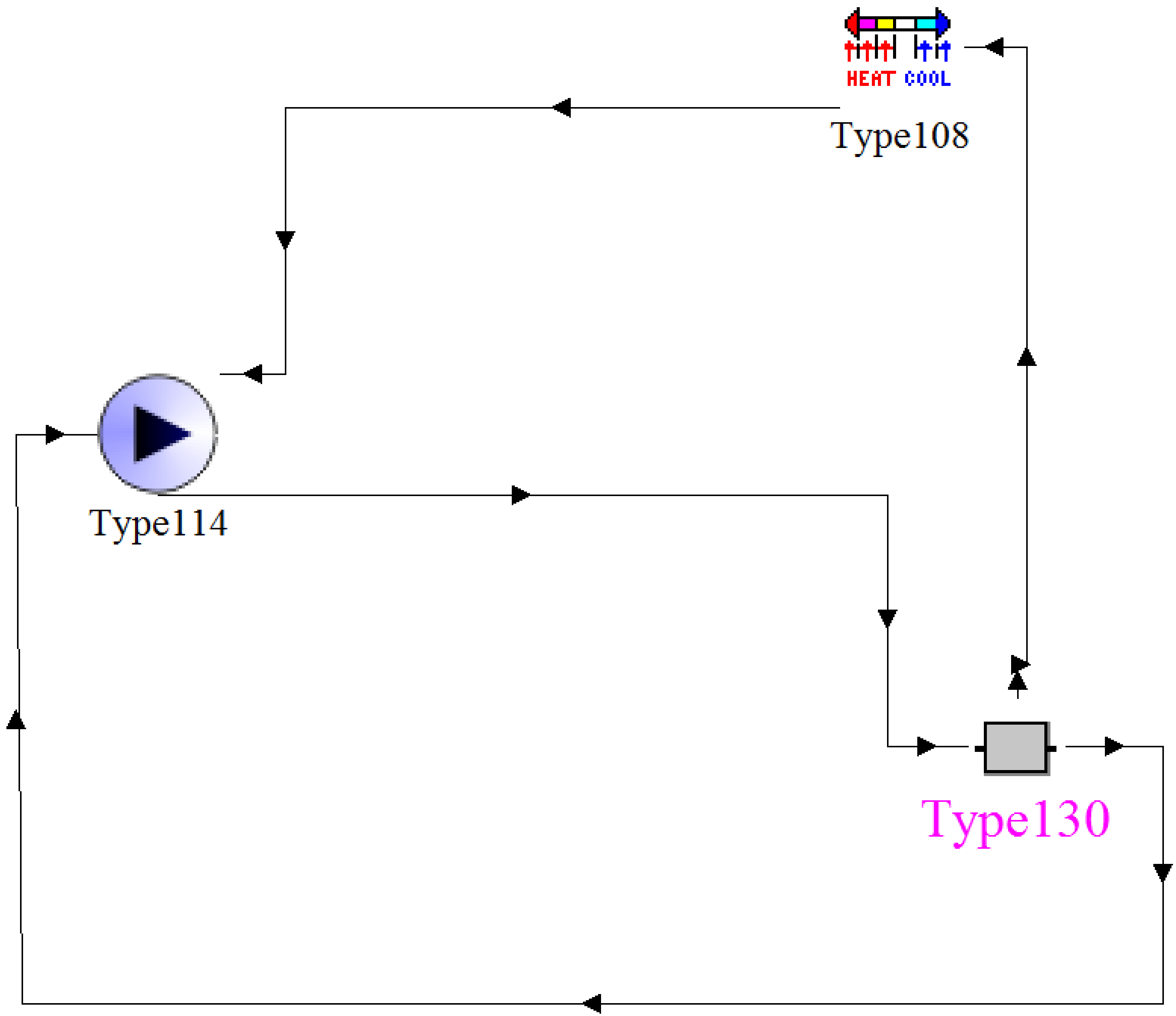
ESP-r’s TRNSYS Coupling Components




SOFC micro−cogeneration device
water tank
warm
supply
air
water−air heat
exchanger
pump
burner
pump
fan
return
air


SOFC micro−cogeneration device
water tank
warm
supply
air
water−air heat
exchanger
HCC−R
Harmonizer
HCC−S
burner
pump
fan
return
air


ESP-r Project Manager: enquiries to esru@strath.ac.uk
Model: Simple star
Connections
Sending comp @ Node to Receiving comp @ Node | Conn Type | Mass Div
a SOFC water node14 --> SOFC water node 6 to compt 1.000
b SOFC-pump water node 1 --> SOFC water node14 to compt 1.000
c SOFC water node 6 --> tank water node 1 to compt 1.000
d tank water node 1 --> SOFC-pump-d water node 1 to compt 0.500
e SOFC-pump-d water node 1 --> SOFC-pump water node 1 to compt 1.000
f tank water node 1 --> SH-pump-d water node 1 to compt 0.500
g blower air node 1 --> water-air-HX air node 2 to compt 1.000
h water-air-HX water node 3 --> tank water node 1 to compt 1.000
i house zone air --> blower air node 1 zone/amb 1.000
j SH-pump-d water node 1 --> TRNSYS-S-1 water node 1 to compt 1.000
k TRNSYS-R-1 water node 1 --> water-air-HX water node 3 to compt 1.000
l TRNSYS-S-1 water node 1 --> TRNSYS-R-1 water node 1 to compt 1.000
+ add/delete/copy
? Help
- Exit
mech-room
elev
azi
capture
image control
12 TRNSYS-R-1 node 1 (from another component.) TRNSYS-S-1 node 1 details: 1.00 0.00
12 TRNSYS-R-1 node 1 (from another component.) TRNSYS-S-1 node 1 details: 1.00 0.00
No of component containments = 2
Component | Containment descr. | Type
1 SOFC zone: mech-room 3 details: 1.00 0.00 0.00
2 tank zone: mech-room 3 details: 1.00 0.00 0.00
Data base contains 108 components.
capture
window
copyright


HEAT COOL
Type108
Type114
Type130

SOFC (rows 1–14)

tank (rows 15–17)

SH-pump (row 20)

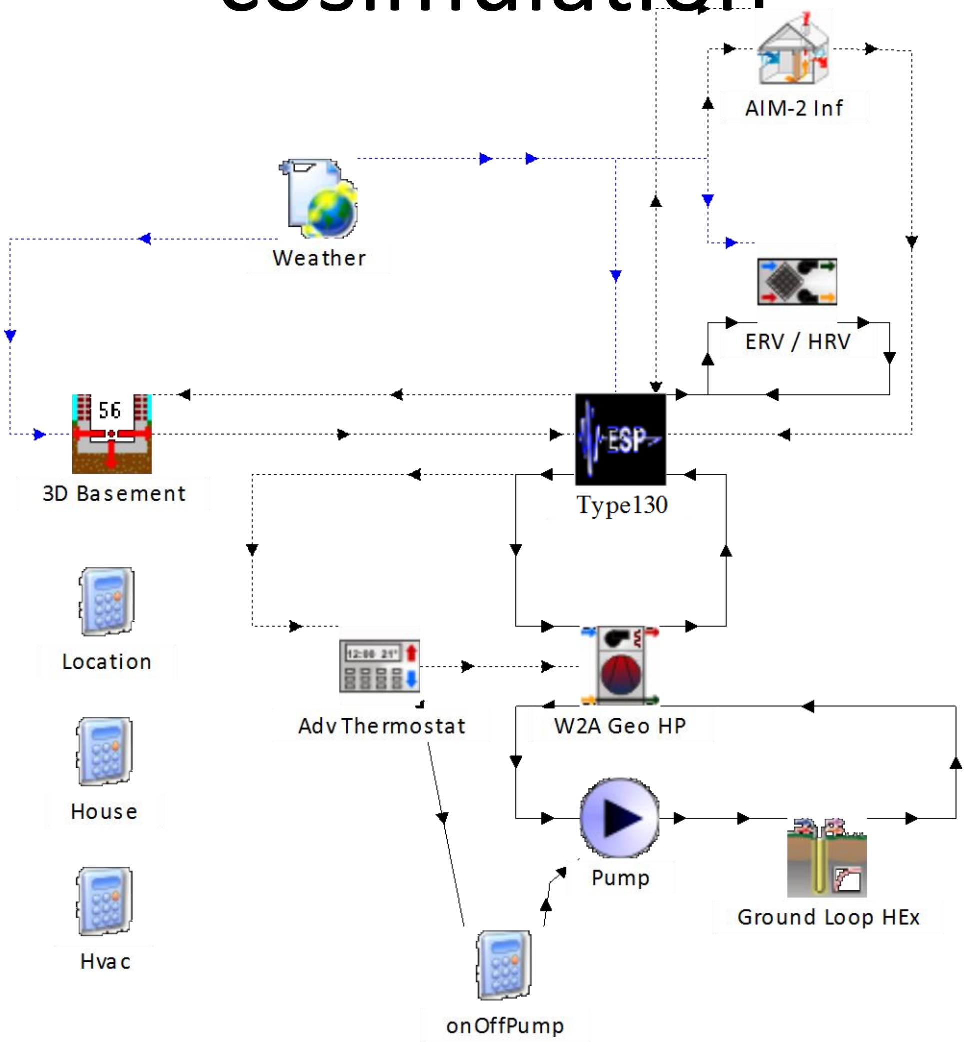
water-air HX (rows 22–24)

$$\begin{bmatrix}
a_{1,1}&&&&&&&&&&&&&&&&&&&&&&&& \\
&a_{2,2}&&&&&&&&&&&&&&&&&&&&&&& \\
&&a_{3,3}&&&&&&&&&&&&&&&&&&&&&& \\
&&&a_{4,4}&&&&&&&&&&&&&&&&&&&&& \\
&&&a_{5,4}&a_{5,5}&&&&&&&&&&&&&&&&&&&& \\
&&&&a_{6,5}&a_{6,6}&a_{6,7}&&&&&&&a_{6,14}&&&&&&&&&&& \\
&&&&a_{7,5}&&a_{7,7}&&&&&&&&&&&&&&&&&& \\
&&&&&&a_{8,7}&a_{8,8}&&&&&&&&&&&&&&&&& \\
&&&&&&&a_{9,8}&a_{9,9}&&&&&&&&&&&&&&&& \\
&&&&&&&&&a_{10,10}&&&&&&&&&&&&&&& \\
&&&&&&&&&&a_{11,11}&&&&&&&&&&&&&& \\
&&&&&&&&&&&a_{12,12}&&&&&&&&&&&&& \\
&&&&&&&&&&&&a_{13,13}&&&&&&&&&&&& \\
&&&&&&&&&&&&&a_{14,14}&&&&a_{14,18}&&&&&&& \\
&&&&&a_{15,6}&&&&&&&&&a_{15,15}&&&&&&&&&a_{15,24}& \\
&&&&&&&&&&&&&&&a_{16,16}&&&&&&&&& \\
&&&&&&&&&&&&&&&a_{17,16}&a_{17,17}&&&&&&&& \\
&&&&&&&&&&&&&&&&&a_{18,18}&a_{18,19}&&&&&& \\
&&&&&&&&&&&&&&a_{19,15}&&&&a_{19,19}&&&&&& \\
&&&&&&&&&&&&&&&&&&&a_{20,20}&a_{20,21}&&&& \\
&&&&&&&&&&&&&&a_{21,15}&&&&&&a_{21,21}&&&& \\
&&&&&&&&&&&&&&&&&&&&&a_{22,22}&a_{22,23}&a_{22,24}& \\
&&&&&&&&&&&&&&&&&&&&&a_{23,22}&a_{23,23}&&a_{23,25} \\
&&&&&&&&&&&&&&&&&&&a_{24,20}&&a_{24,22}&&a_{24,24}& \\
&&&&&&&&&&&&&&&&&&&&&&&&a_{25,25}
\end{bmatrix}
\times
\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \\ T_{10} \\ T_{11} \\ T_{12} \\ T_{13} \\ T_{14} \\ T_{15} \\ T_{16} \\ T_{17} \\ T_{18} \\ T_{19} \\ T_{20} \\ T_{21} \\ T_{22} \\ T_{23} \\ T_{24} \\ T_{25} \end{bmatrix}
=
\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \\ z_9 \\ z_{10} \\ z_{11} \\ z_{12} \\ z_{13} \\ z_{14} \\ z_{15} \\ z_{16} \\ z_{17} \\ z_{18} \\ z_{19} \\ z_{20} \\ z_{21} \\ z_{22} \\ z_{23} \\ z_{24} \\ z_{25} \end{bmatrix}$$

TRNSYS Changes

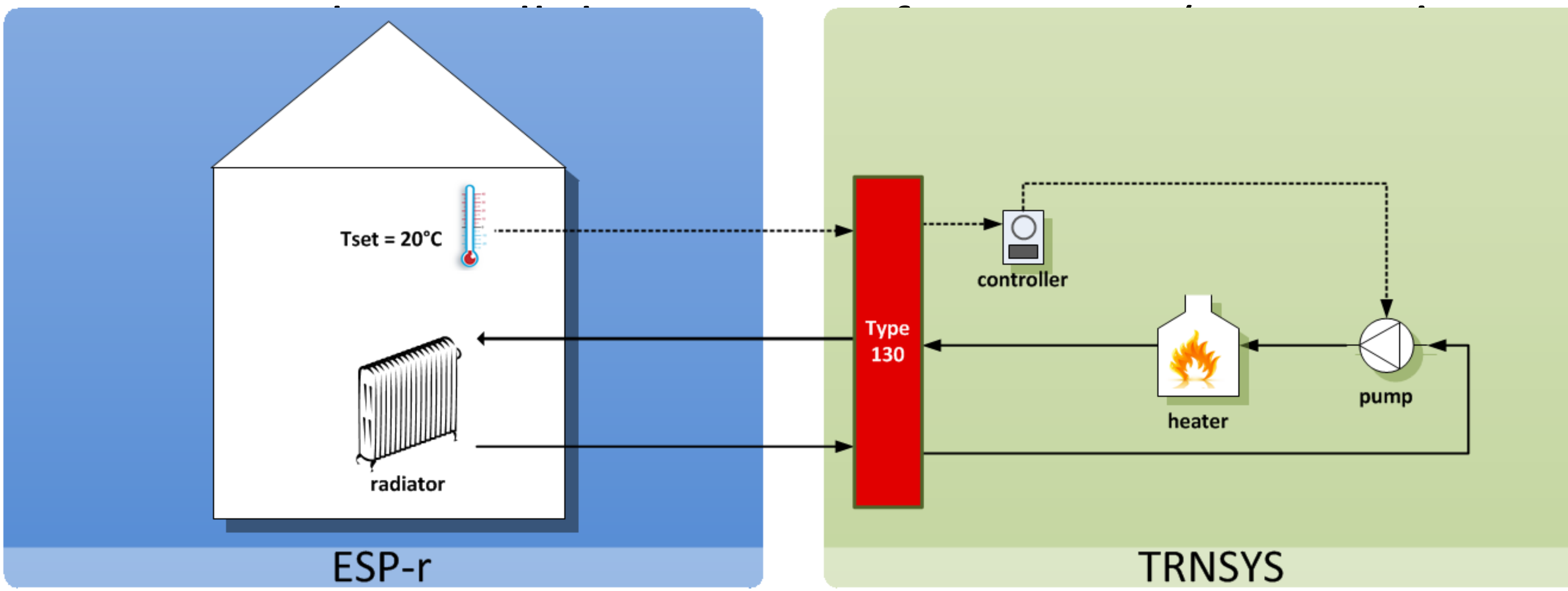
- Philosophy
- Source code changes
  - A new category of Type
  - Overall convergence vs. TRNSYS convergence

TRNSYS philosophy applied to cosimulation

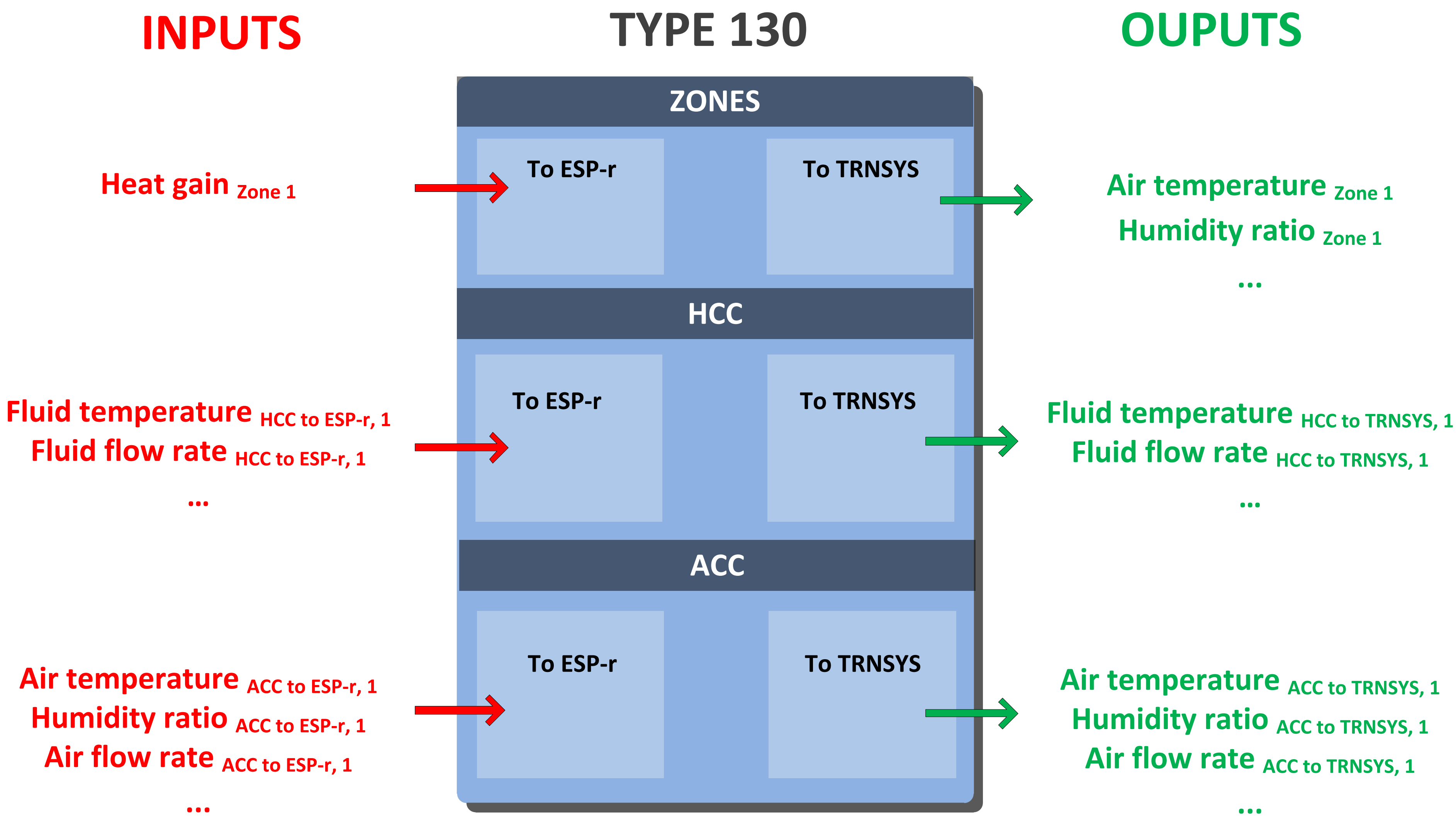


Communication through Type 130

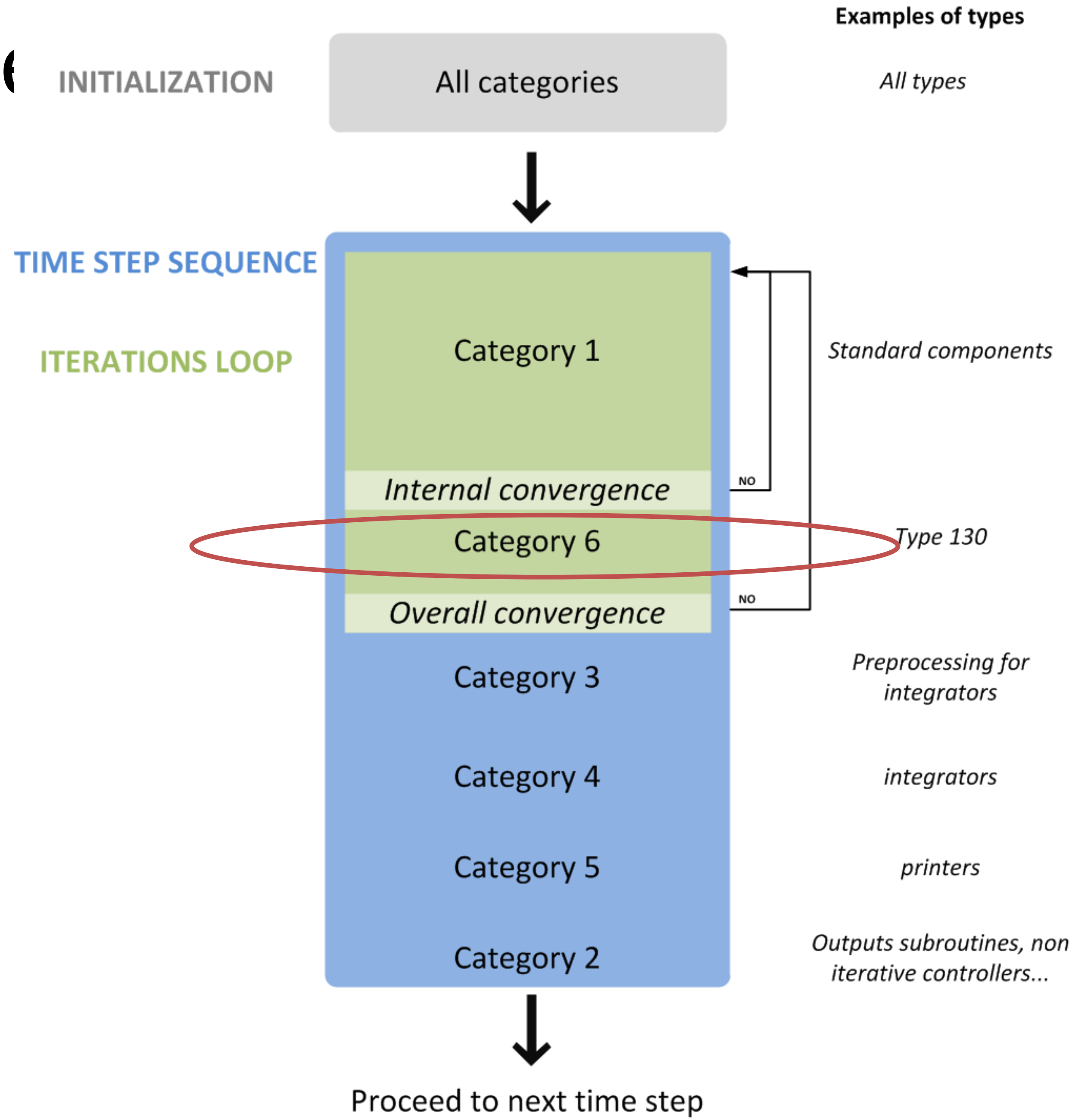
- New category of TRNSYS Type
  - Data Exchanger
  - Collects all data to be passed to ESP-r (Type 130's inputs)



