# Sous-Station de Réseau de Chaleur
## Architecture, Contrôle et Innovation

JEUDI 27 MAI 2021

**N. Lamaison**

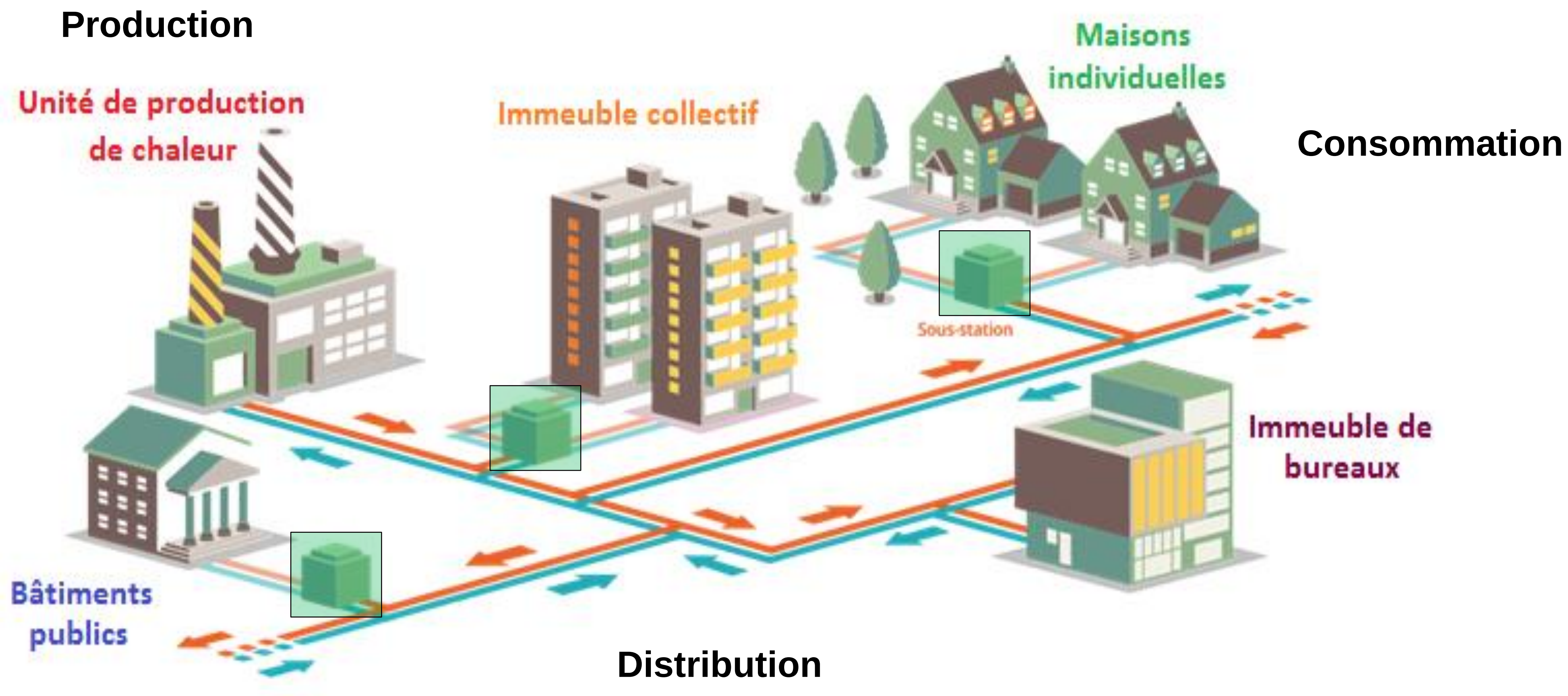
- **Donner un aperçu de la technologie actuelle des sous-stations**
- **Présenter un ensemble de sujets de recherche traités au CEA Liten**

- **Introduction: Généralités sur les réseaux de chaleur et les sous-stations**

- **Architecture et contrôle**
    - Logique de contrôle globale
    - Différentes architectures primaire / secondaire
    - Détaille d’une architecture
    - Equipements
    - Dimensionnement
    - Analyse de données
    - Challenges futurs

- **Innovation**
    - Topic 1: Critical Temperature
    - Topic 2: Prosumer Substation
    - Topic 3: Innovative Design with Primary Storage
    - Topic 4: Advanced Control
    - Topic 5: Flat Substation
    - Topic 6: Faults detection in substation

# GÉNÉRALITÉS SUR LES RÉSEAUX DE CHALEUR ET LES SOUS-STATIONS


Production
Unité de production
de chaleur
Immeuble collectif
Maisons
individuelles
Consommation
Sous-station
Immeuble de
bureaux
Bâtiments
publics
Distribution

**Heat production unit**

Biomass boiler, CHP, Waste incineration, etc.