Type 130 Inputs / Outputs



Why a ne


Examples of types
INITIALIZATION
All categories
All types
TIME STEP SEQUENCE
ITERATIONS LOOP
Category 1
Standard components
NO
Internal convergence
Category 6
Type 130
NO
Overall convergence
Category 3
Preprocessing for integrators
Category 4
integrators
Category 5
printers
Category 2
Outputs subroutines, non iterative controllers...
Proceed to next time step

Type 130 and convergence

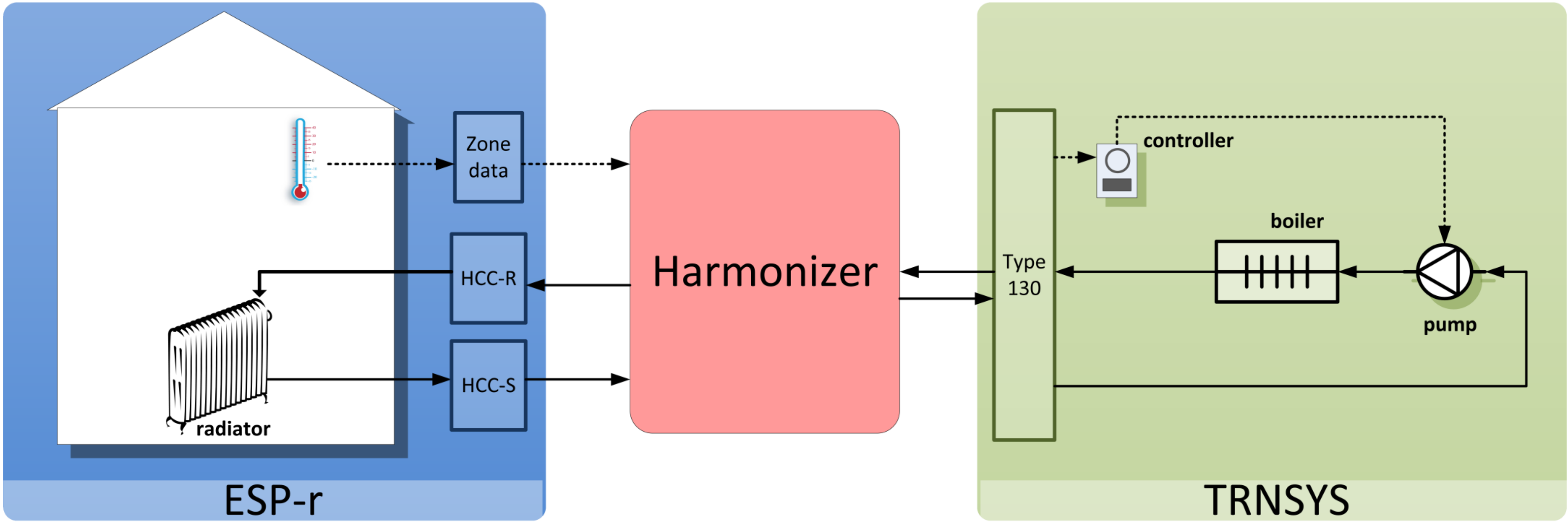
- TRNSYS convergence vs. overall (co-simulation) convergence
  - "data exchangers" are called by TRNSYS once all Types have converged at the current time step
  - Type 130 then checks whether the external program (i.e. ESP-r) has converged
    - Yes: allow TRNSYS to proceed to the next time step
    - No: "restart" this time step

      transparent to other types, they just see this as more iterations at this time step because some other part of the simulation has not converged

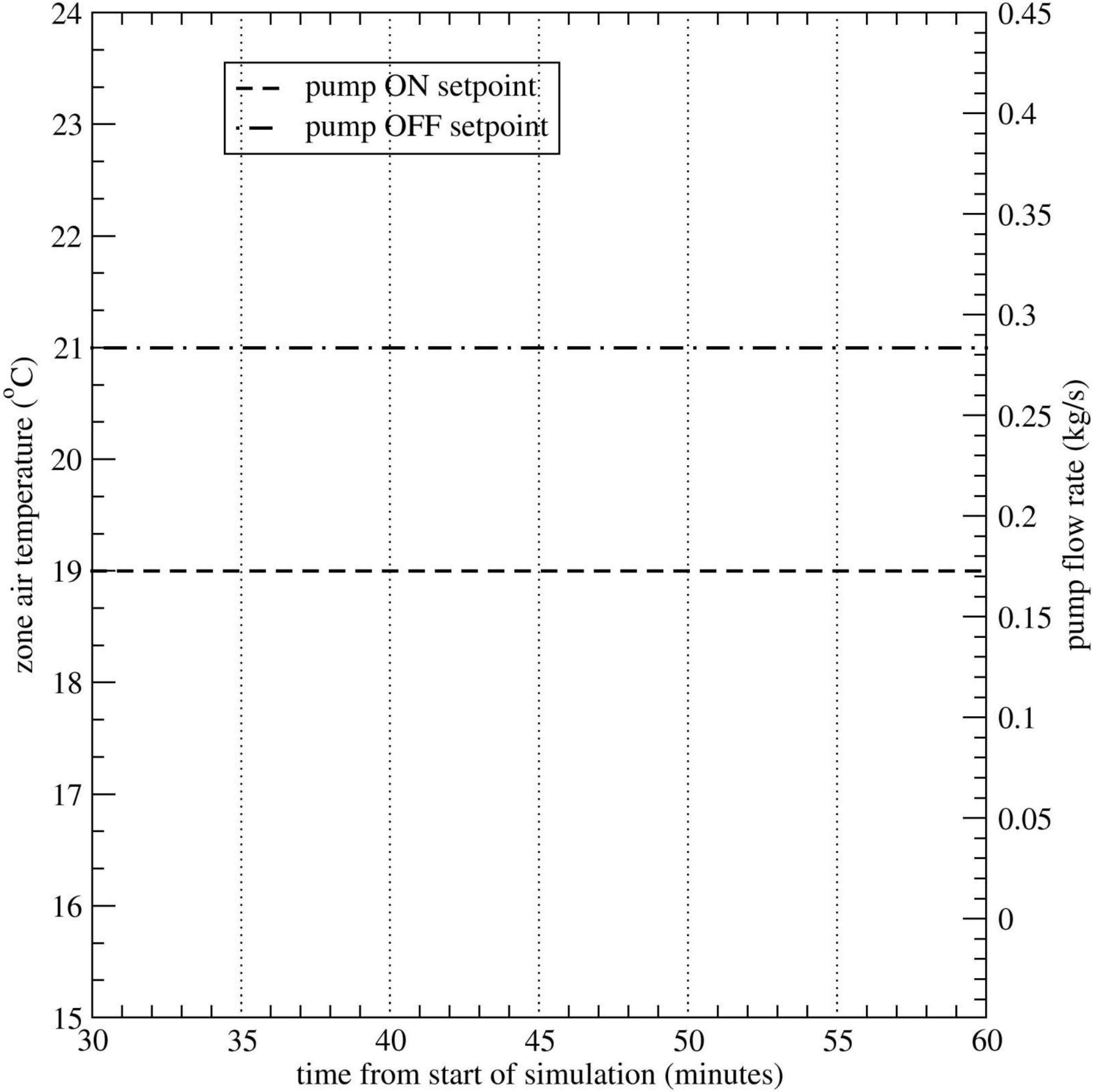
Type 130 calling sequence

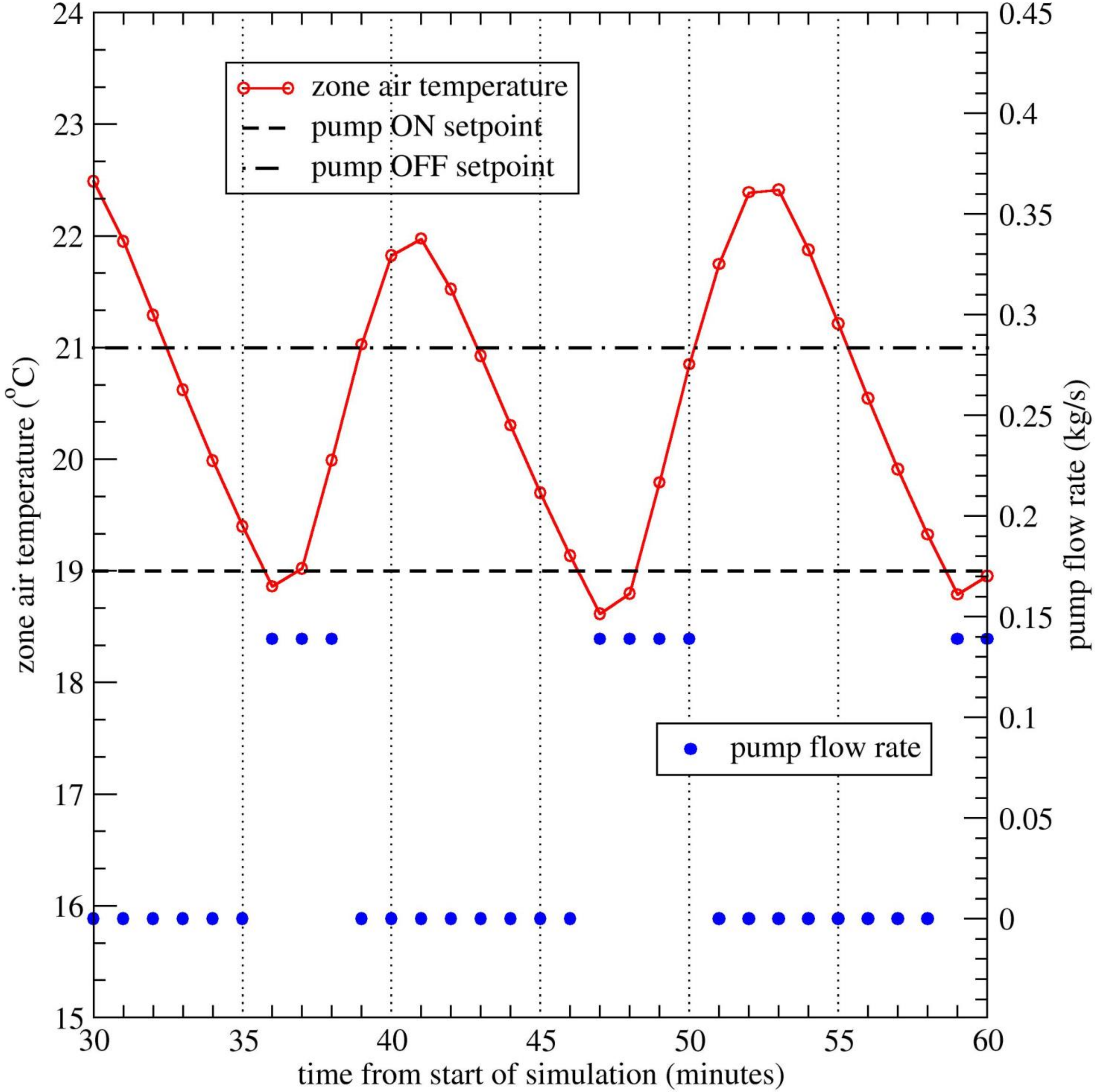
STANDARD TYPE	TYPE 130
1. Version signing call *- set type version*	**1. Version signing call** *- Set type version : 17*
2. Initialization call *- array sizing, memory allocation, file opening, parameter checking, ...*	**2. Initialization call** *- Load Harmonizer dll* *- Set parameters, outputs, inputs*
3. First call of a time step *- first call in the current time step for this type*	**3. First call of a time step** *- Get data from Harmonizer and set outputs*
4. Standard iteration call *- get input values* *- perform calculations* *- set output values*	**4. Standard iteration call** *- not used*
	5. Overall convergence checking call *- Pass input values to Harmonizer* *- Tell Harmonizer that TRNSYS has converged* *- Check for overall convergence (ESP-r converged as well?)* *Yes: Tell TRNSYS to proceed to next time step* *No: Restart iterations of current time step*
5. Post convergence call *- printing, integrating...* *- reset counters, update storage variables*	**6. Post convergence call** *- not used*
6. Last call of the simulation *- close external data files, calculate summary information...*	**7. Last call of the simulation** *- Get last input values and pass them to Harmonizer*

Does it work ?



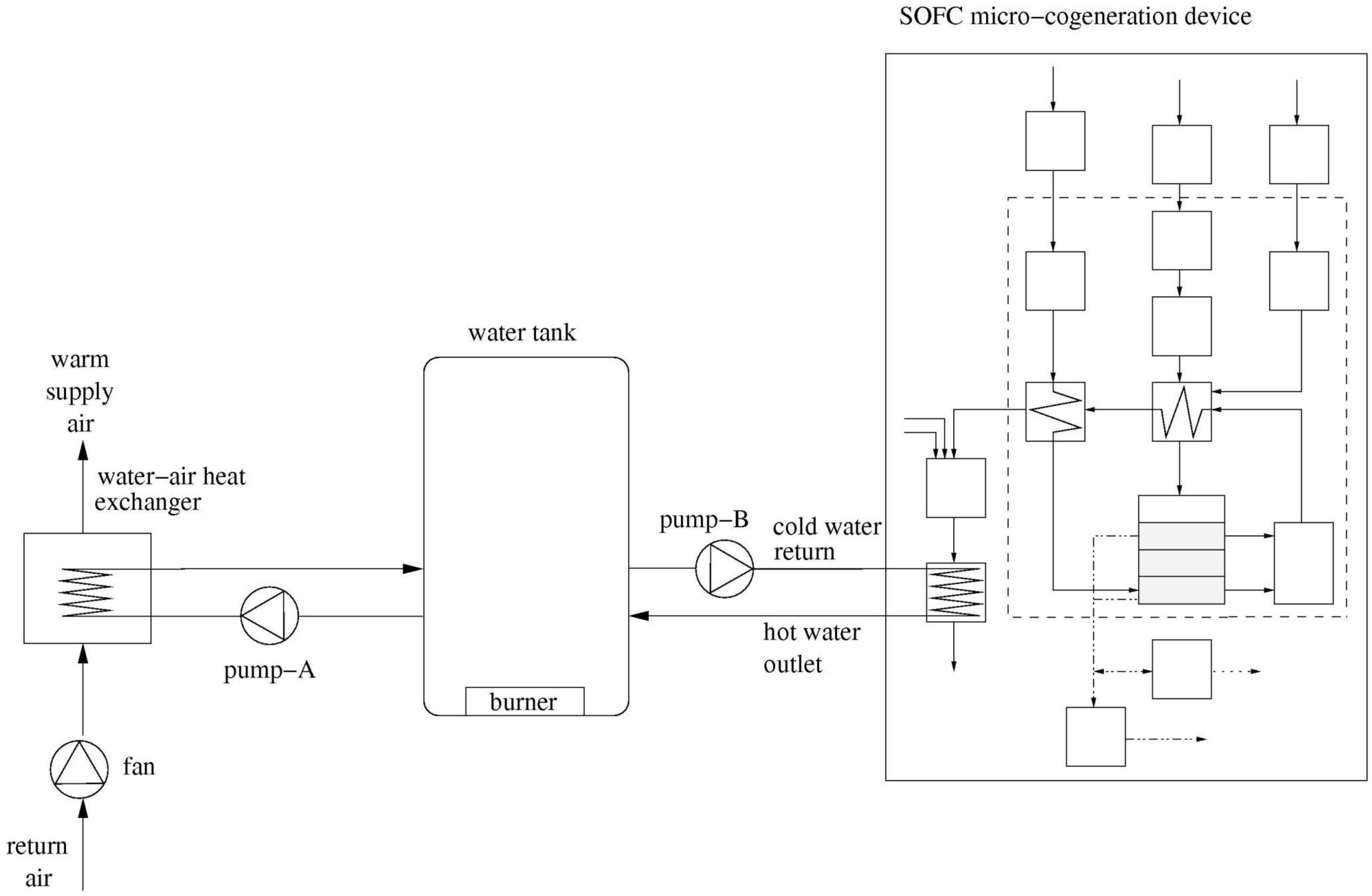
Zone data
HCC-R
HCC-S
radiator
ESP-r
Harmonizer
Type 130
controller
boiler
pump
TRNSYS


pump ON setpoint
pump OFF setpoint
zone air temperature (°C)
pump flow rate (kg/s)
time from start of simulation (minutes)
24
23
22
21
20
19
18
17
16
15
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
30
35
40
45
50
55
60

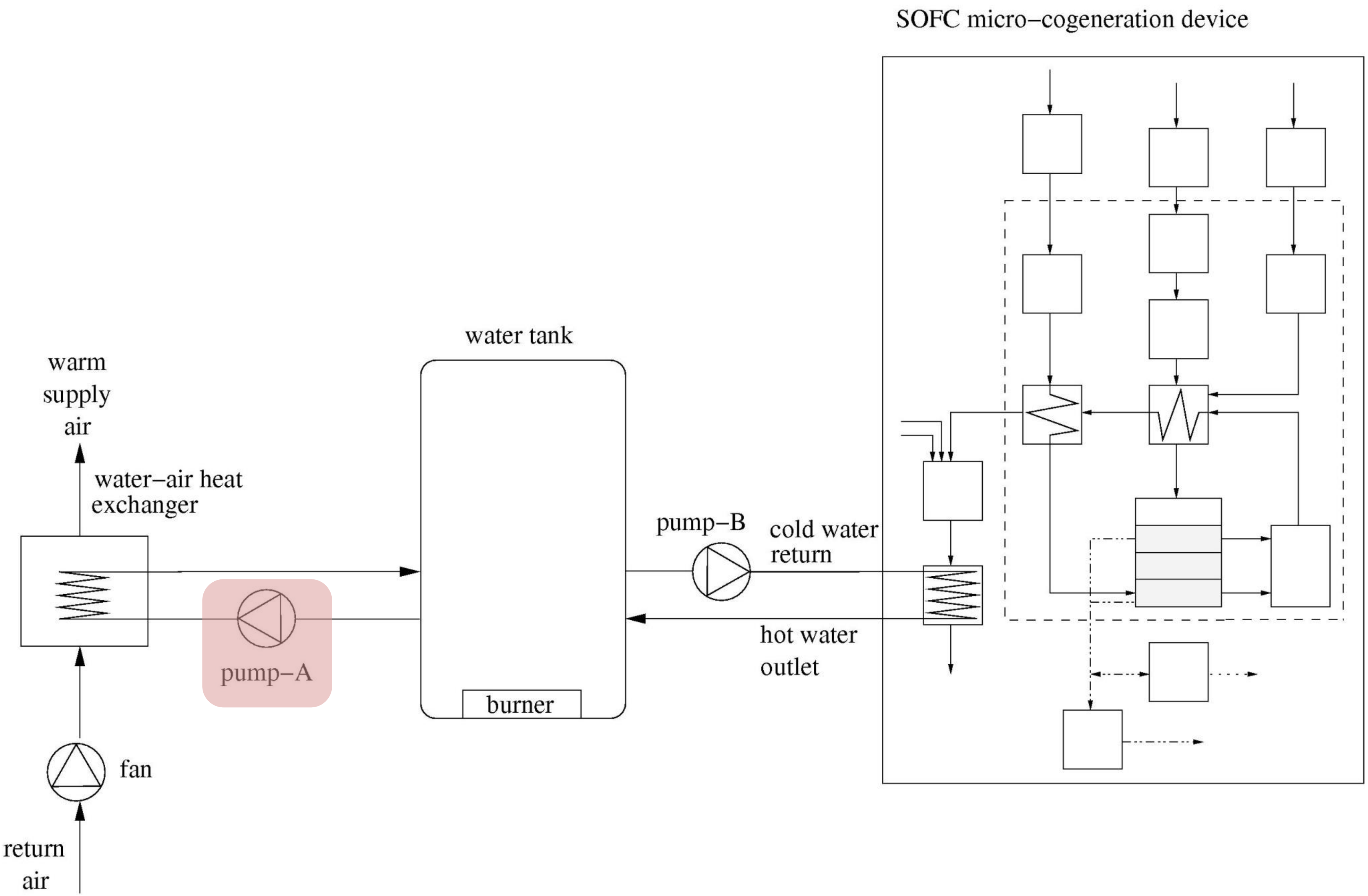


zone air temperature
pump ON setpoint
pump OFF setpoint
pump flow rate
zone air temperature (°C)
pump flow rate (kg/s)
time from start of simulation (minutes)
15
16
17
18
19
20
21
22
23
24
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
30
35
40
45
50
55
60

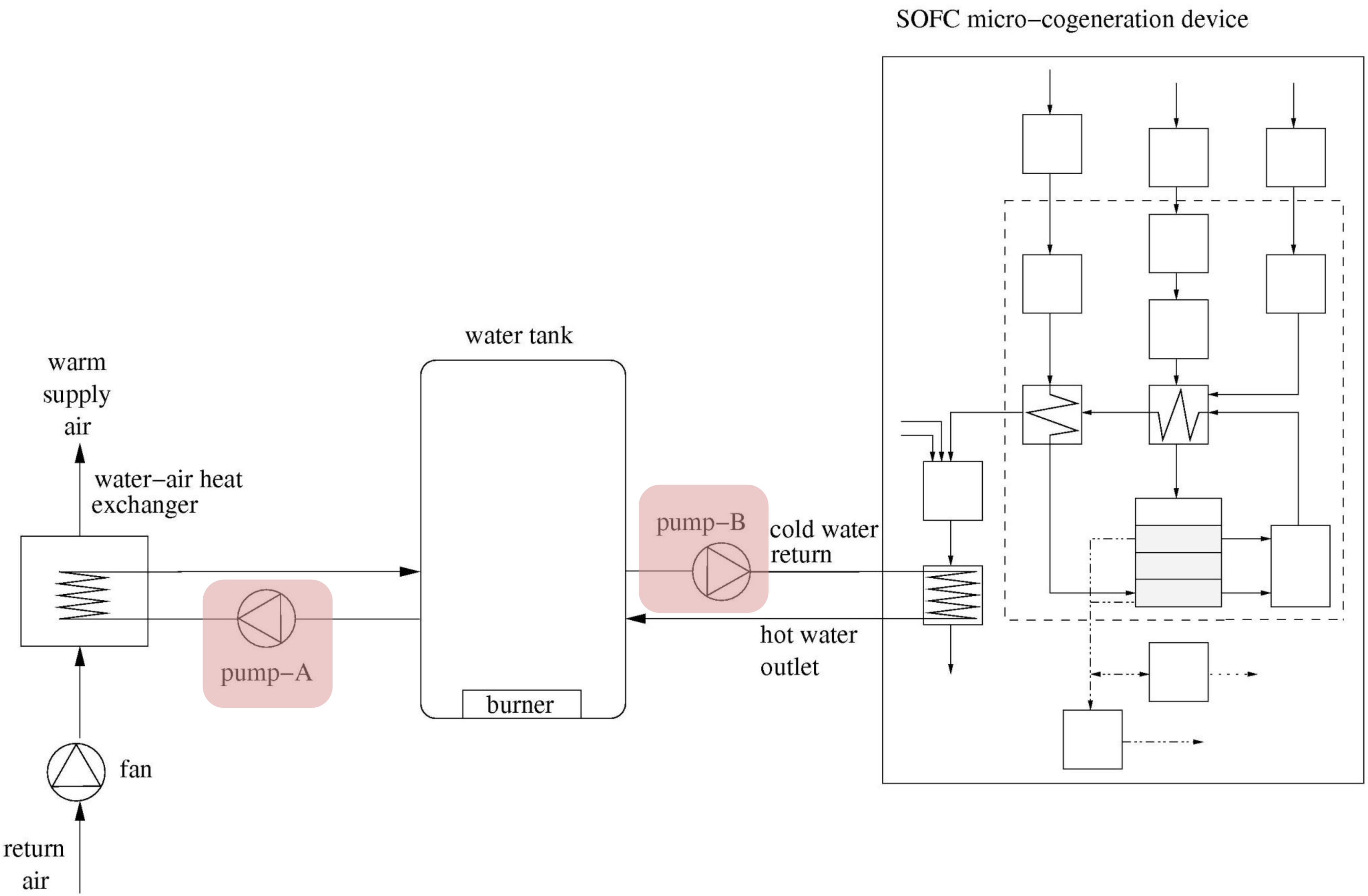
E0


SOFC micro–cogeneration device
water tank
warm supply air
water–air heat exchanger
pump–B
cold water return
pump–A
hot water outlet
burner
fan
return air

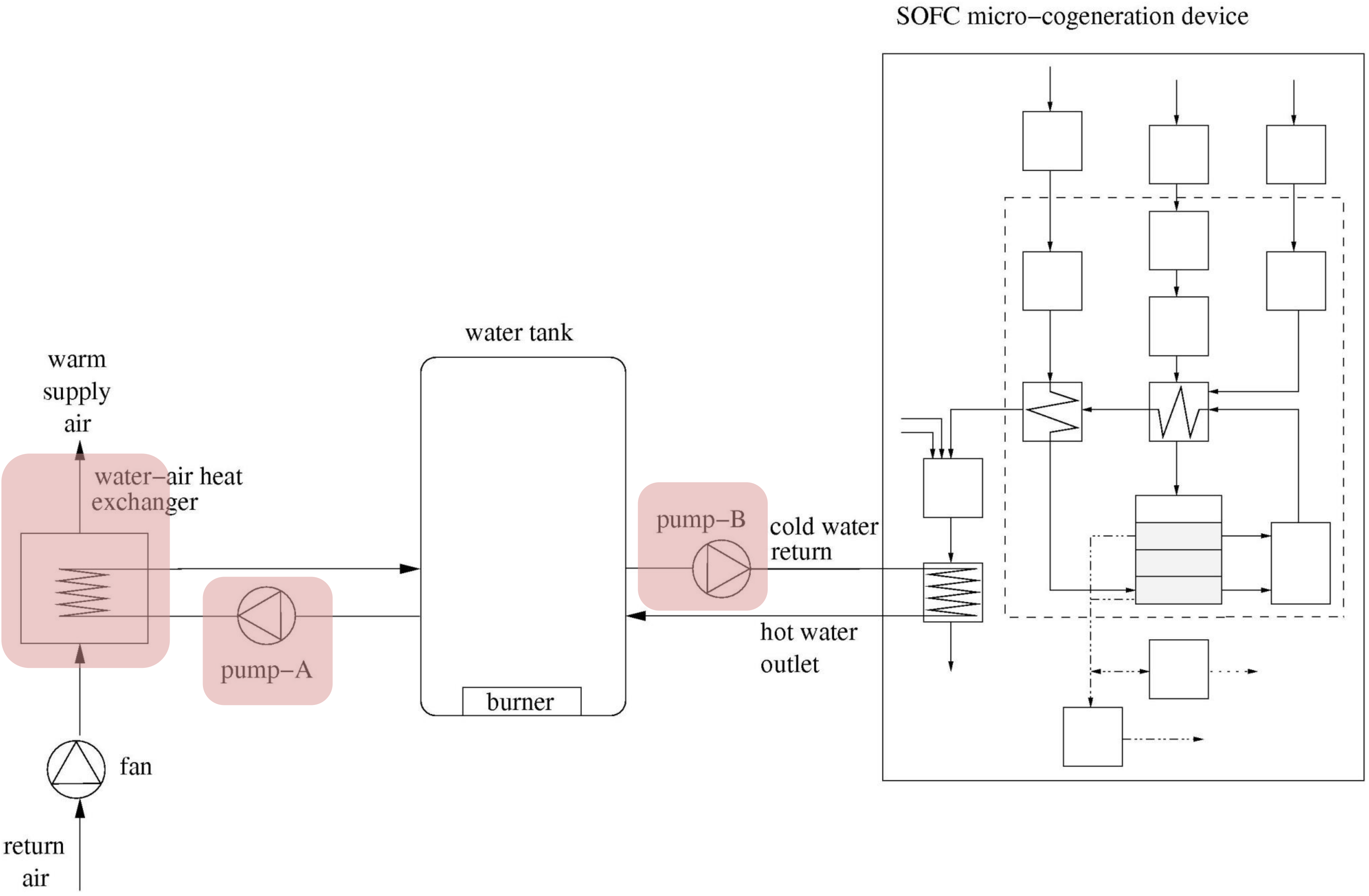
E1

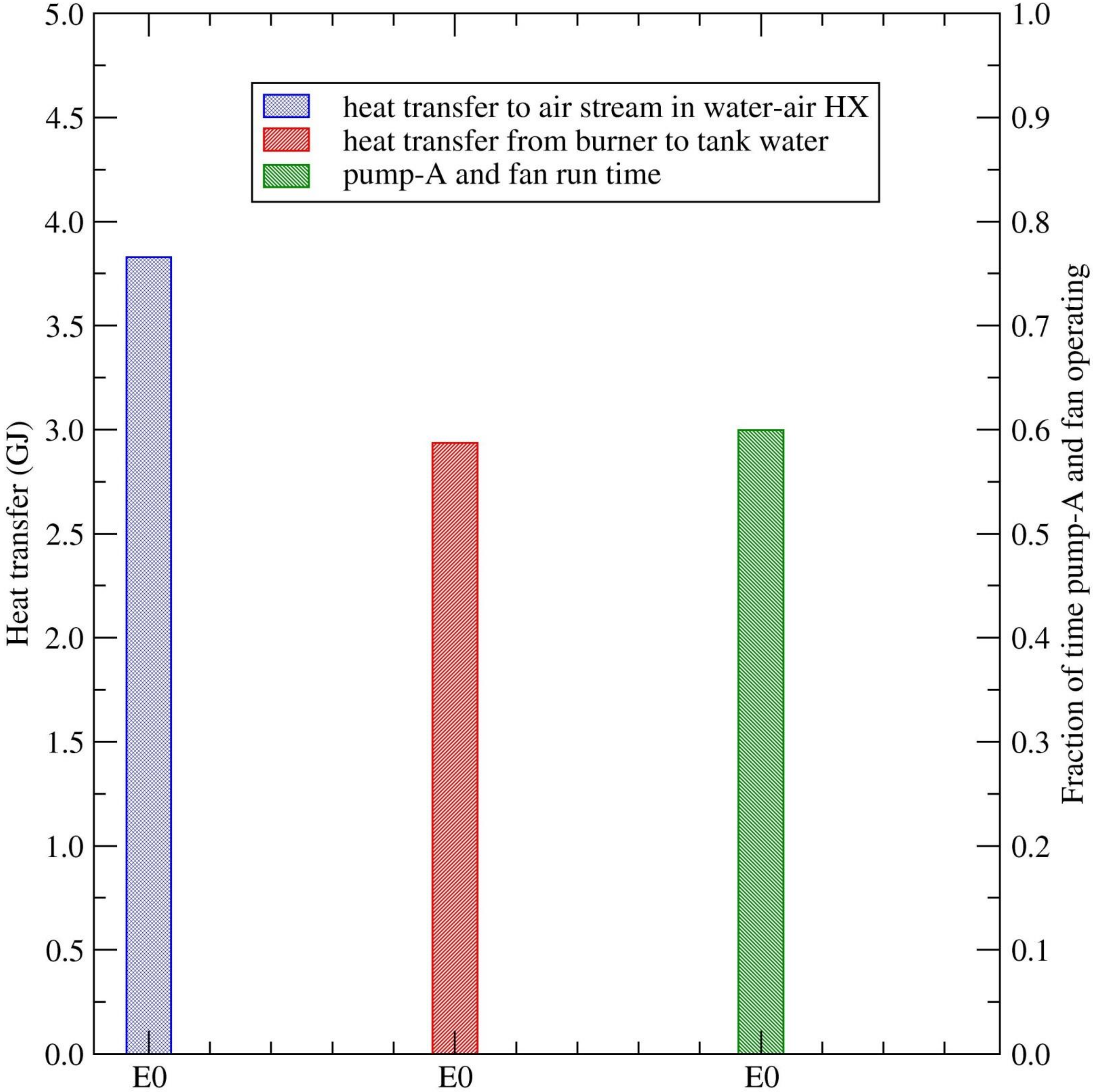

SOFC micro–cogeneration device
water tank
warm
supply
air
water–air heat
exchanger
pump–B
cold water
return
pump–A
burner
hot water
outlet
fan
return
air

E2

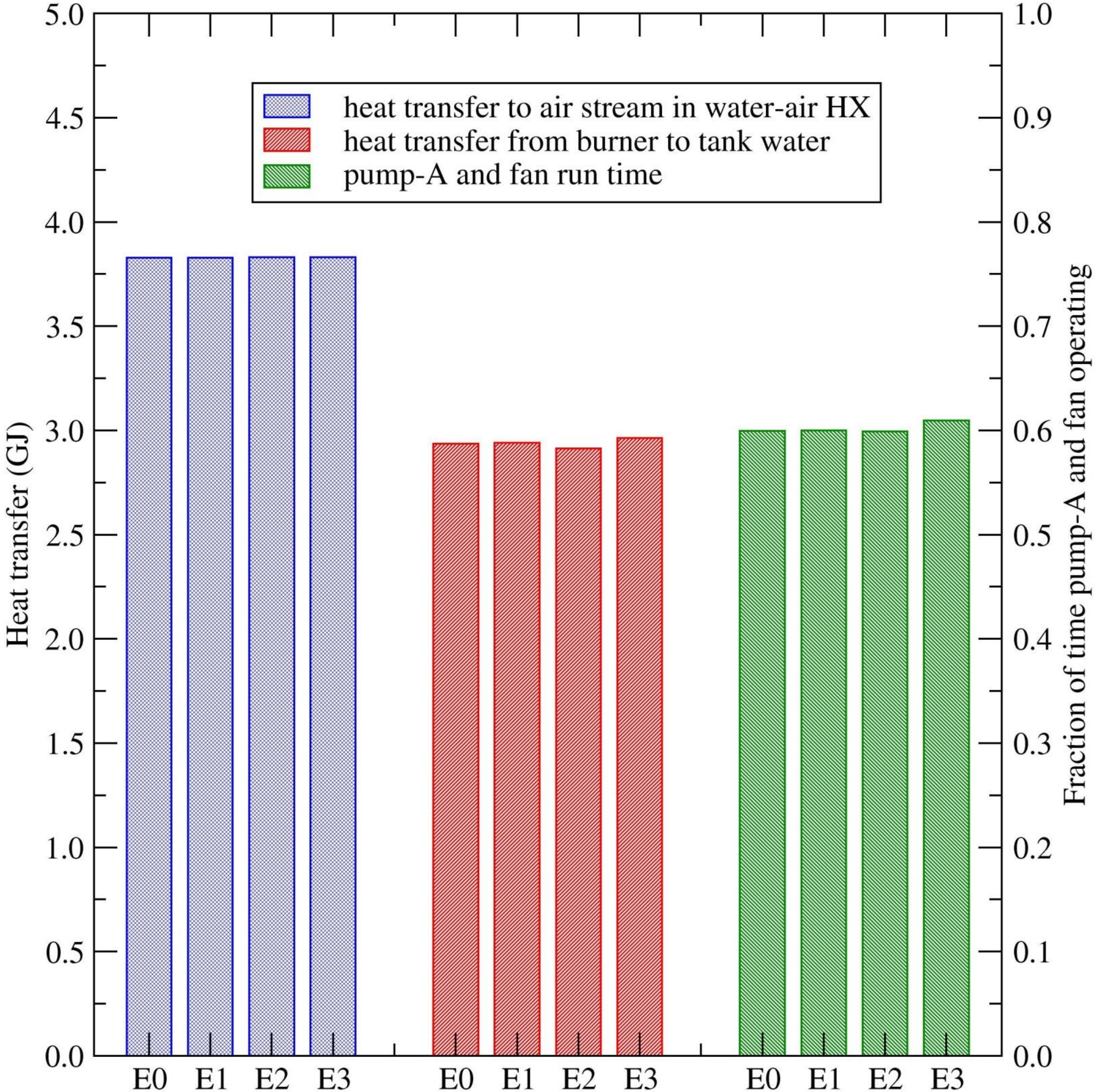

SOFC micro–cogeneration device
water tank
warm
supply
air
water–air heat
exchanger
pump–A
pump–B
cold water
return
hot water
outlet
burner
fan
return
air

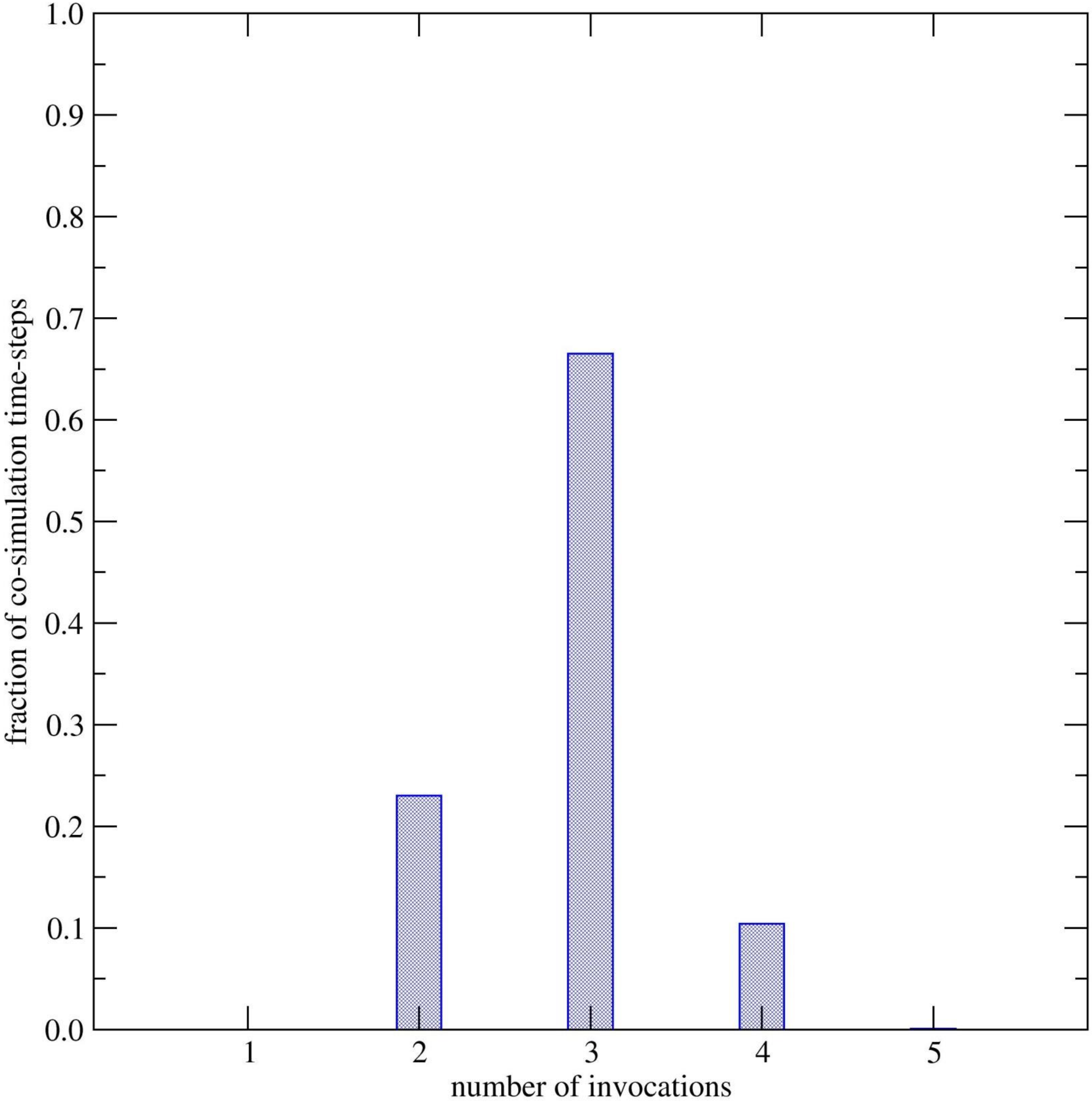
E3


SOFC micro–cogeneration device
water tank
burner
warm supply air
water–air heat exchanger
pump–A
pump–B
cold water return
hot water outlet
fan
return air

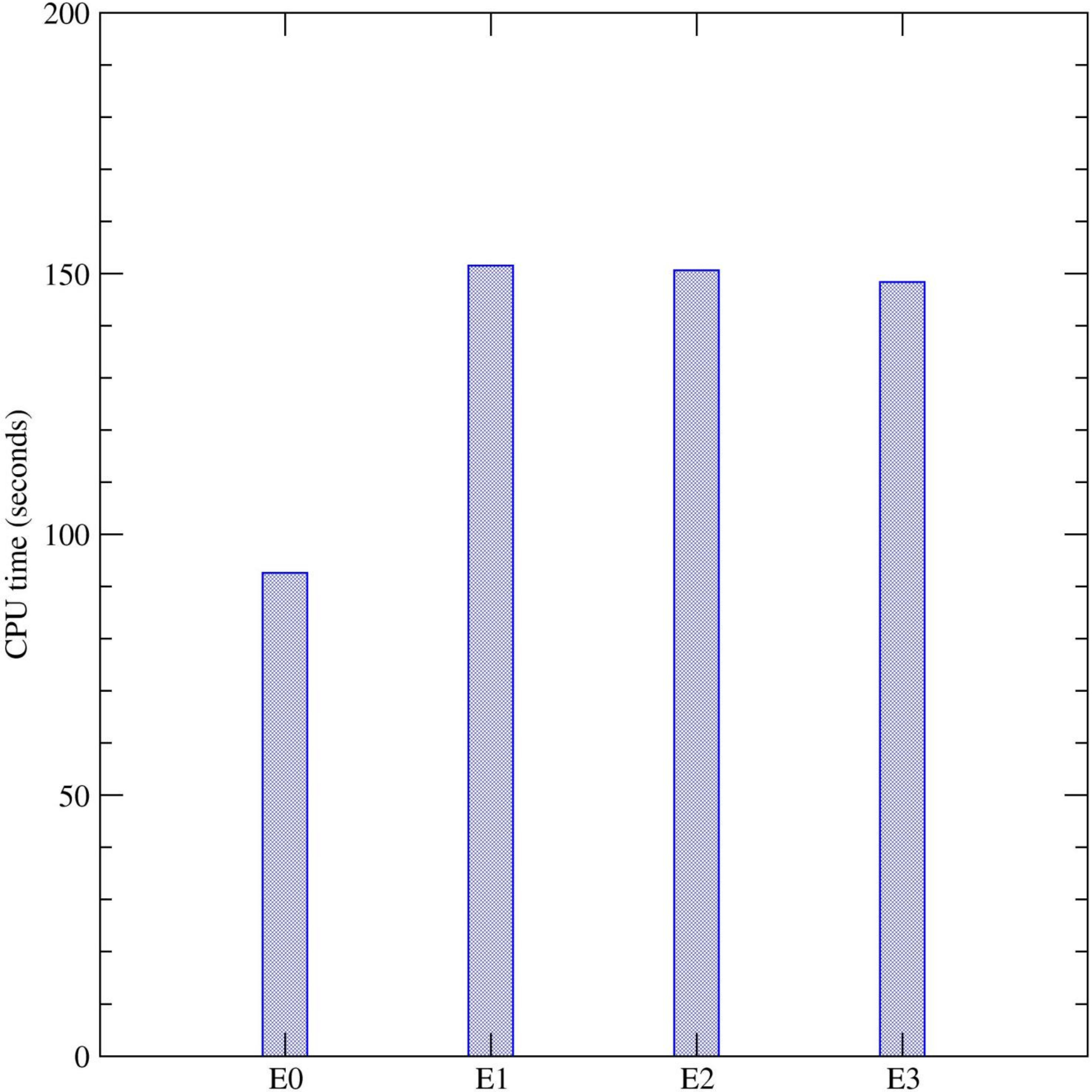


heat transfer to air stream in water-air HX
heat transfer from burner to tank water
pump-A and fan run time
Heat transfer (GJ)
Fraction of time pump-A and fan operating
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
E0
E0
E0


heat transfer to air stream in water-air HX
heat transfer from burner to tank water
pump-A and fan run time
Heat transfer (GJ)
Fraction of time pump-A and fan operating
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
E0
E1
E2
E3
E0
E1
E2
E3
E0
E1
E2
E3