**Heat carrier Fluid**

Pressurized water, steam

**Distribution network**

Two-pipes (supply / return)

**Customers**

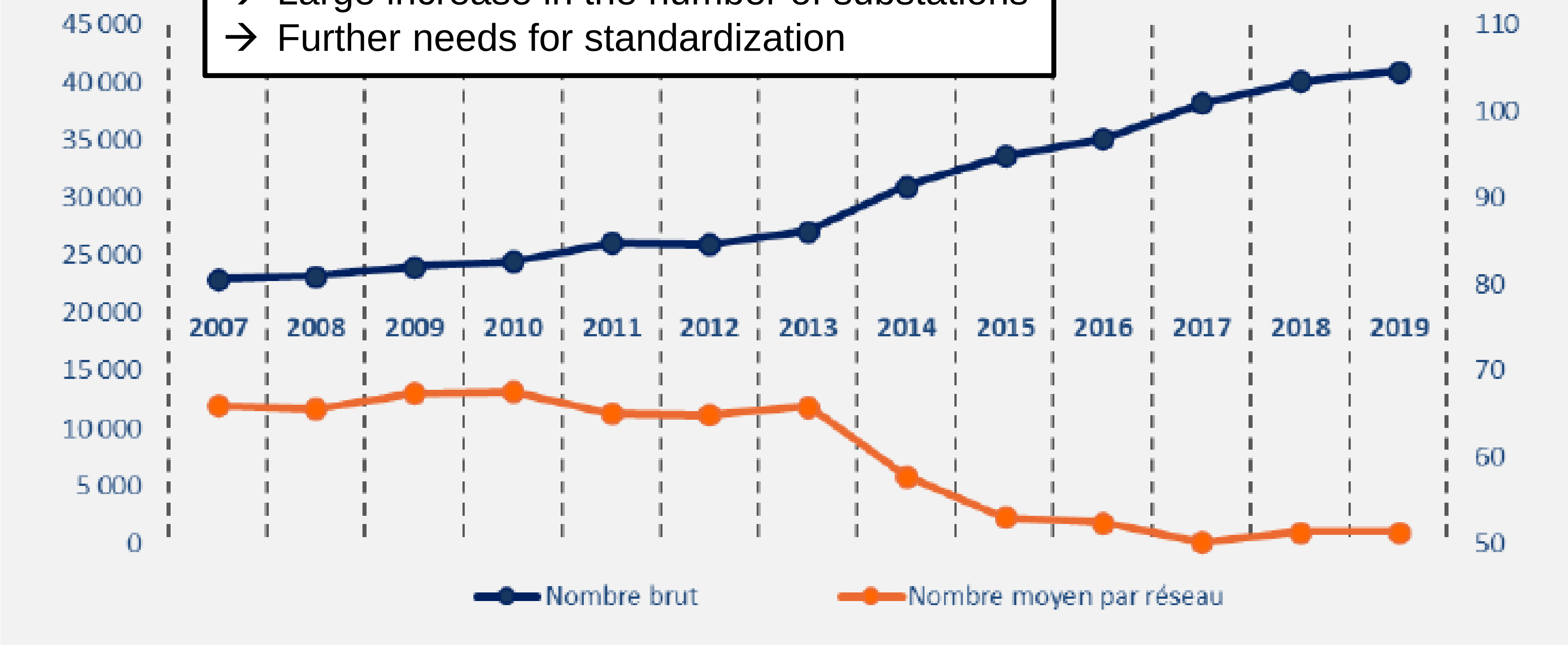
- DHW production
- Space heating
- (Industrial processes)

**Sub-station**

Where heat is delivered to the customer

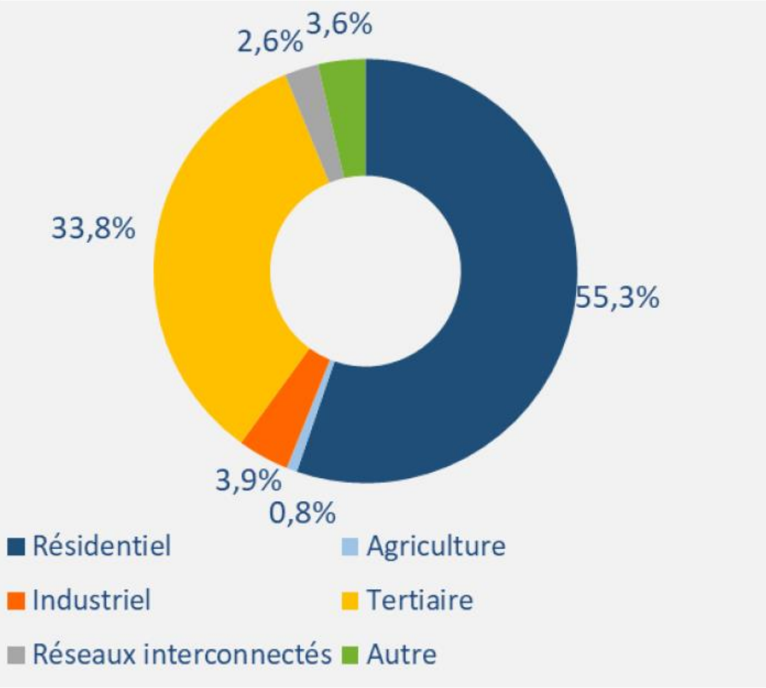
« Les réseaux de Chaleur – Le service chaleur à domicile », Agence française pour la maîtrise de l'énergie, Paris, 1991

**Develoment of DHN**
→ Large increase in the number of substations
→ Further needs for standardization



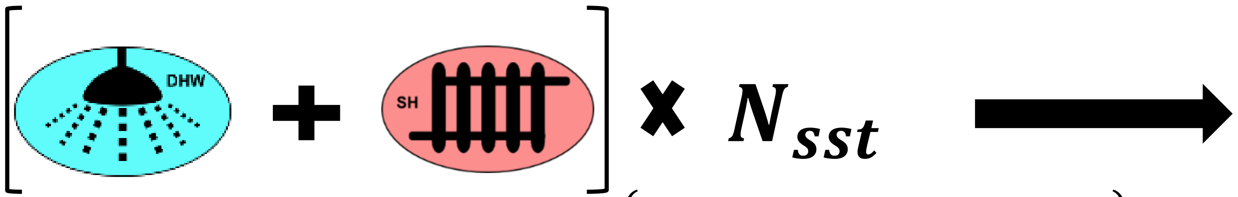

**Number of Substations**

**Delivery at customer**




SNCU, "Les réseaux de chaleur et de froid - Résultats de l'enquête annuelle: Chiffres clés,analyses & évolution - Données 2019," 2020