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
fraction of co-simulation time-steps
1
2
3
4
5
number of invocations

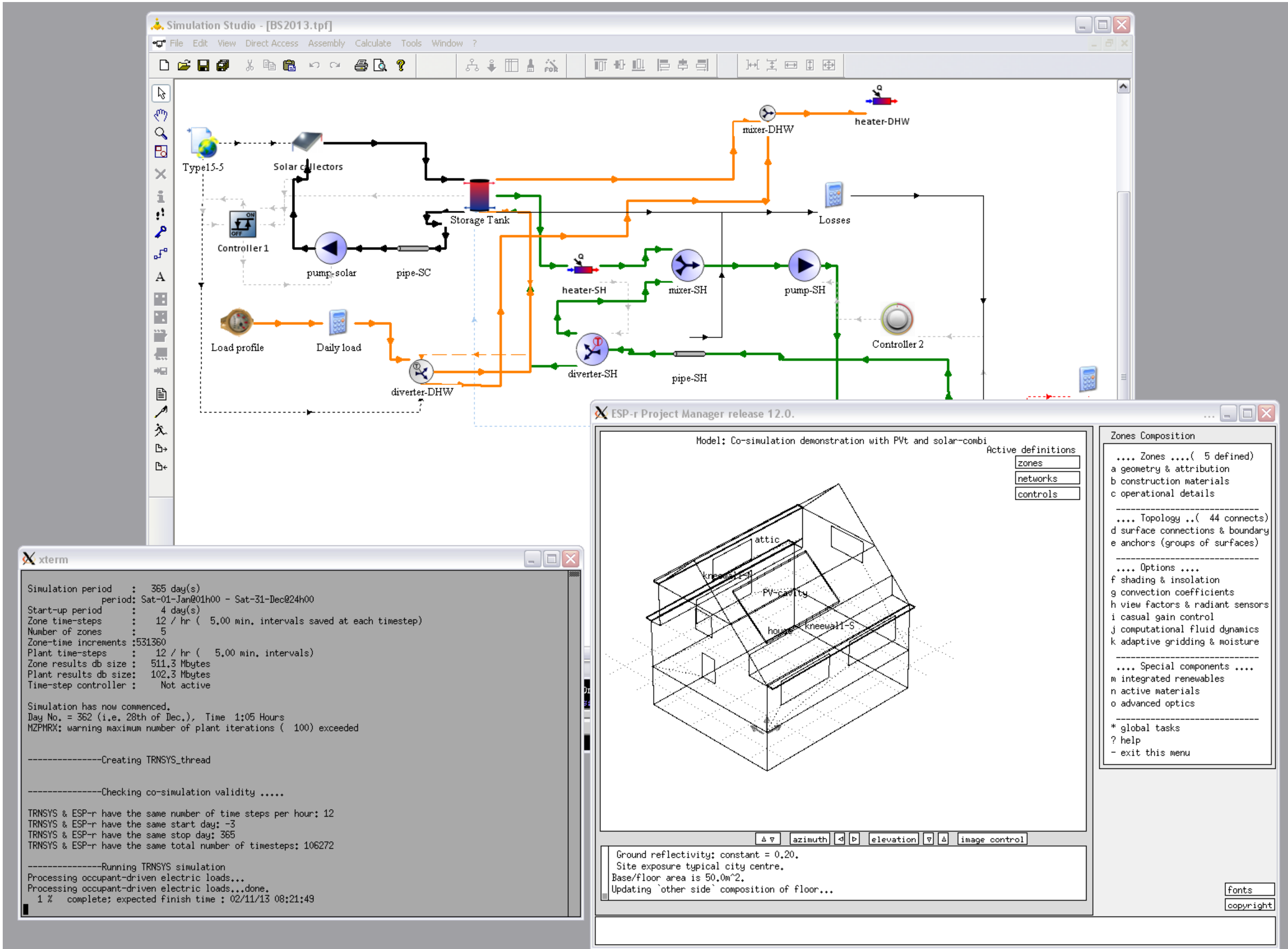


200
150
100
50
0
CPU time (seconds)
E0
E1
E2
E3

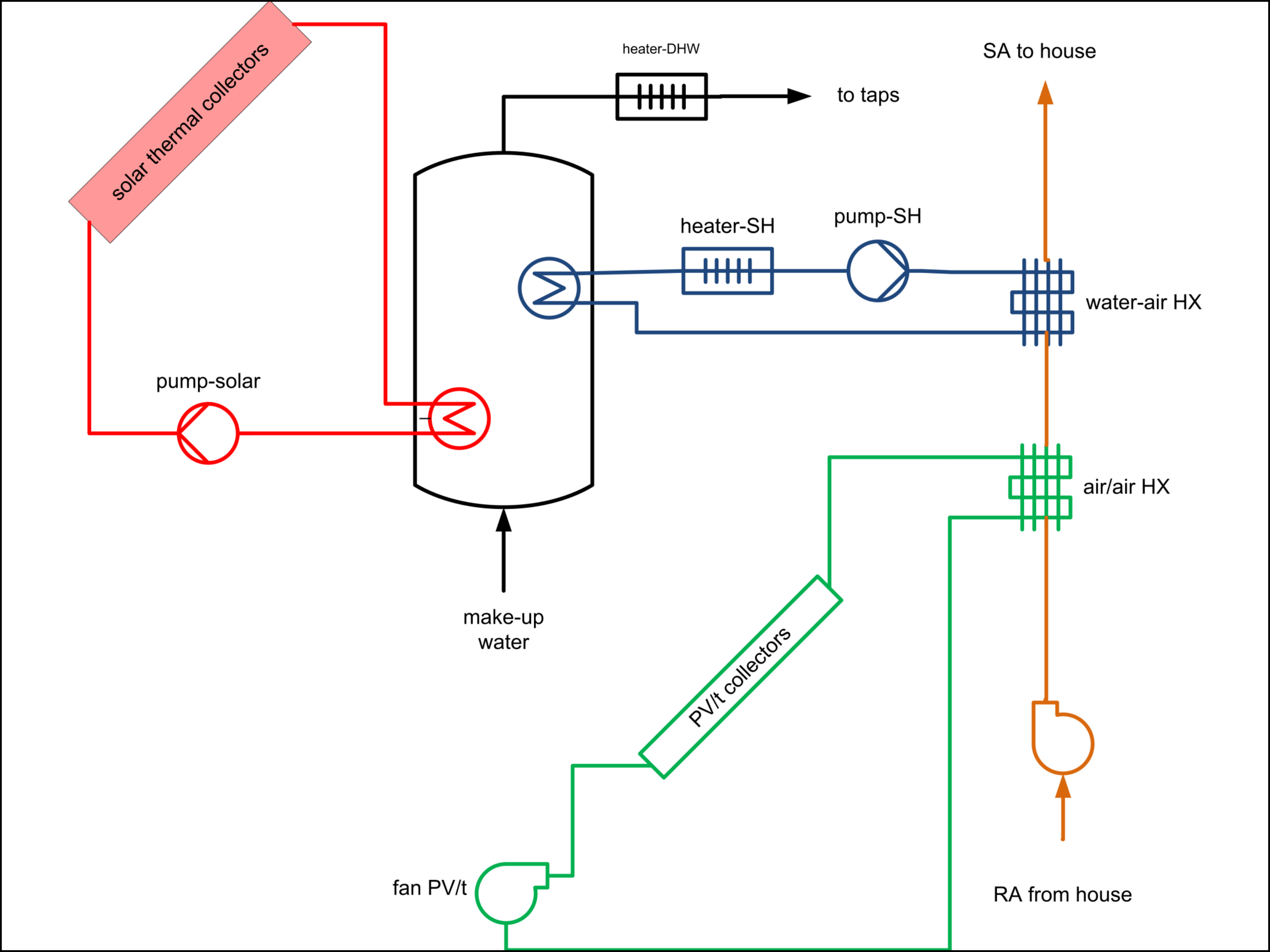
What can it do ?

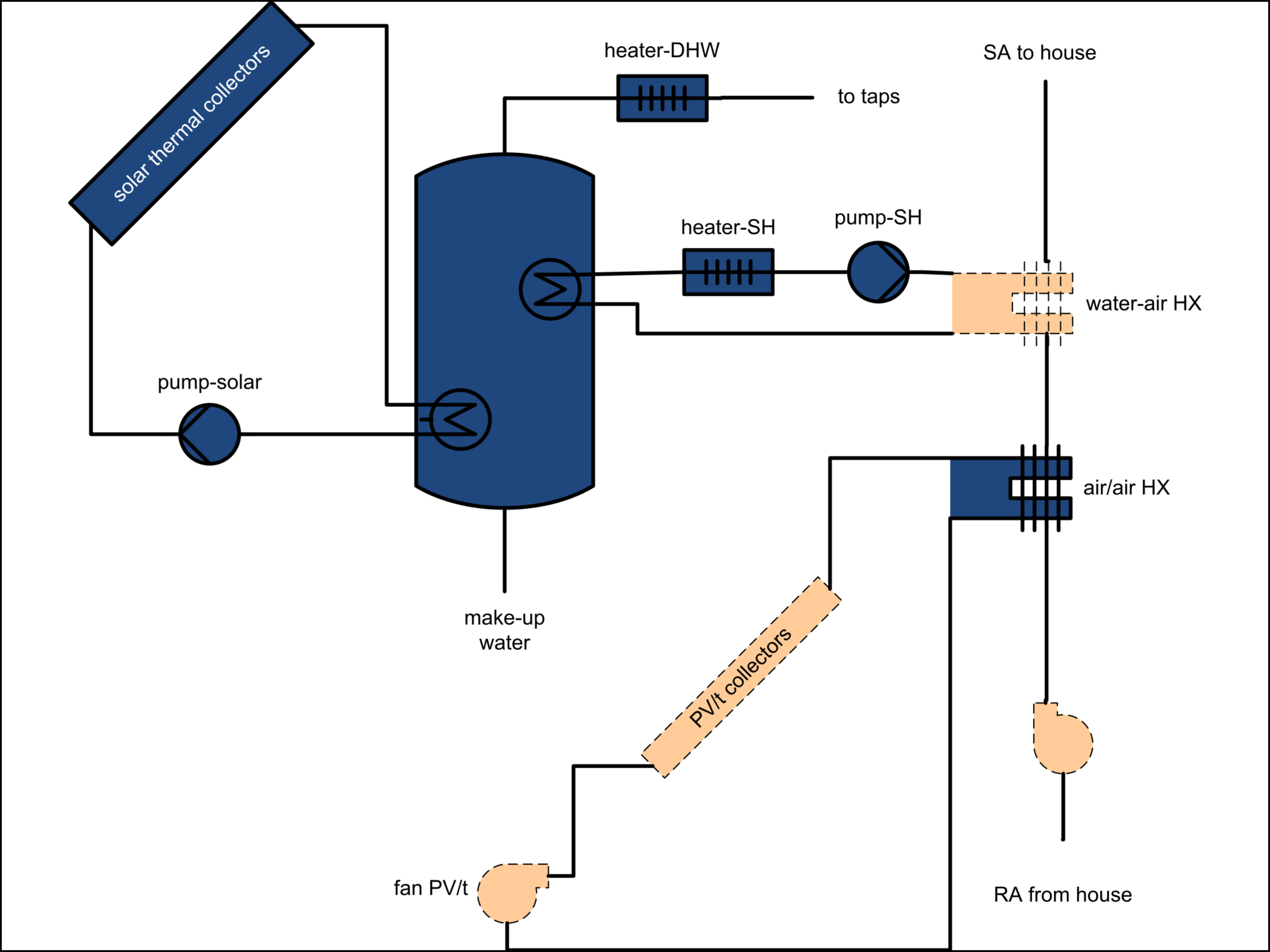
Case study

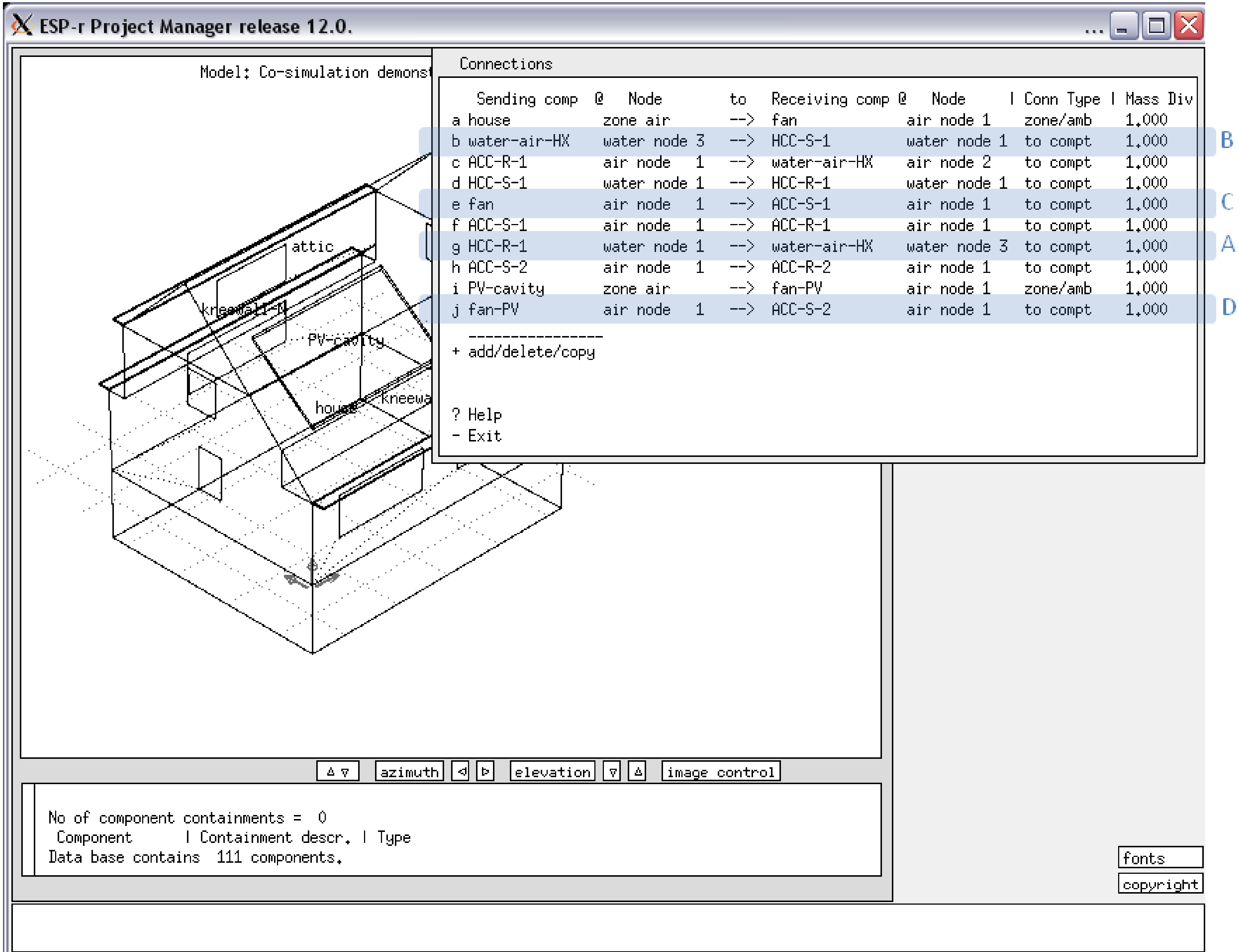
- Low-energy house:
  - High levels of insulation.
  - About 6% south glazing / floor area.
- Active energy systems:
  - Air-based heating system.
  - PV/thermal tempering return air.
  - Solar thermal collector with water storage serving DHW and space heating.
  - Heat recovery ventilator.
  - External venetian blinds with automated control.



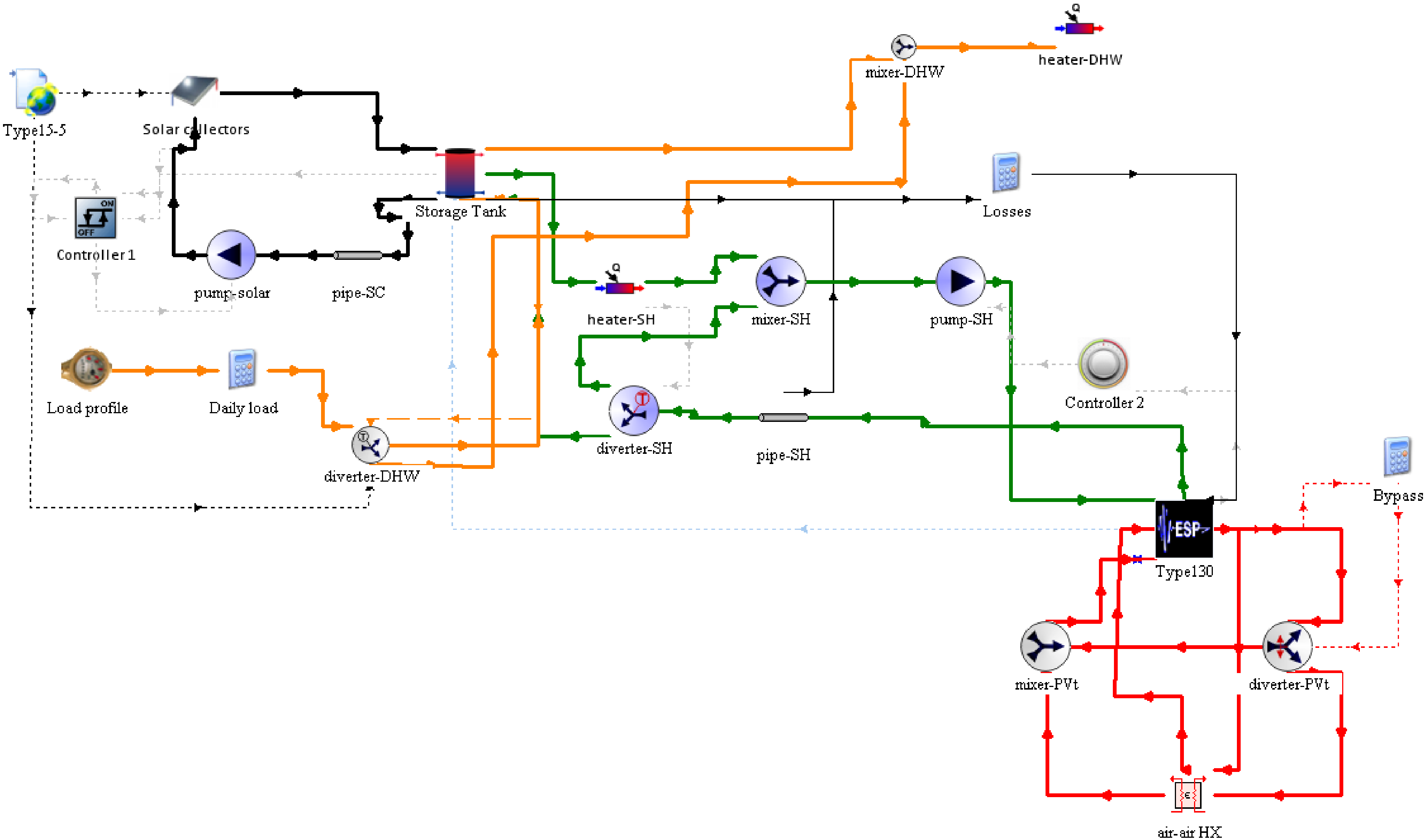
Simulation Studio - [BS2013.tpf]
File Edit View Direct Access Assembly Calculate Tools Window ?
Type15-5
Solar collectors
Storage Tank
Controller 1
pump-solar
pipe-SC
Losses
mixer-DHW
heater-DHW
heater-SH
mixer-SH
pump-SH
Controller 2
Load profile
Daily load
diverter-DHW
diverter-SH
pipe-SH
xterm
Simulation period : 365 day(s)
period: Sat-01-Jan@01h00 - Sat-31-Dec@24h00
Start-up period : 4 day(s)
Zone time-steps : 12 / hr (5.00 min. intervals saved at each timestep)
Number of zones : 5
Zone-time increments :531360
Plant time-steps : 12 / hr (5.00 min. intervals)
Zone results db size : 511.3 Mbytes
Plant results db size: 102.3 Mbytes
Time-step controller : Not active
Simulation has now commenced.
Day No. = 362 (i.e. 28th of Dec.), Time 1:05 Hours
MZPMRX: warning maximum number of plant iterations (100) exceeded
--------------Creating TRNSYS_thread
--------------Checking co-simulation validity .....
TRNSYS & ESP-r have the same number of time steps per hour: 12
TRNSYS & ESP-r have the same start day: -3
TRNSYS & ESP-r have the same stop day: 365
TRNSYS & ESP-r have the same total number of timesteps: 106272
--------------Running TRNSYS simulation
Processing occupant-driven electric loads...
Processing occupant-driven electric loads...done.
1 % complete; expected finish time : 02/11/13 08:21:49
ESP-r Project Manager release 12.0.
Model: Co-simulation demonstration with PVt and solar-combi
Active definitions
zones
networks
controls
attic
kneewall-N
PV-cavity
house
kneewall-S
azimuth
elevation
image control
Ground reflectivity: constant = 0.20.
Site exposure typical city centre.
Base/floor area is 50.0m^2.
Updating `other side` composition of floor...
Zones Composition
.... Zones ....(5 defined)
a geometry & attribution
b construction materials
c operational details
.... Topology ..(44 connects)
d surface connections & boundary
e anchors (groups of surfaces)
.... Options ....
f shading & insolation
g convection coefficients
h view factors & radiant sensors
i casual gain control
j computational fluid dynamics
k adaptive gridding & moisture
.... Special components ....
m integrated renewables
n active materials
o advanced optics
* global tasks
? help
- exit this menu
fonts
copyright