# Heat loads



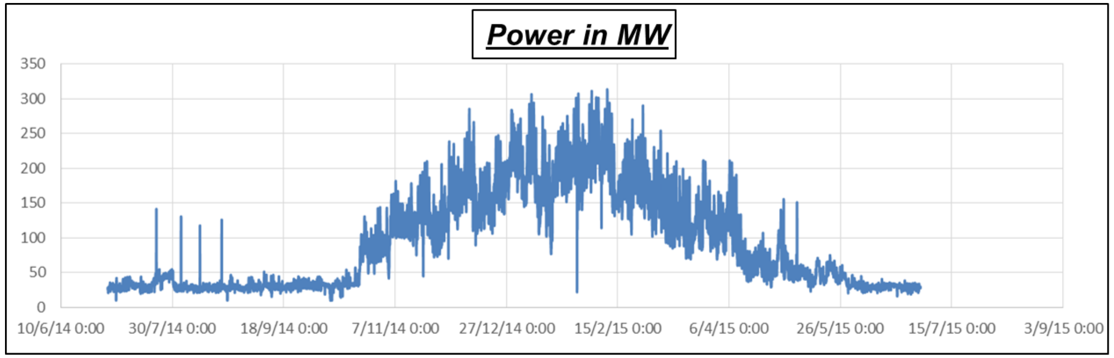

$$\left[ Q_{DHW} + Q_{heating} \right] \times N_{sst}$$

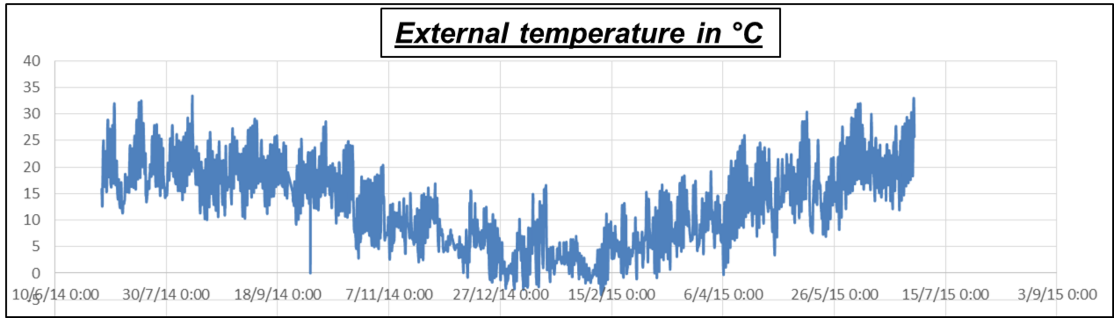
$Q_{DHW}$

$Q_{heating} = f(T_{ext}, Q_{internal,gains}, Q_{solar})$

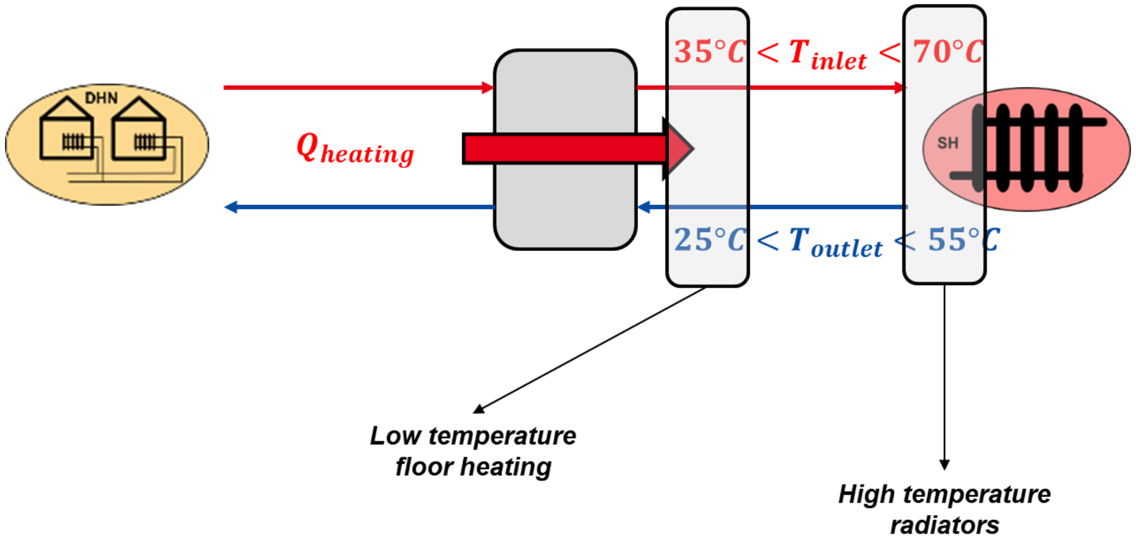
Daily and Weekly variations

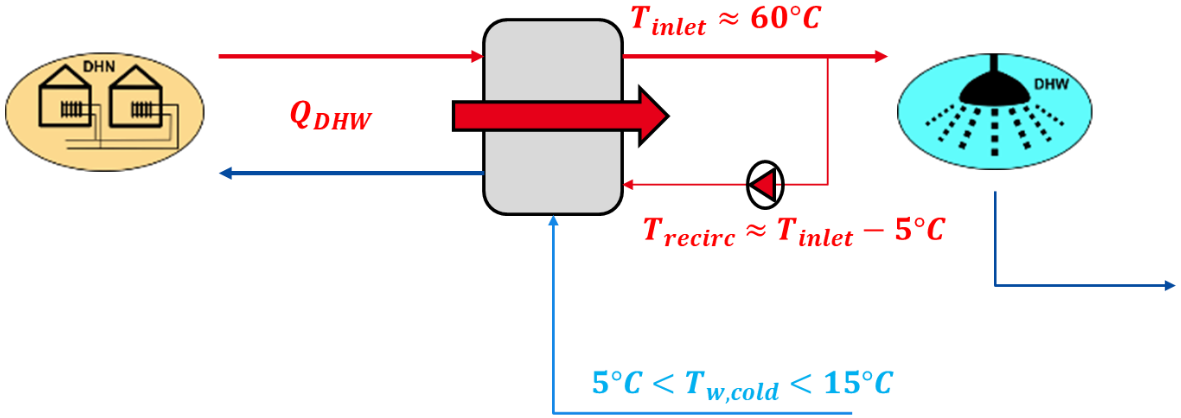
Seasonal and daily variations



# Temperature Levels




WARNING

***Legionella growth: from 20 °C to 45 °C***

RATED POWER

40kW | 300kW | 700kW | 10MW


Flat substation
(DHW and SH separated)


~ 30 poorly insulated housings

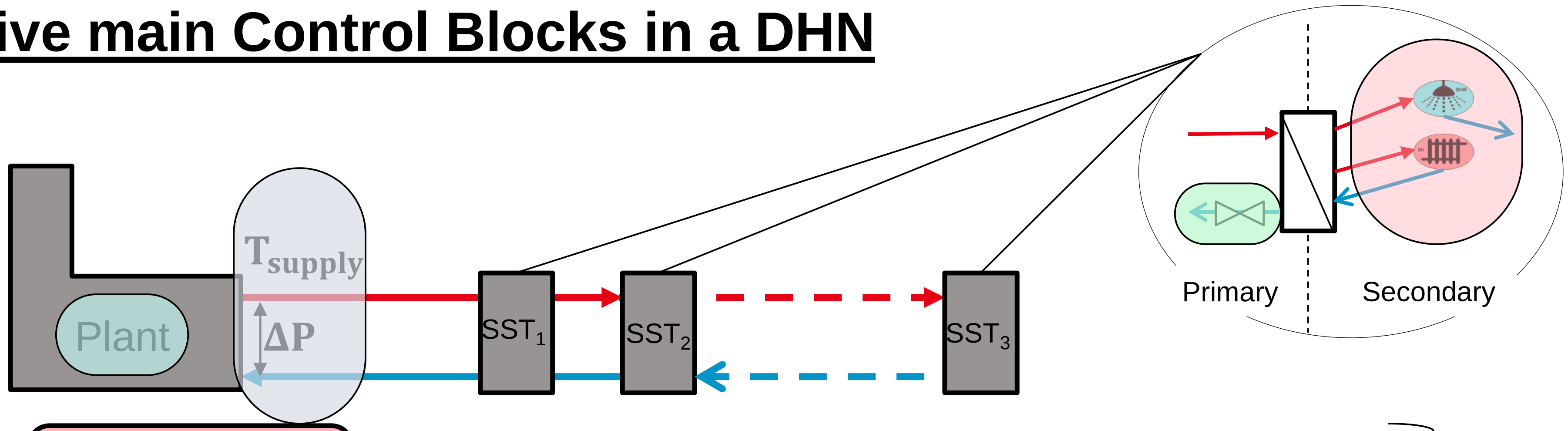

~ 70 poorly insulated housings


Area Substation between HP and LP networks

| Electrical Network Substation | Thermal Network Substation |
|---|---|
| Voltage Level Lowering | Temperature and Pressure Level Lowering |
| Significant High to Low Voltage difference | Small High to Low Temperature and Pressure difference |
| Located far from Buildings and serve a large area (to avoid risks) | Located close to the Building it is supplying (to reduce heat loss) |
| Transformers | Heat Exchangers and Valves |
| Fuses | Differential pressure control valve and flow limiters |
| Utility company ownership | Shared ownership (building owner and utility company) |
| Very standardized | Standardization still needed to further reduce costs |