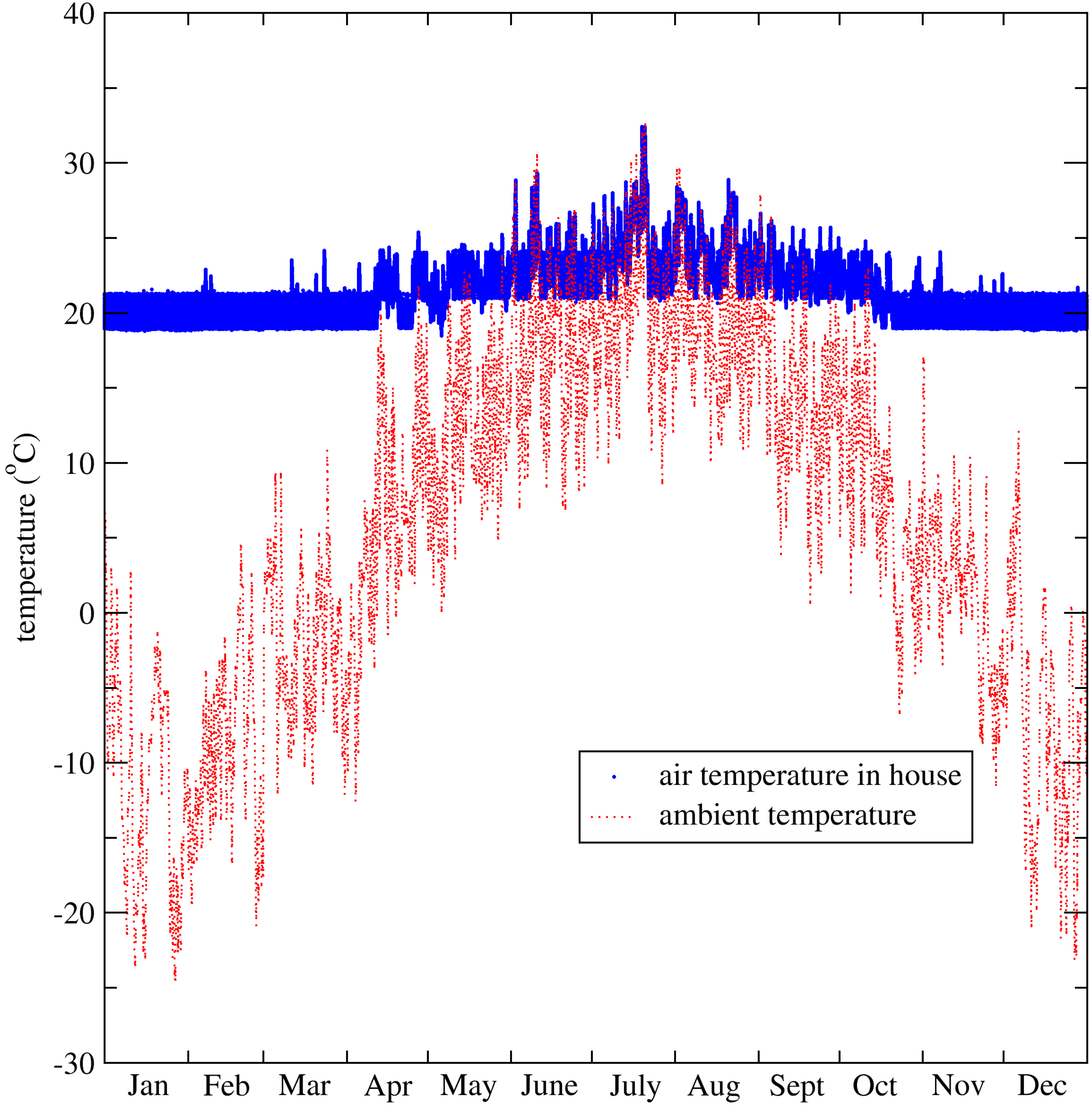

solar thermal collectors
heater-DHW
to taps
SA to house
heater-SH
pump-SH
water-air HX
pump-solar
air/air HX
make-up
water
PV/t collectors
fan PV/t
RA from house


solar thermal collectors
heater-DHW
to taps
SA to house
heater-SH
pump-SH
water-air HX
pump-solar
air/air HX
make-up
water
PV/t collectors
fan PV/t
RA from house

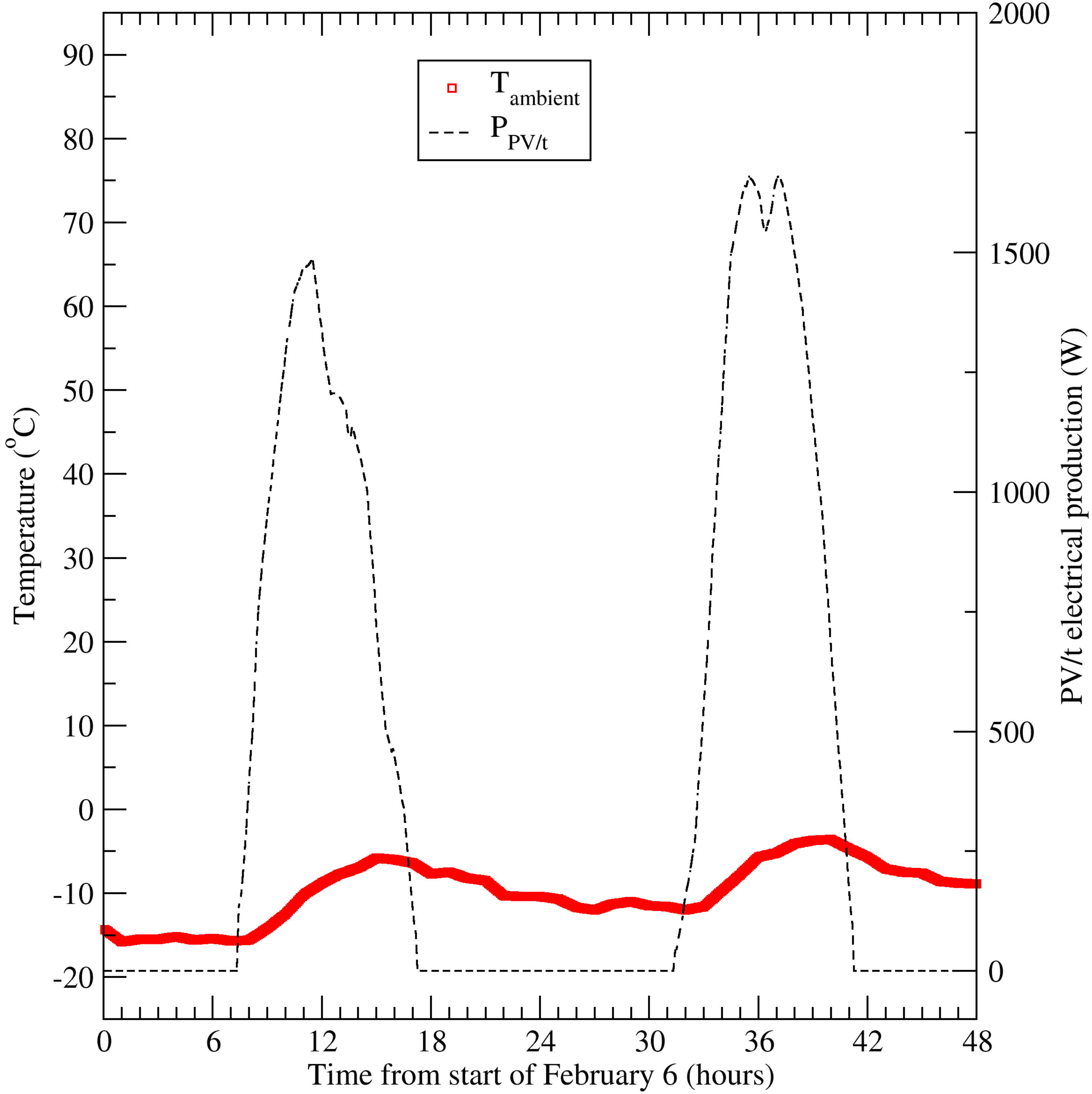

ESP-r Project Manager release 12.0.
Model: Co-simulation demonst
attic
kneewall-N
PV-cavity
house
kneewa
Connections
Sending comp @ Node to Receiving comp @ Node | Conn Type | Mass Div
a house zone air --> fan air node 1 zone/amb 1.000
b water-air-HX water node 3 --> HCC-S-1 water node 1 to compt 1.000 B
c ACC-R-1 air node 1 --> water-air-HX air node 2 to compt 1.000
d HCC-S-1 water node 1 --> HCC-R-1 water node 1 to compt 1.000
e fan air node 1 --> ACC-S-1 air node 1 to compt 1.000 C
f ACC-S-1 air node 1 --> ACC-R-1 air node 1 to compt 1.000
g HCC-R-1 water node 1 --> water-air-HX water node 3 to compt 1.000 A
h ACC-S-2 air node 1 --> ACC-R-2 air node 1 to compt 1.000
i PV-cavity zone air --> fan-PV air node 1 zone/amb 1.000
j fan-PV air node 1 --> ACC-S-2 air node 1 to compt 1.000 D

+ add/delete/copy
? Help
- Exit
azimuth
elevation
image control
No of component containments = 0
Component | Containment descr. | Type
Data base contains 111 components.
fonts
copyright

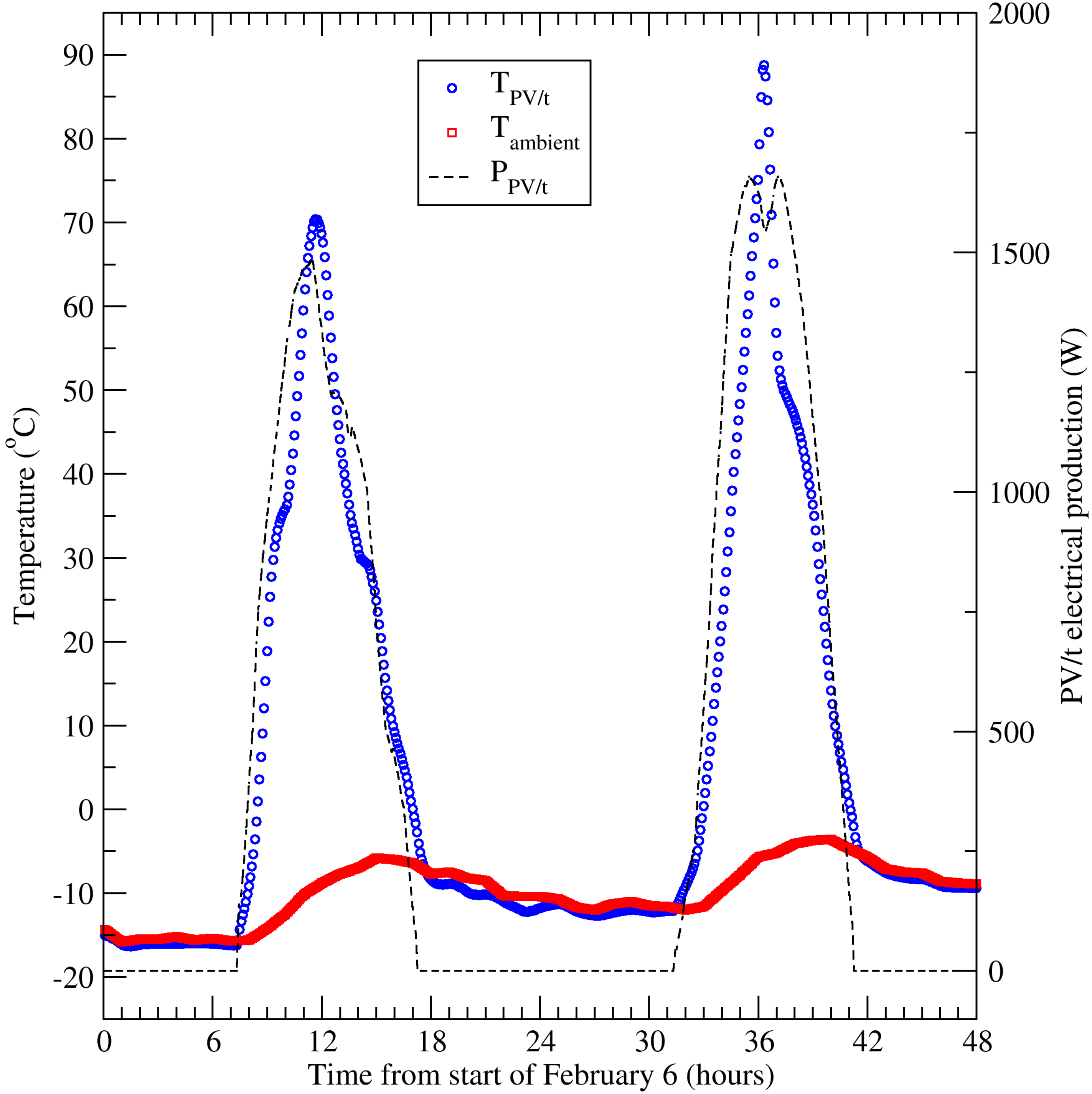

Type15-5
Solar collectors
Controller 1
pump-solar
pipe-SC
Storage Tank
mixer-DHW
heater-DHW
Losses
heater-SH
mixer-SH
pump-SH
Controller 2
Load profile
Daily load
diverter-DHW
diverter-SH
pipe-SH
Type130
Bypass
mixer-PVt
diverter-PVt
air-air HX



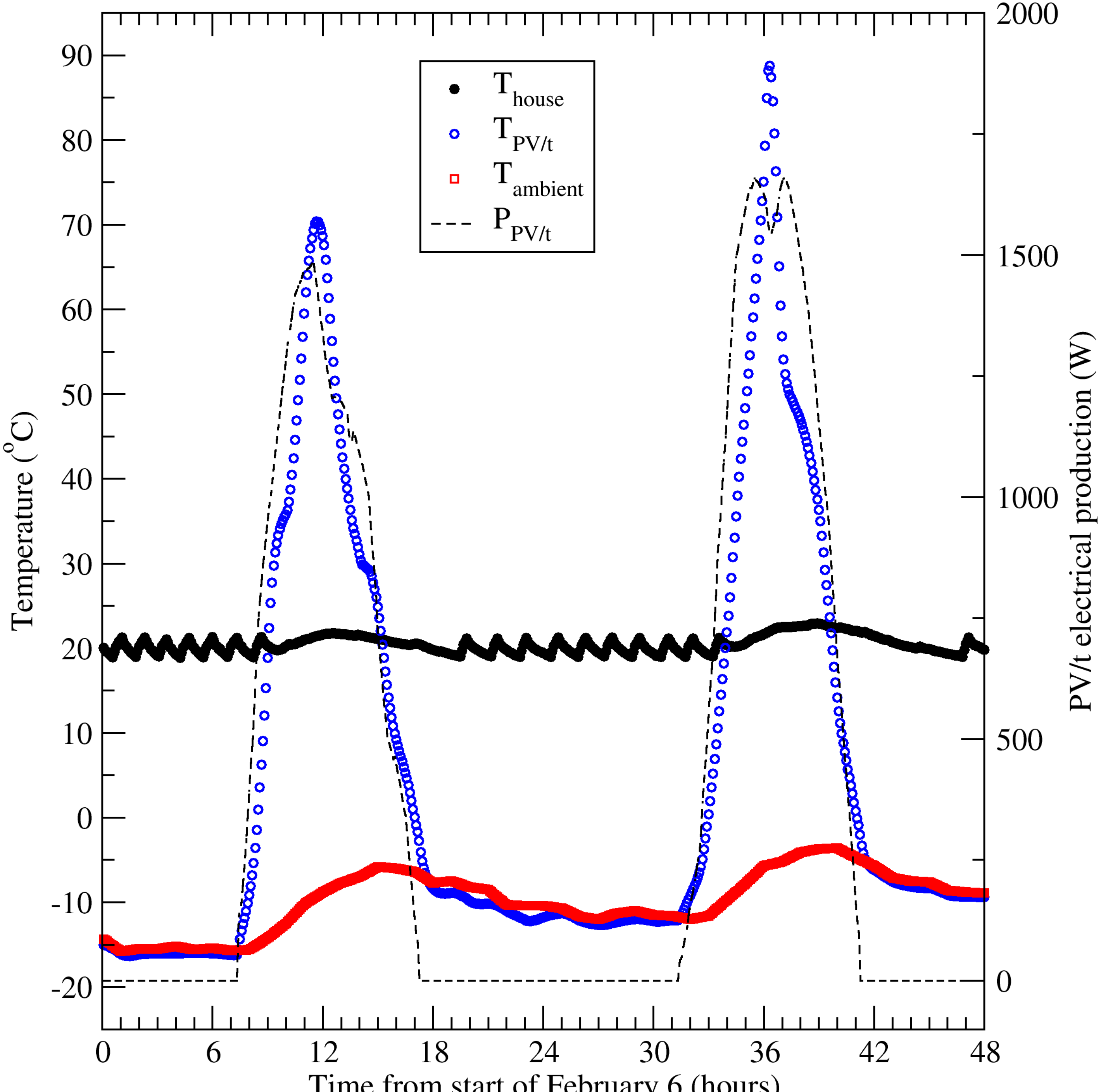
40
30
20
10
0
-10
-20
-30
temperature (°C)
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
air temperature in house
ambient temperature



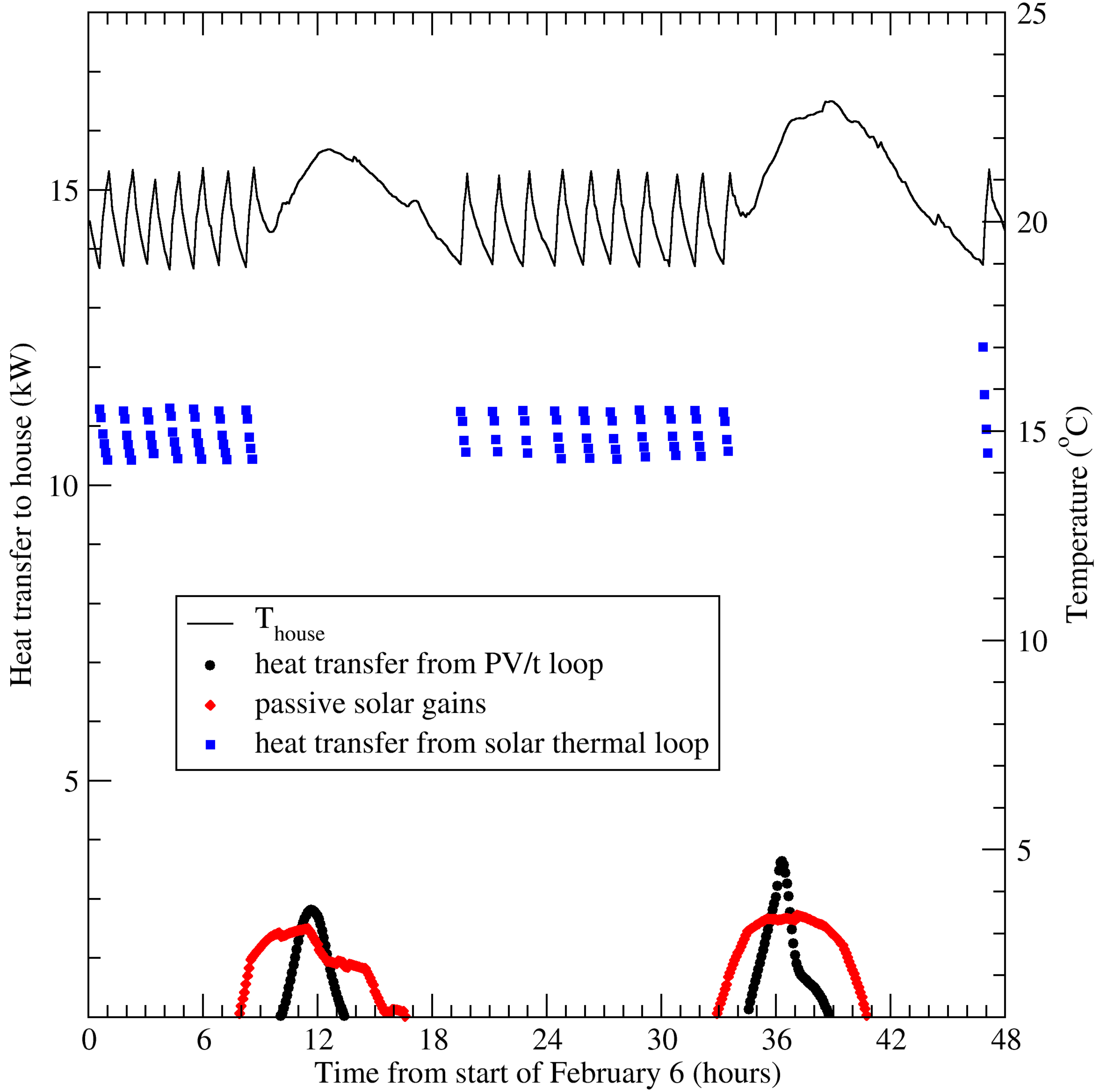
T ambient
P PV/t
Temperature (°C)
PV/t electrical production (W)
Time from start of February 6 (hours)
90
80
70
60
50
40
30
20
10
0
-10
-20
2000
1500
1000
500
0
0
6
12
18
24
30
36
42
48