# ARCHITECTURE ET CONTROLE

# Five main Control Blocks in a DHN




Substations set both:
- Mass flow rate
- Return temperature

**Heat Demand Control** — Manual Tap opening for DHW and Thermostatic Valve of customers

**Flow Control** — SST valve opening to satisfy a given secondary side temperature

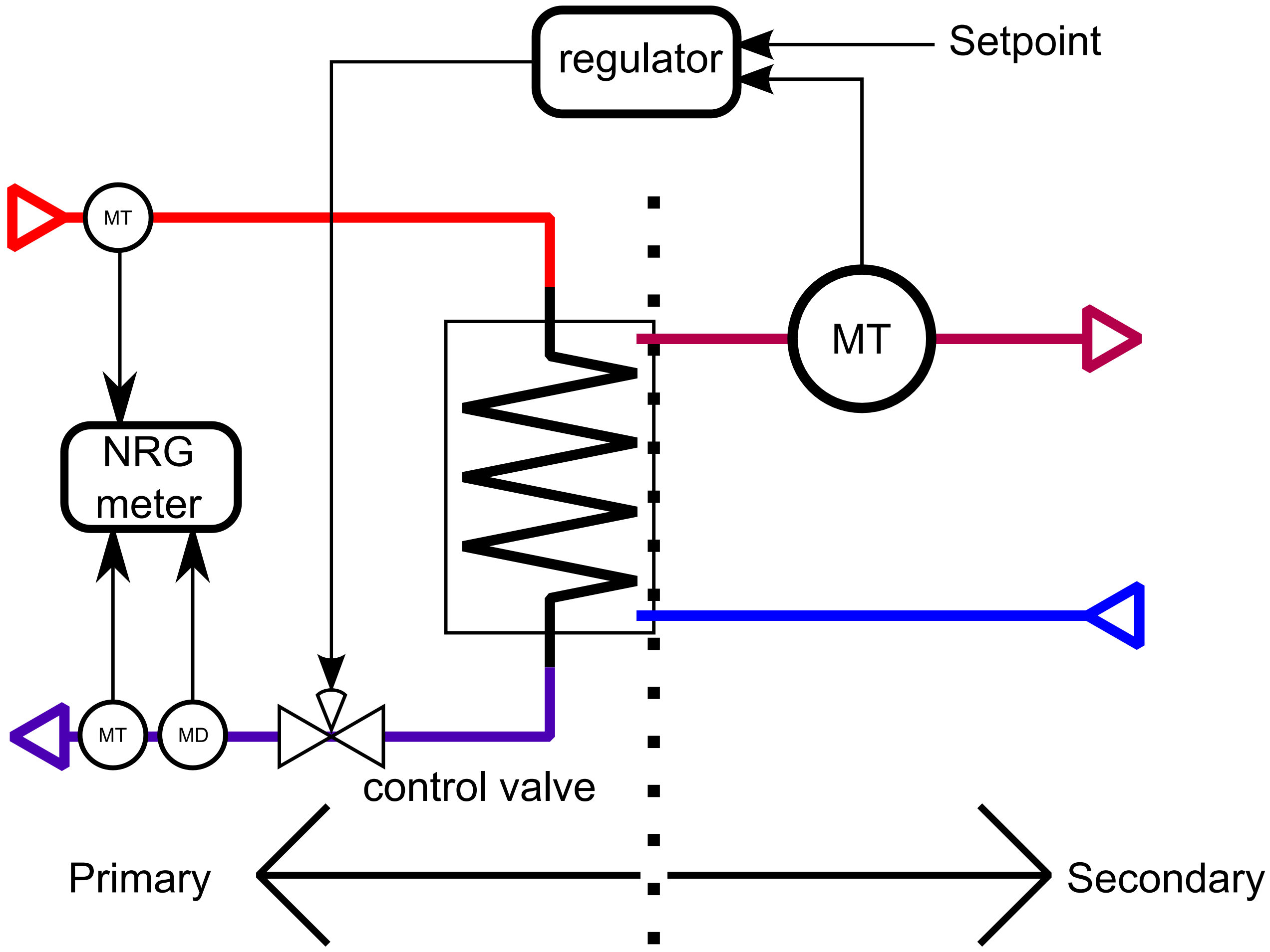
} Consumption

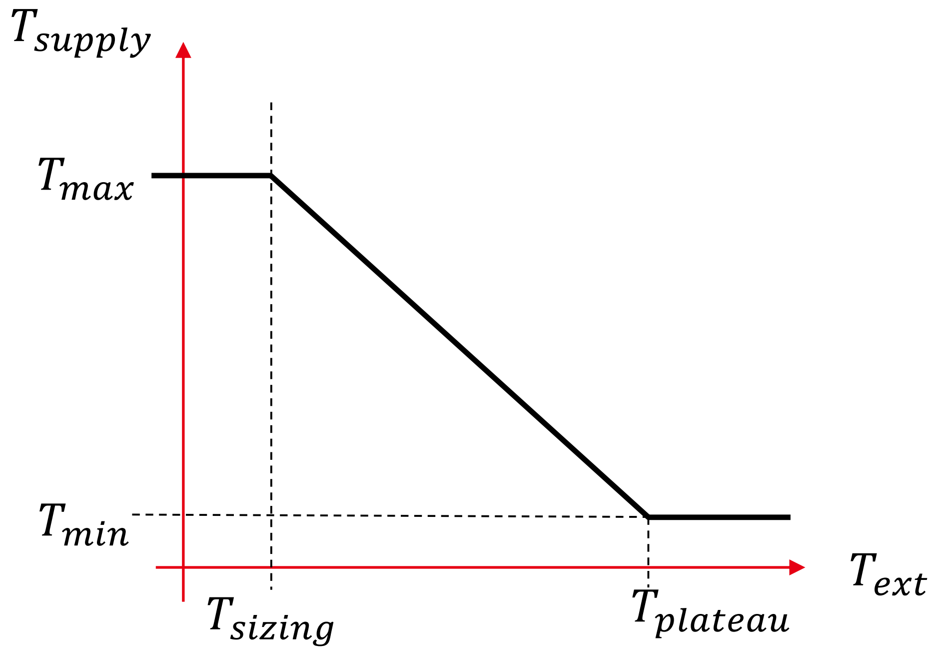
**Differential Pressure Control** **Supply Temperature Control**

} Distribution

**Production Control** — Status of Heat Generators (on/off)
Commitment Factor (for multi production plants)

} Production

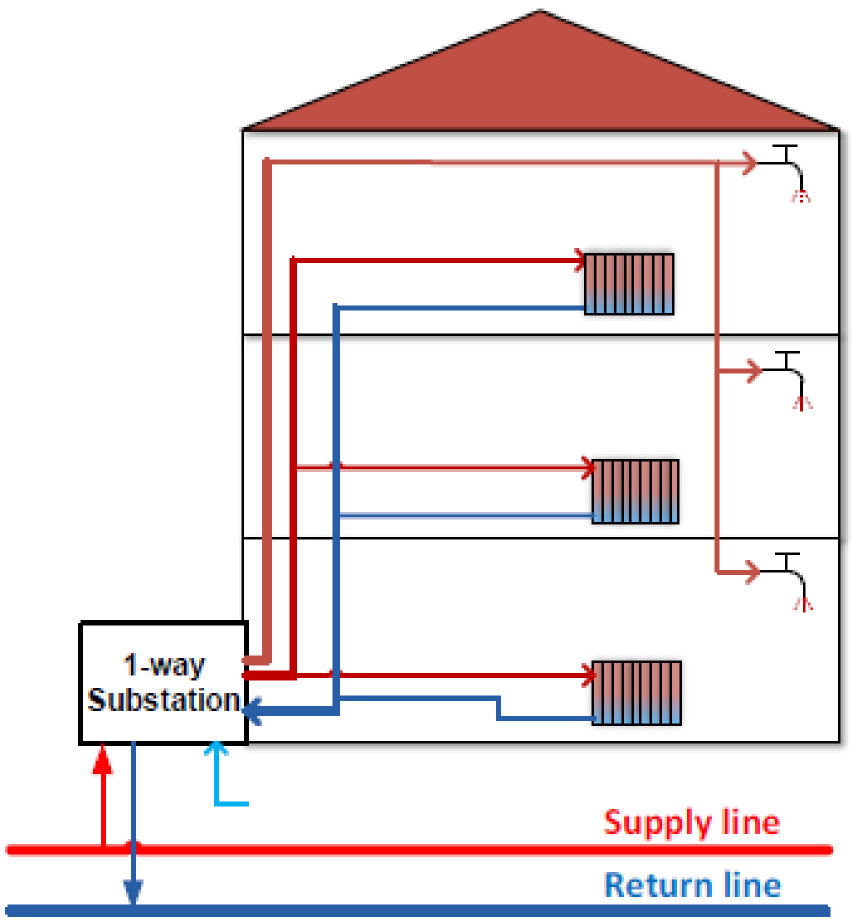


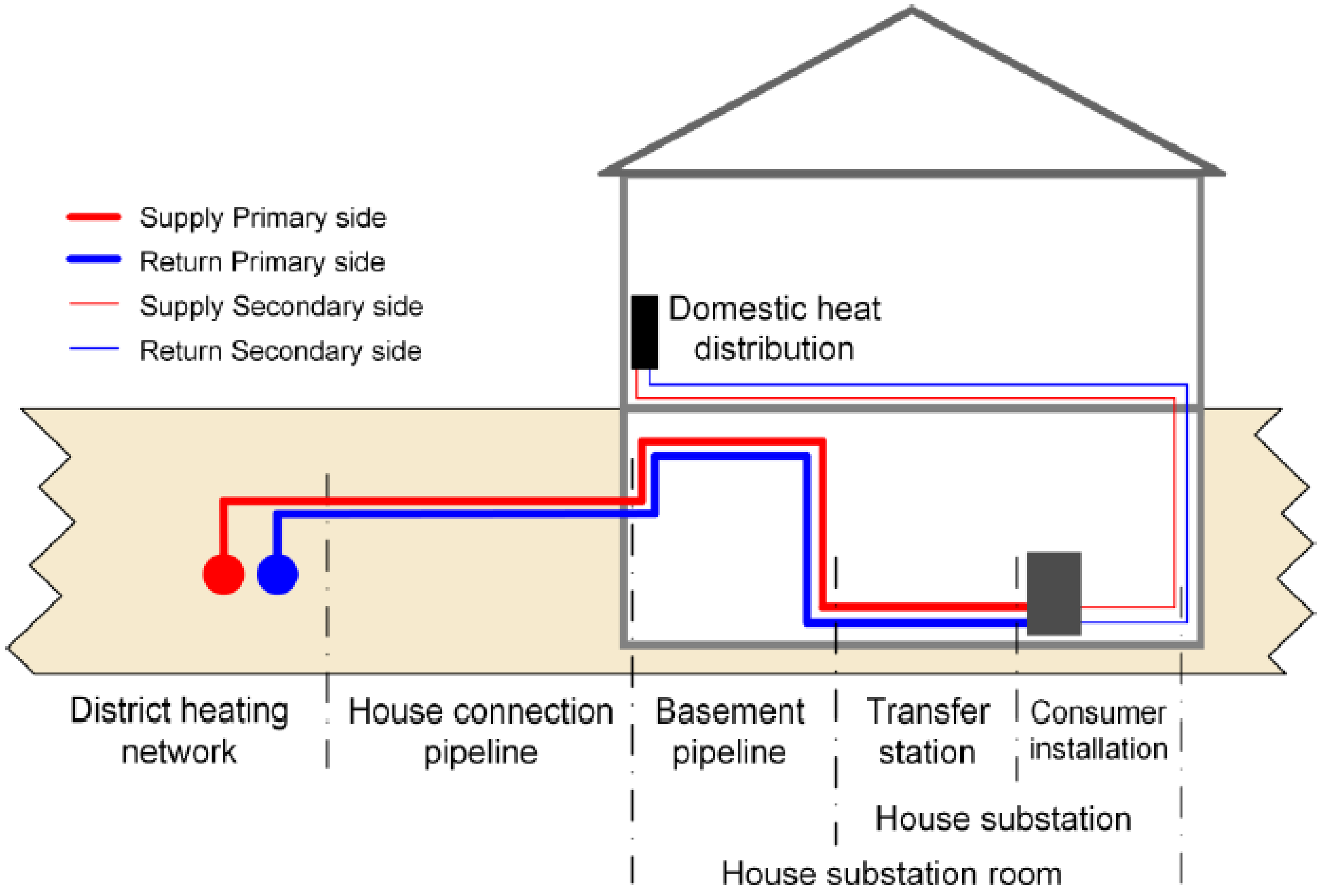




**Optimal Operation**

Reduce the return temperature
- → Lower HL in return line
- → Higher efficiency of the production units
- → Lower mass flow rate in the network

## Main layout for building substation

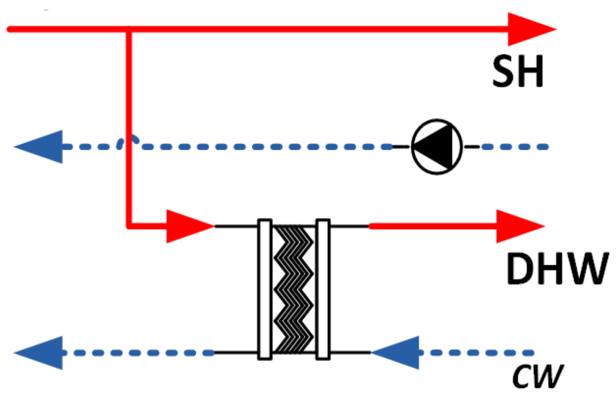