T_PV/t
T_ambient
P_PV/t
Temperature (°C)
PV/t electrical production (W)
Time from start of February 6 (hours)
90
80
70
60
50
40
30
20
10
0
-10
-20
2000
1500
1000
500
0
0
6
12
18
24
30
36
42
48



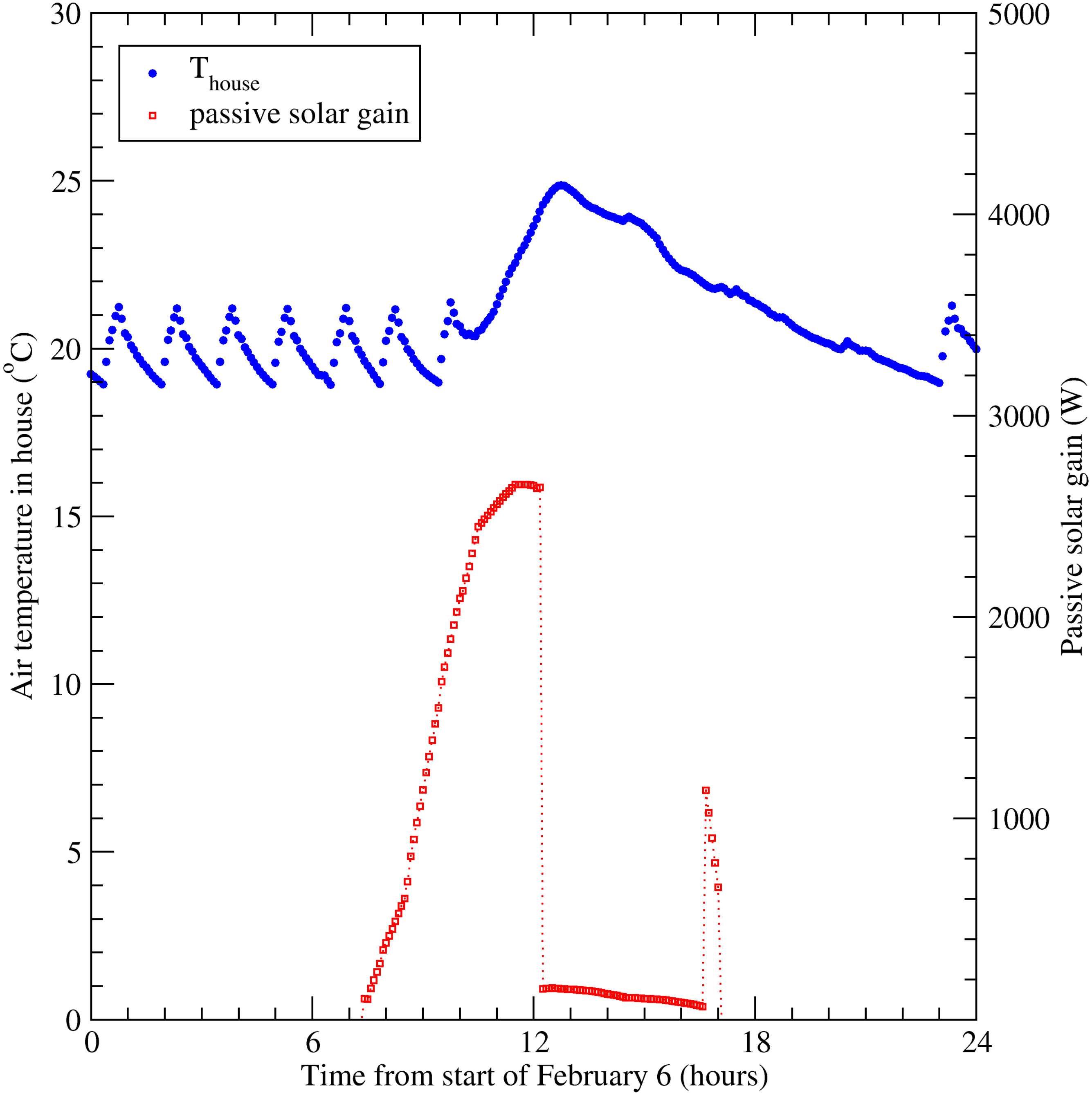
T_house
T_PV/t
T_ambient
P_PV/t
Temperature (°C)
PV/t electrical production (W)
Time from start of February 6 (hours)
90
80
70
60
50
40
30
20
10
0
-10
-20
2000
1500
1000
500
0
0 6 12 18 24 30 36 42 48



Heat transfer to house (kW)
Temperature (°C)
Time from start of February 6 (hours)
0
6
12
18
24
30
36
42
48
5
10
15
20
25
T_{house}
heat transfer from PV/t loop
passive solar gains
heat transfer from solar thermal loop

Necessity of strong coupling

- Design measure:
  - Increase air flow rate through PV/t cavity to increase heat transfer rate in air/air HX.



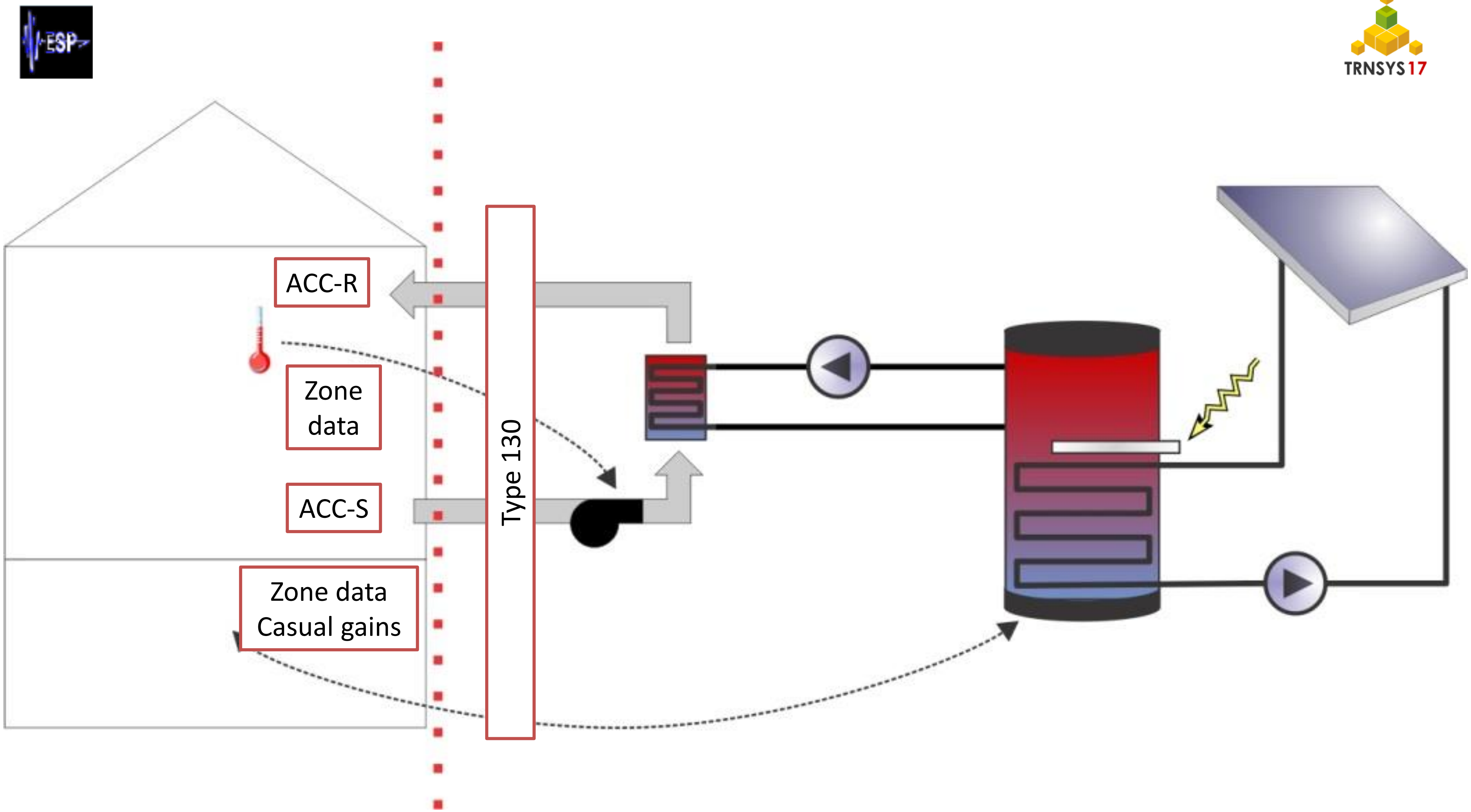
T_{house}
passive solar gain
Air temperature in house (°C)
Passive solar gain (W)
Time from start of February 6 (hours)
0
5
10
15
20
25
30
0
6
12
18
24
1000
2000
3000
4000
5000

Configuring a co-simulation : Demonstration

What?

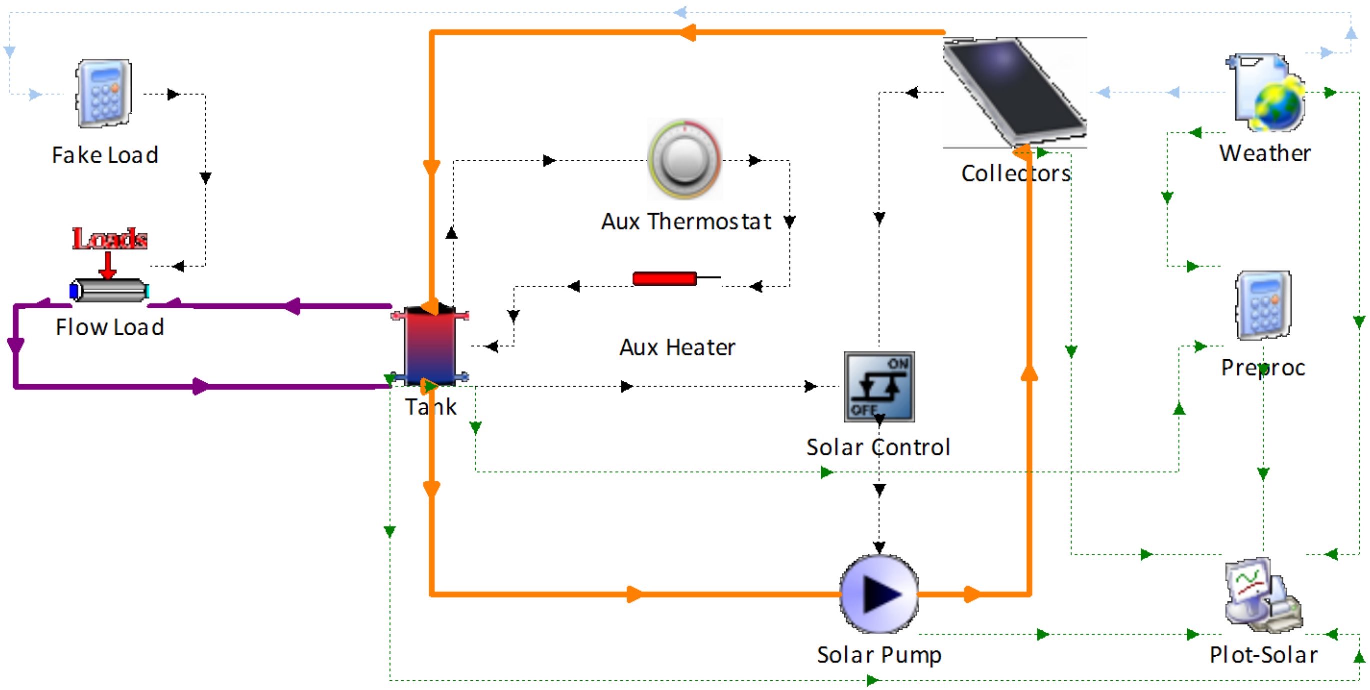
- Simple house model in ESP-r
  - Main floor, basement and attic
- Simple solar thermal system in TRNSYS
  - Use it for air-based heating (demo)
  - Use it for hydronic heating (hands-on)
- All simulations run from January 17 to February 5th
  - 14 days + 3-day warm-up
  - 5 min time step

Demo

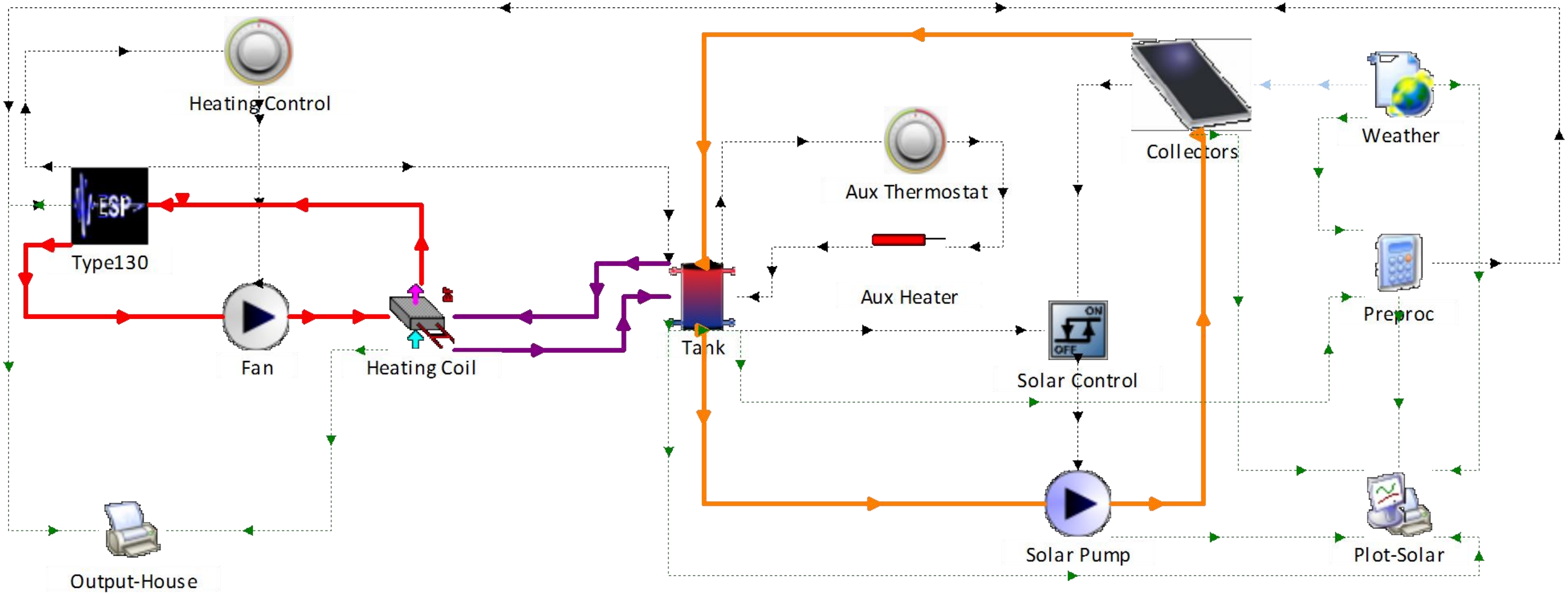


ESP-r
TRNSYS 17
ACC-R
Zone data
ACC-S
Zone data
Casual gains
Type 130

TRNSYS Starting point

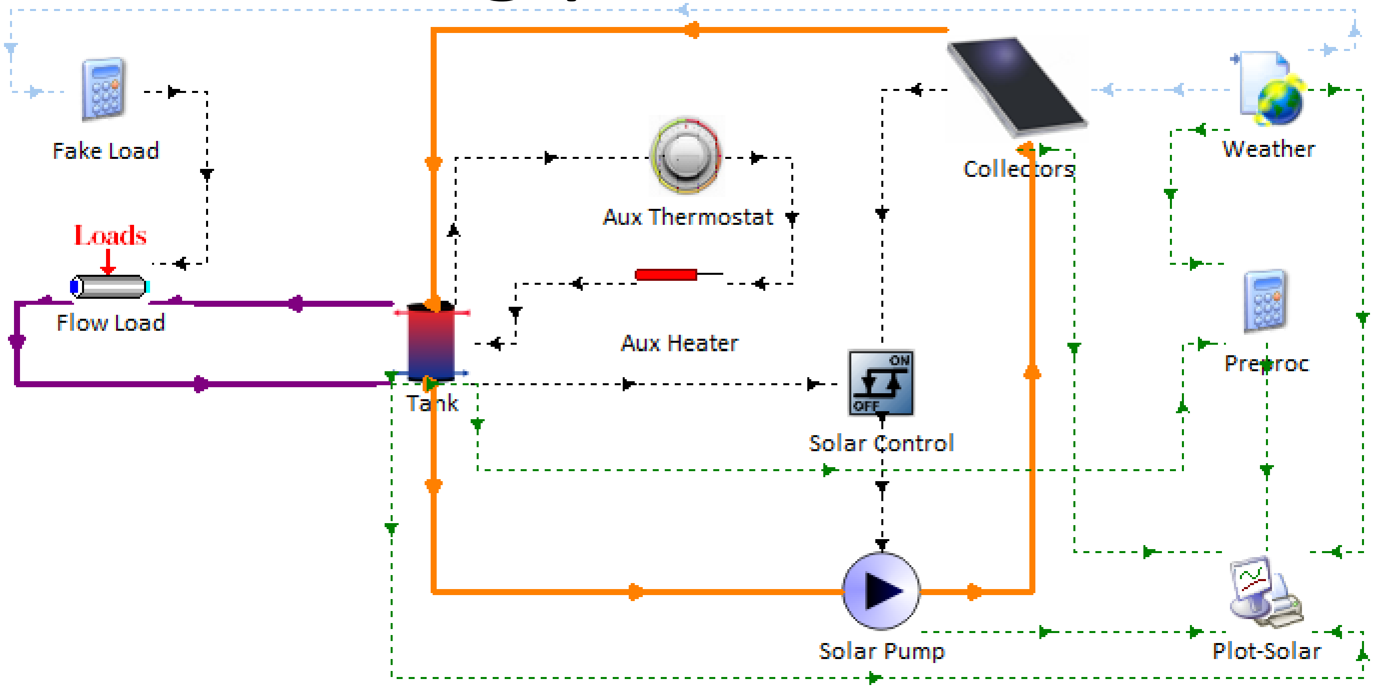


TRNSYS Project



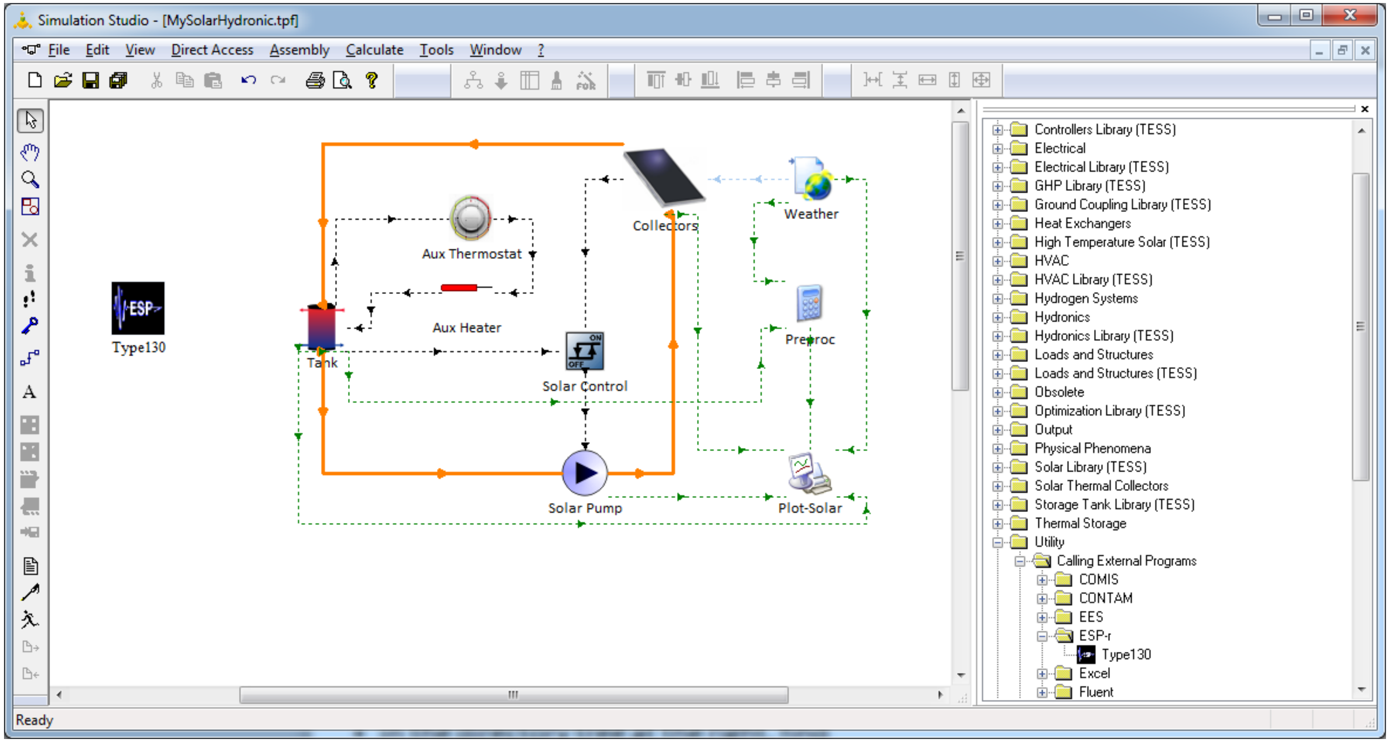
Configuring a co-simulation : Exercise

Starting point



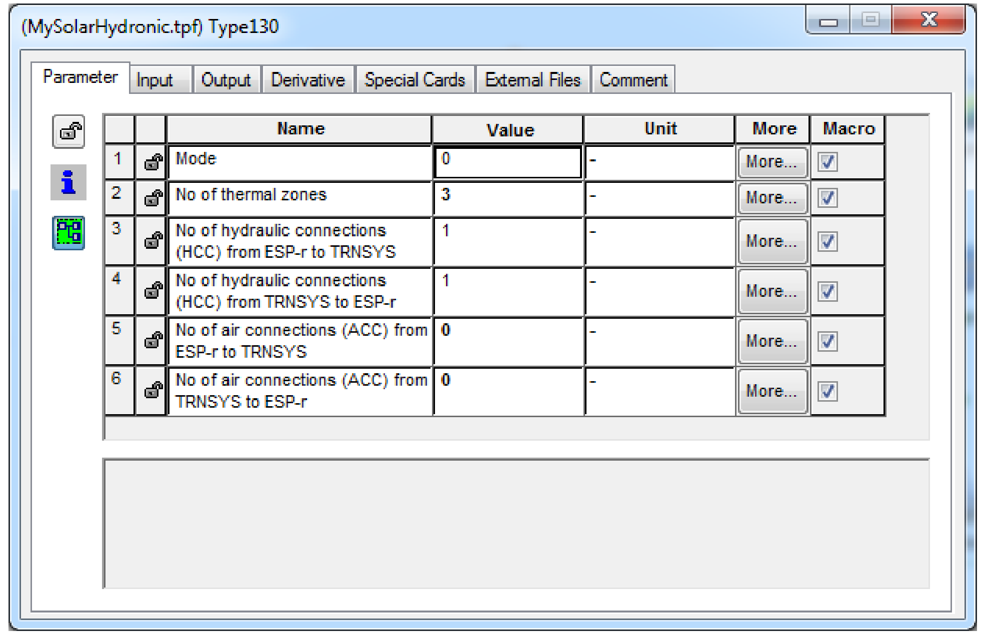
- Launch Simulation Studio
- Open C:\Trnsys17\MyProjects\CosimWorkshop\Hands-on\SolarOnly.tpf
- Run (F8 or Calculate/Run Simulation)
- Explore results (zoom, shift + mouse)
- Save as C:\Trnsys17\MyProjects\CosimWorkshop\Hands-on\MySolarHydronic.tpf

Remove fake load and add link to ESP-r (Type 130)



- Delete components (Calculator and “Loads”) – links are deleted automatically
- In the directory tree at the right, find Utility\Calling External Programs\ESP-r\Type130
- Drag it to the project (on the cloud you need to select fist and insist)

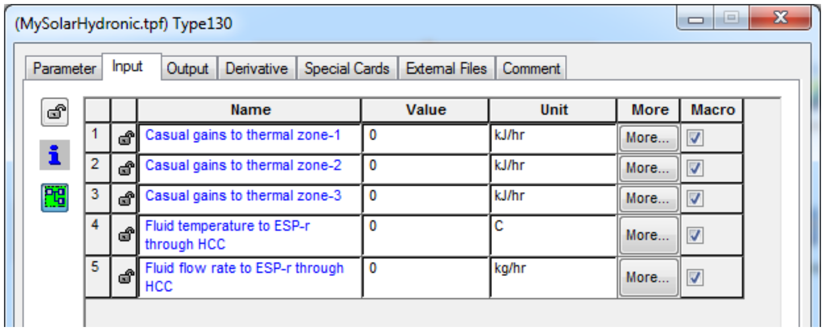
Configure link to ESP-r (Type 130)

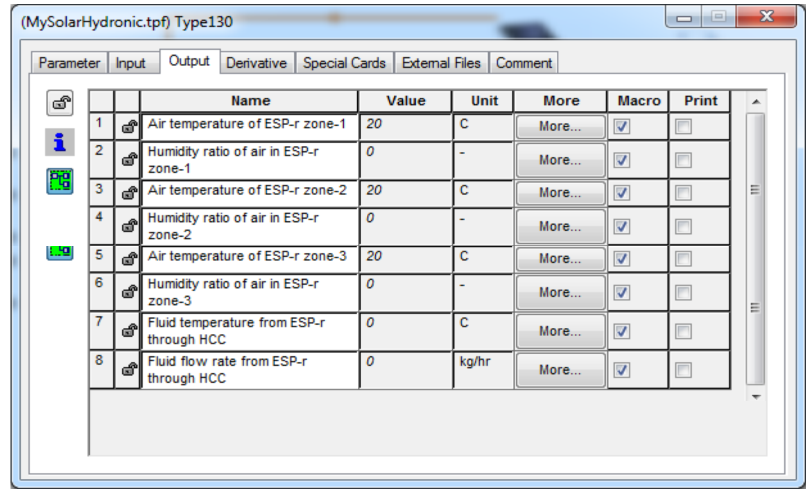


	Name	Value	Unit	More	Macro
1	Mode	0	-	More...	☑
2	No of thermal zones	3	-	More...	☑
3	No of hydraulic connections (HCC) from ESP-r to TRNSYS	1	-	More...	☑
4	No of hydraulic connections (HCC) from TRNSYS to ESP-r	1	-	More...	☑
5	No of air connections (ACC) from ESP-r to TRNSYS	0	-	More...	☑
6	No of air connections (ACC) from TRNSYS to ESP-r	0	-	More...	☑

- Double-click on icon
- Change parameters:
  - 3 thermal zones (parameter 2)
  - 0 air connections (parameters 5 and 6)
  - Others unchanged (e.g. hydraulic connections: 1

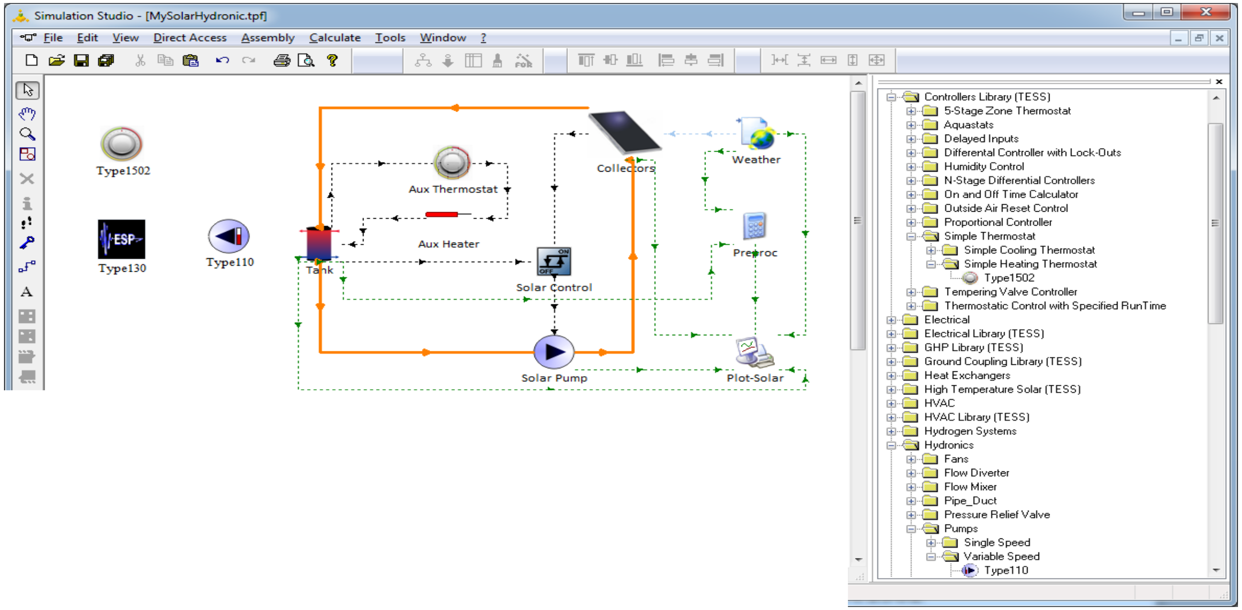
Explore Type 130 inputs and outputs





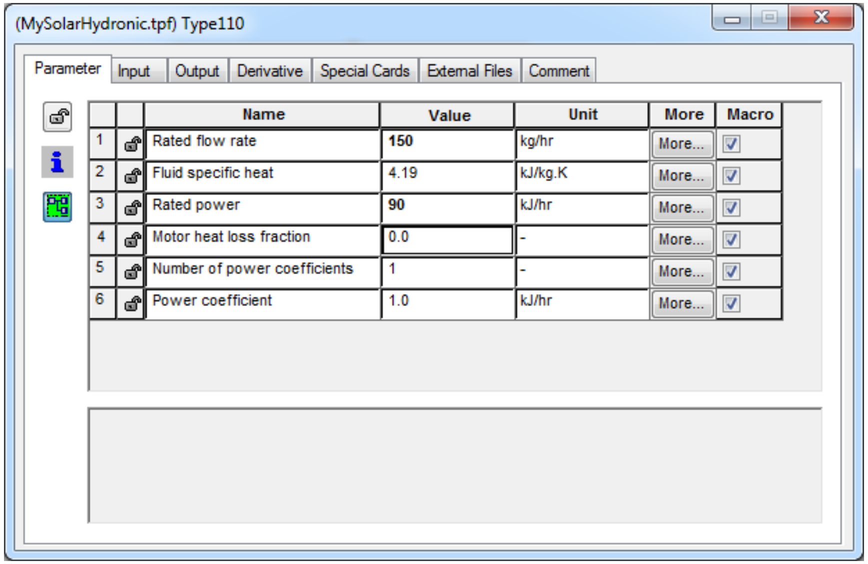
- Different tabs in the proforma (window that opens when you double-click on icon)
- Inputs
  - Casual gains for each zone
  - Inlet flowrate and temperature for hydronic connection (HCC)
- Outputs
  - Temperature and humidity of each zone
  - Temperature and flowrate of hydronic connection (HCC)

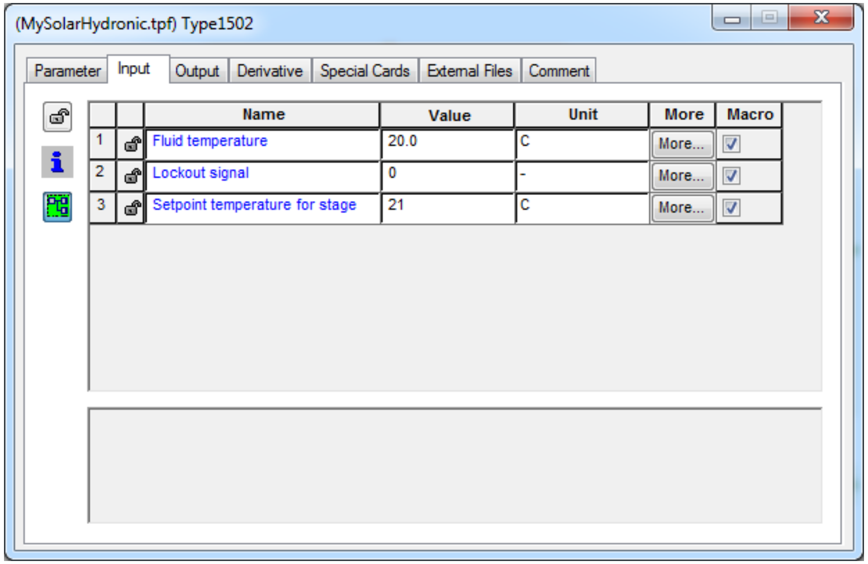
Add components for hydronic loop



- Pump
  - Hydronics\Pumps\Variable Speed\Type110
  - Note: to flip icon, right-click, Graphic/Flip horizontal
- Thermostat
  - Controllers Library (TESS)\Simple Thermostat …
    … \Simple Heating Thermostat\Type1502

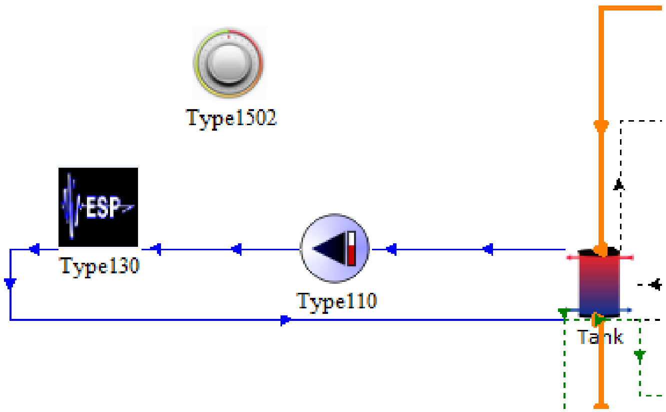
Configure pump and thermostat

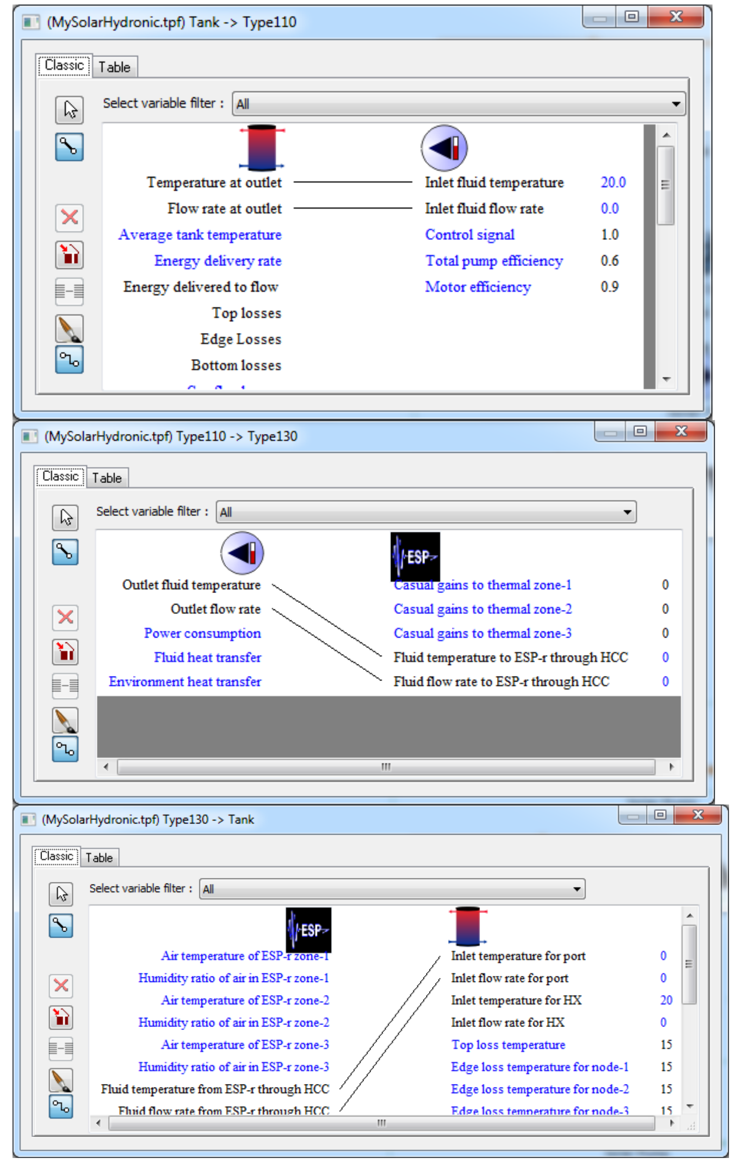




- Pump parameters
  - Rated Flowrate (parameter 1): 150 kg/h
  - Rated power (parameter 3): 90 kJ/h, i.e. 25 W
- Thermostat inputs
  - Setpoint temperature (input 3): 21 °C
    Will not be connected so will keep the entered value – for connected inputs, the entered value is only the initial condition
  - Note: the setpoint is centered around a 2 °C deadband (parameter 3, unchanged)

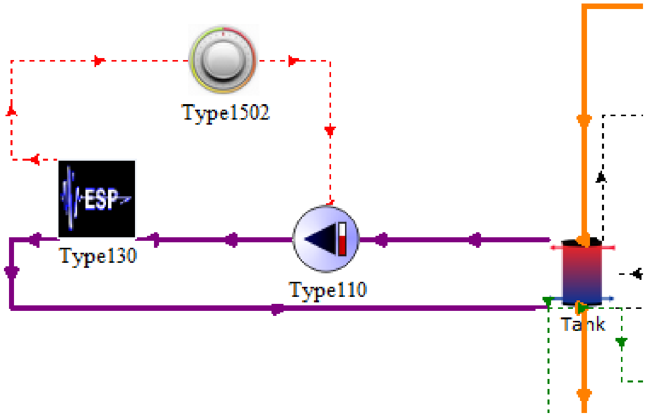
Define the hydronic loop

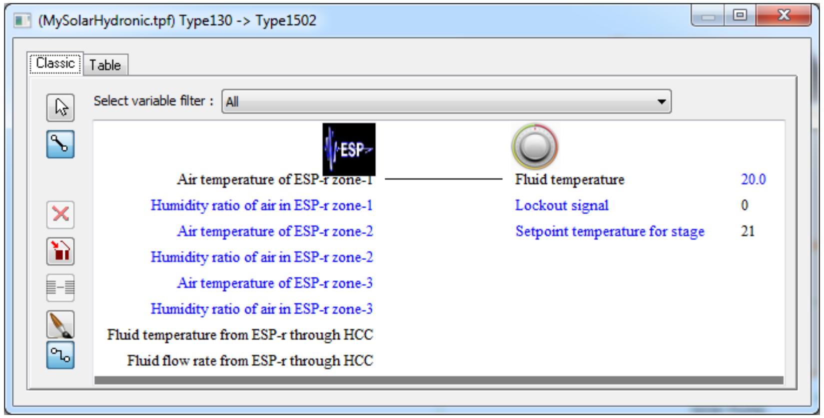




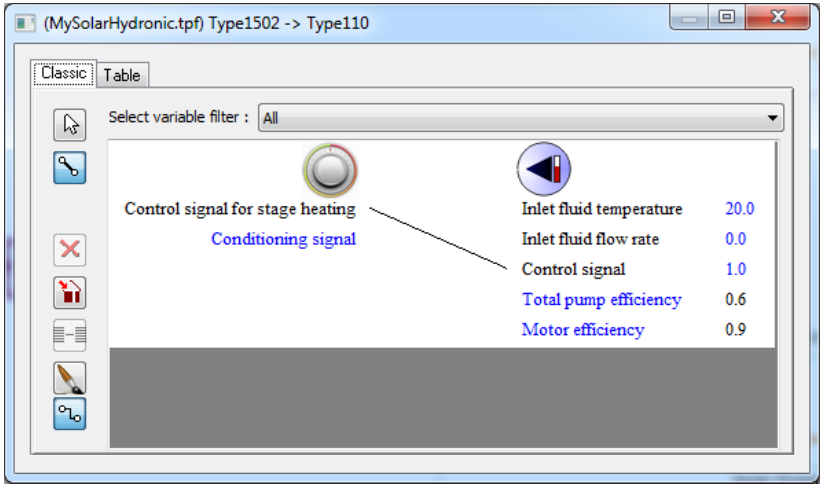
- Use Link tool (arrow on the left)
  - Double-click on link to set actual connections (automatically when creating link)
- Link Tank to Pump
  - Temp and flow at outlet to inlet temp and flow
- Link Pump to Type 130
  - Outlet temp and flow to temp and flow through HCC
- Link Type 130 to Tank
  - Temp and flow from HCC to temp and flow at inlet port
  - , Pump to Type 130, Type 130 to Tank

Define the control loop



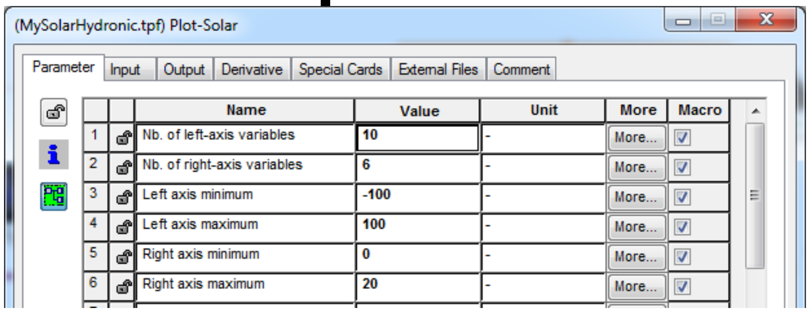


- Use Link tool (arrow on the left)
  - Double-click on link to set actual connections (automatically when creating link)
- Link Type 130 to thermostat (Type 1502)
  - Air temp of zone 1 (main floor) to “fluid” temperature
- Link thermostat to pump
  - Control signal to control signal

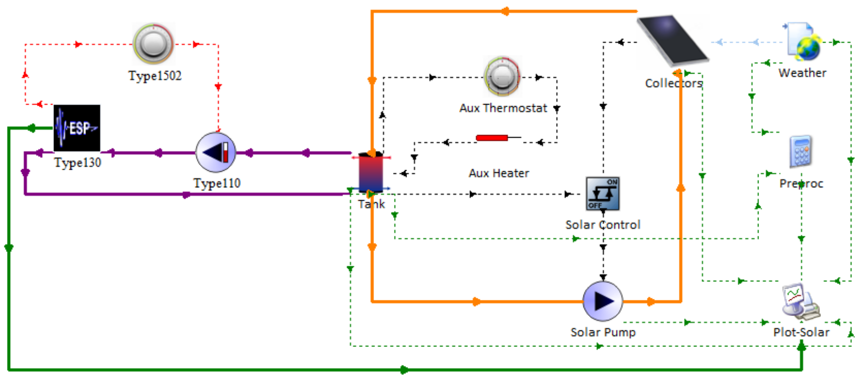


Add outputs to online plotter

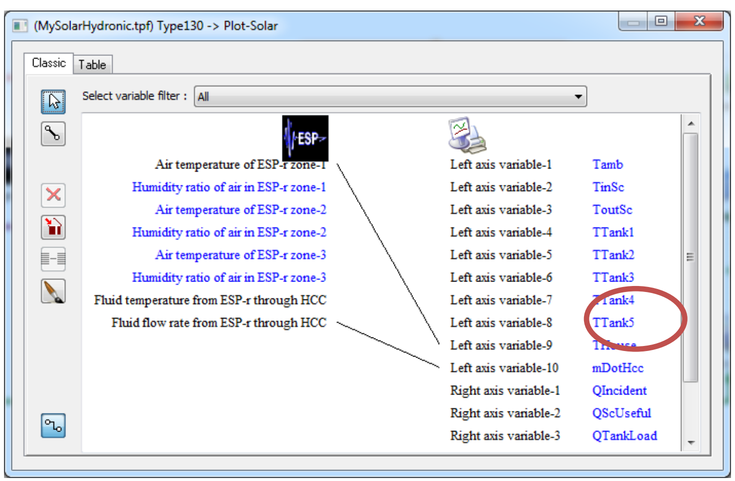
- Double-click on online plotter and change parameter 1 to have 10 variables



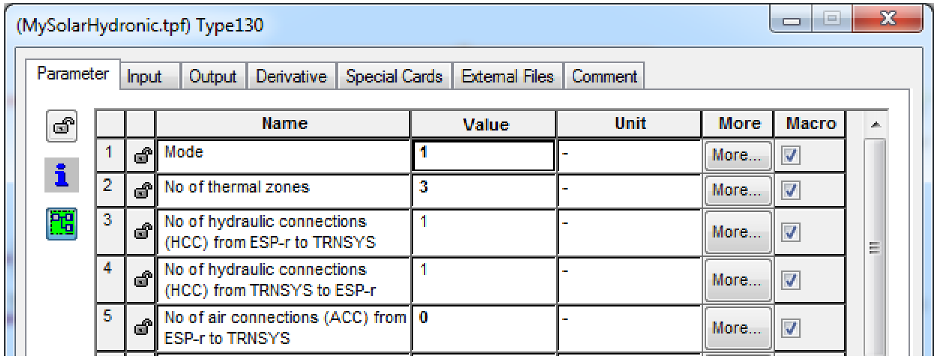
- Link Type 130 to online plotter
  - Connect temp of zone 1 and flow from HCC to the 2 empty inputs



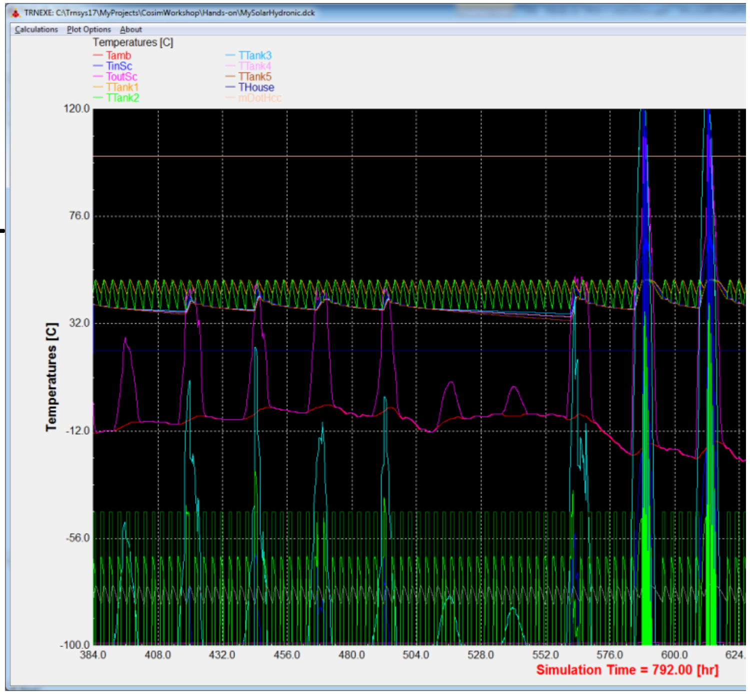
- Change name of variables in “input” tab of online plotter
  - double-click, switch to input tab and change Tamb by THouse and mDotHcc
  - Can be done in the link window by selecting the arrow tool and double-clicking on the name in blue



Test the simulation in TRNSYS only

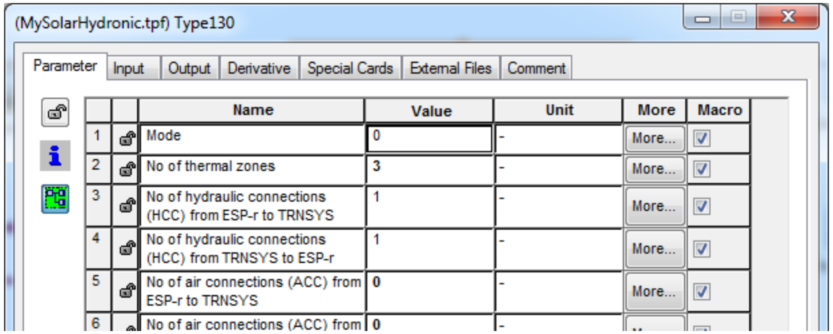


- Set Type130 in test mode
  - Double-click, change parameter 1 to 1
- Run
  - Simulation runs with constants (fake) outputs from Type 130
  - Useful to check whether connections make sense

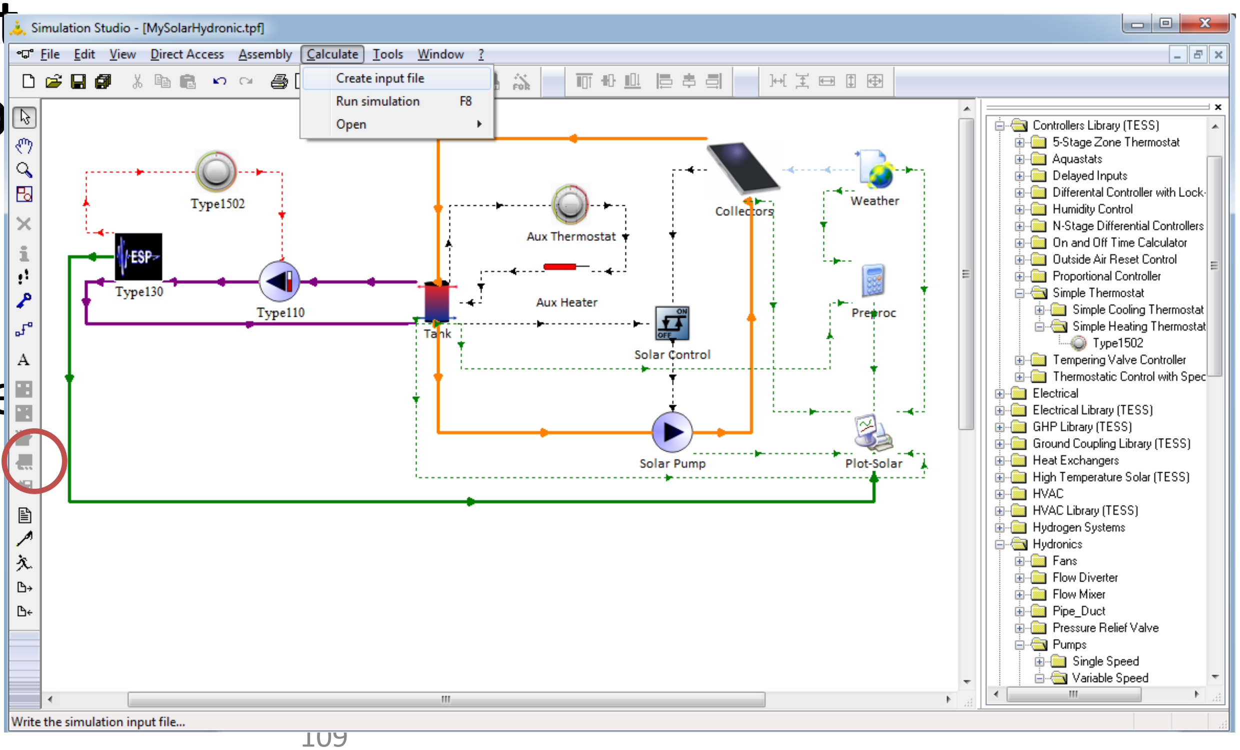


Prepare the input file for cosimulation

- Set Type130 back to normal mode
  - Double-click, change parameter 1 to 0



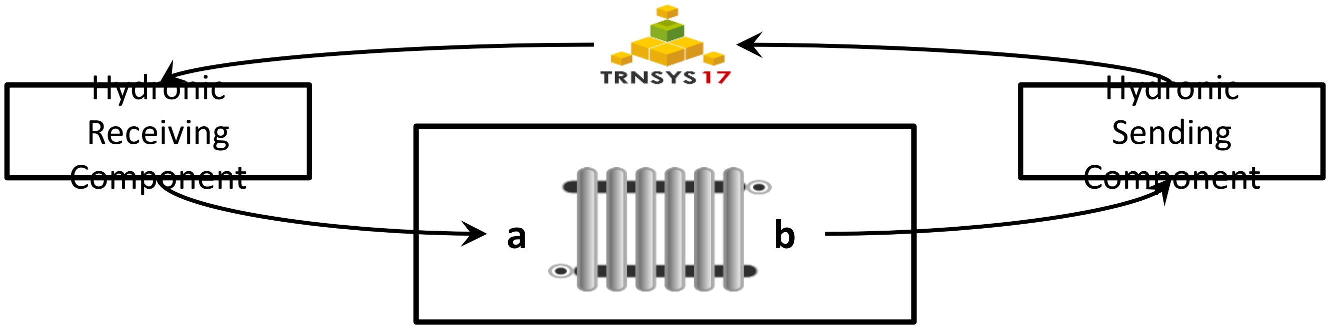
- Do NOT run, but generate the input file ("Deck" file)
  - Calculate / Create Input file or "pen" icon



Co-simulation Workshop
Exercise: ESP-r Plant Network Setup
May 22nd, 2013

Part 2: ESP-r Plant Network

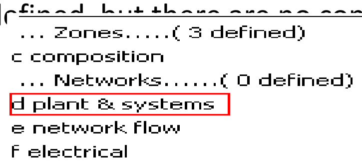
This section guides you through the setup of a simple hydronic heating system in ESP-r . A radiator is modeled in ESP-r and is supplied by a hot water stream in TRNSYS. A visual representation of this network is provided below.



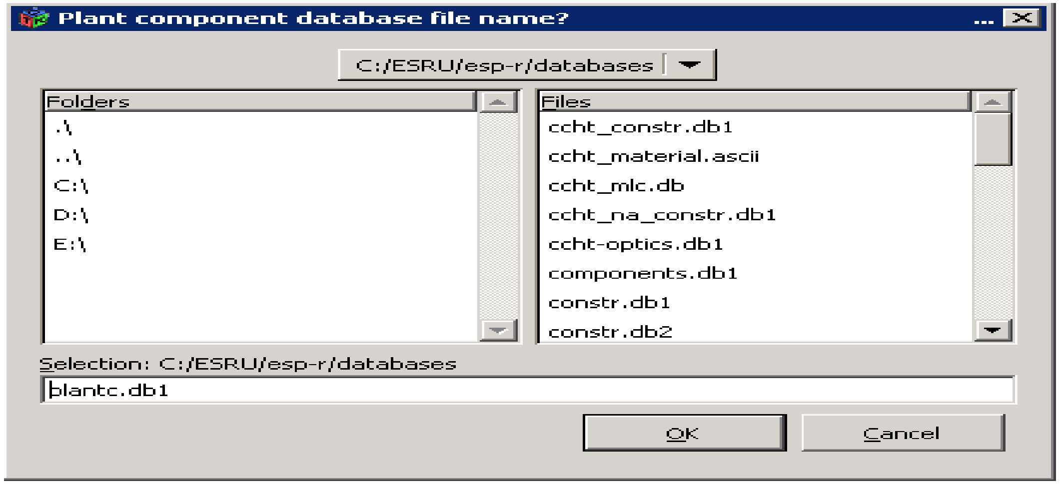
Part 2: ESP-r Plant Network Cont'd

Section A: Define Components and Connections

1. Launch ESP-r.
2. Under **Model Selection** click **open existing** then select **other.**
3. Under Folders double click **C:**, then **Cosim_demo**, then **cfg**. Under files, select **Cosim_demo.cfg**
4. A window will pop up warning you that files are out of date. Select **default(yes).**
5. Once the model has loaded navigate to **Current model** in the right side pane and select **browse/edit/simulate.**
6. You will see that 3 zones have been defined, but there are no controls or networks. Click on **plant & systems** under **Network.**



7. Select **Explicit** since were are going to model individual components of the plant network. ESP-r will inform you that there is currently no network. Select **yes** to create one.
8. Accept the default name for the plant network file name, then select **yes** to proceed with network definition.
9. ESP-r will now ask you to point to the plant component databases. Use the default network that is provided:



Part 2: ESP-r Plant Network Cont'd

10. Since this is a hydronic system, select **Water-Based heating system**, then click **exit menu**.
11. First we will define the components. Click on **Components**. Then select **Add** components. Select **wet central heating** then **domestic hot water radiator** (selection "b"). Then click **exit menu** at the bottom of the pane.
12. You will be asked to supply a name. Let's call it "Radiator" for simplicity. We will be prompted to change component parameters. Select **yes.**
13. You should then see the

```
 Plant comp : Radiator
a Component total mass (kg)                        :  25.000      *
b Mass weighted average specific heat (J/kgK)      :  600.00
c Radiator exponent (-)                            :  1.3000      *
d Nominal heat emission of radiator (W)            :  1005.0      *
e Nominal supply temperature (C)                   :  90.000      *
f Nominal exit temperature (C)                     :  70.000      *
g Nominal environment temperature (C)              :  20.000      *
h Index of coupled building zone (-)               :  0.0000      *
i Number of walls used for defining Te (-)         :  0.0000
j Index of 1st wall for defining Te (-)            :  0.0000
k Weighting factor 1st wall when defining Te (-)   :  0.0000
l Index of 2nd wall for defining Te (-)            :  0.0000
m Weighting factor 2nd wall when defining Te (-)   :  0.0000
* All items in list
 ______________________________________________

? help
- exit this menu
```

14. Click on all the parameters with an asterisk (*) beside them in the above image, then click **exit menu.**
15. Input the values given in the Table below . The index for zone coupling is **1** (The main zone).

Component mass (kg)	50
Specific heat (J/kg K)	600
Radiator exponent	1.6
Nominal emission (W)	2500
Nominal supply (°C)	45
Nominal return (°C)	30
Nominal environment (°C)	21

Part 2: ESP-r Plant Network Cont'd

16. Review the parameters to make sure everything is correct, then select **exit menu**.
17. Radiator should now be listed under **Components**.
18. The second step is to add the coupling plant components.

0 Page --- part: 1 of 3 ---

19. Click **add**, then **solar and other**. The coupling components are on the last page of the components list. Click on
20. Select the **HCC-T**. This is the component that sends data from ESP-r back to TRNSYS. Then click **exit menu** and name it "HSC". This time, we do not want to change the component data, so select **default (no).**
21. Do the same for the **HCC-E**. Name it "HRC". This is the component that receives data from TRNSYS. Your component list should now look like this:

Components

	Name	ref no.	Type
a	Radiator	12	water heating
b	HSC	106	solar and other
c	HRC	107	solar and other

+ Add/Delete/Copy

22. All the components we will be using in ESP-r has been defined. Now we need to define the linkages between the components. Exit out of the components list and back to the **Plant Network** main menu. Select **Connections**. Note that ESP-r has no visualization for plant networks. The plant diagram on page 1 now comes in handy.
23. Select **Add**, then you will first be prompted for a receiving component. We'll start with the **Radiator**. The radiator is a 2-node model. The inlet of the Radiator is **node a**, so select that as receiving then click **exit menu.**
24. The inlet of the radiator is fed by **another component**, so select that option from the menu and then click **exit menu**.
25. The radiator is supplied by the **HCC-E** component, or "HRC" in our case, so select that. 100% of the flow coming out of HRC is entering the radiator, so leave the mass diversion ratio at the default value of **1.**
26. Now establish the connection between the receiving component "HSC" and the **Radiator** (outlet **node b**).
27. To complete the r ... as the receiving compon

Connections

	Sending comp @	Node	to	Receiving comp @	Node	Conn Type	Mass Div
a	HRC	water node 1	-->	Radiator	water node 1	to compt	1.000
b	Radiator	water node 2	-->	HSC	water node 1	to compt	1.000
c	HSC	water node 1	-->	HRC	water node 1	to compt	1.000

+ add/delete/copy

Part 2: ESP-r Plant Network Cont'd

28. Once all the connections look good, exit out of the **Connections** menu, then exit out of the **Plant Network** menu. You will be asked if you want to save any changes. Select **yes**. Accept the file name and select **yes** to overwrite file.
29. Click **exit** and you should be back at the **browse/edit/simulate menu.**

Section B: Link Plant to Zone

Now that the plant network has been established, we need to create the link between ESP-r's plant and thermal zone solvers. This link tells the plant network, specifically the radiator in our case, where to inject the flux from the plant component. This linkage is accomplished through ESP-r's control files. The following will guide you through setup of this linkage for this exercise.

1. Under **Controls** in the **browse/edit/simulate** window, select **zones** (selection j).
2. Accept the default name, then click **make new file**. This will be a **Just One Day type** control with **1 period.**
3. The **Controls menu** should now be displayed. Click on the control period (**selection e**).
4. The **Editing Options** should now be displayed.

```
Editing Options
a sensor details
b actuator details
c period data
```

5. Since we are establishing a link and not a control scheme, the sensor details is not important here. The **actuator details** however, tell ESP-r how the plant flux is introduced to the zone. Click on **actuator details**.
6. You will be presented with several options. Since this is a radiator, we will select a **mix of convection and radiation**.
7. ESP-r will ask you which zone to supply heat to. For this example, we select **main**.
8. You will be asked to provide a **convective weighting factor**. For this case, lets assume **40**.
9. You should now be back at the **Editing Options** menu. We now need to establish the **period data**.
10. You will be presented with a **Control Periods** menu. There should only be one period, **selection a**. Click on it to edit the data.

```
Control periods
 control loop  1  (active on all daytypes)
 number of periods:  1
 ________________________________________________
 per|start|sensed  |actuated | control law     | data
 no.|time |property|property |                 |
a  1  0.00 db temp   > flux   free floating
 ________________________________________________
```

Part 2: ESP-r Plant Network Cont'd

15. Select **Law**, then select **Flux connection between plant & zone** (selection f) and then click **exit menu**.
16. Select the default values for **number of periods** and **miscellaneous data**.
17. The supply plant component in our case is the **Radiator**, specifically **node b**.
18. The coupling type is **heat flux transfer (2.00)**.
19. For maximum heating flux, input 4000 W (Recall the nominal output for the radiator was 2500 W defined previously.
20. Cooling flux is **0 W**.
21. An **extract component** is then requested. This is for coupling type 1.0 ($mc_p\Delta T$). Although this input is not used for the flux heat transfer coupling that we are using, ESP-r demands a value, so select the **Radiator node b**.
22. You should now be back at the **Control Periods** menu. Exit that menu and the Editing Options menu.
23.

```
 Overall description:
 no overall control description supplied
 Zones control includes  1 functions.
 no zone control description supplied

 The sensor for function  1 senses the temperature of the current zone.
 The actuator for function  1 is mixed convective/radiant flux in main.
There have been  1 periods of validity defined during the year.
 Control is valid Sat-01-Jan to Sat-31-Dec, 1966 with  1 periods.
 Per|Start|Sensing  |Actuating  | Control law description
   1  0.00 db temp   > flux     plant/zone coupling: source plant component 1 plant
component node 2 coupling type hrA(Os-Oa) concurrent. Max heating 4000.00W max cooling
0.00W. Extract plant component 1 and extract node 2.

Zone to contol loop linkages:
zone ( 1) main        << control  0
zone ( 2) basement     << control  0
zone ( 3) attic       << control  0
```

24. The last step is to **link loops to zones** (selection d). The main zone is receiving heat from the radiator and is associated with control function **1**. All other are free floating with control function **0**.
25. Once association is done exit out of the control menu. You will be prompted to save. Select **yes**.

Computer Setup

- Limited to WindowsOS.
- Read the Getting Started manual: 

- TRNSYS:
  - Get a license.
  - Install it.
- ESP-r:
  - Install MinGW.
  - Install a Subversion client (e.g. TortoiseSVN).
  - “svn checkout” ESP-r source code.
  - Install ESP-r under MinGW.
- Harmonizer:
  - Bundled with ESP-r source code.
  - Run ESP-r Install script with “—co-sim” option.

Conclusions

- ESP-r / TRNSYS co-simulation:
  - Exploits complementary strengths.
  - More highly resolved treatment of integrated architectural/energy systems.
- Strong (aka onion) coupling:
  - Enables collaborative treatment of HVAC systems.
  - Critical when building and energy systems tightly coupled.
- Stability and numerical accuracy demonstrated.
- Availability:
  - ESP-r version 12.0.
  - TRNSYS version 17.1.
  - Harmonizer bundled with ESP-r source code.
  - Limited to WindowsOS.
- Computational burden modest:
  - 60-65% increase in runtimes relative to mono-simulation.