Handbook on Planning of District Heating Networks, EnergieSchweiz

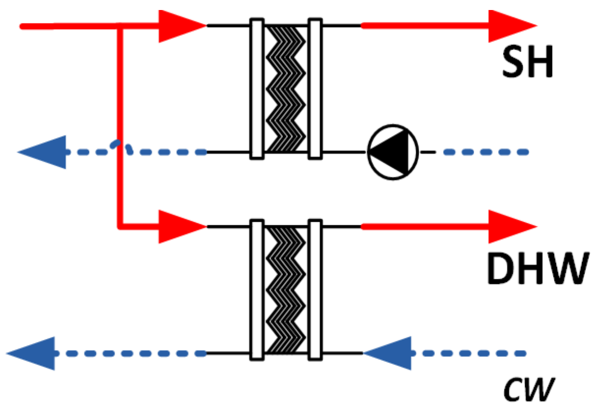
**3 main layouts**

Direct SH and Closed DHW supply



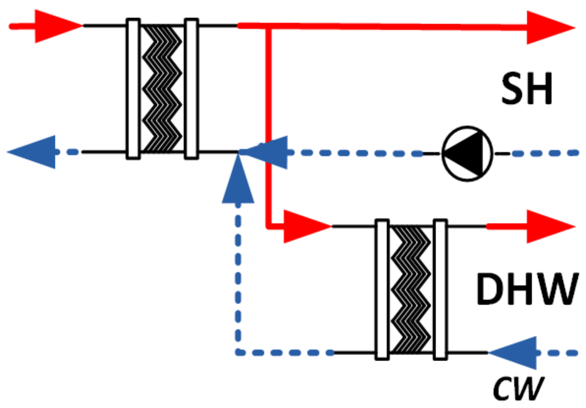

- \+ Low cost
- \+ No HEX pinch for SH
- • Reference in Germany / Denmark

Indirect SH and Closed DHW supply




- \+ Protects hydronic system (pressure surges, corrosion due to oxygen content)
- \+ Low pressure requirements for hydronic system
- \+ Reduced damage if leaks
- \+ Reduced noise propagation
- • Reference in Sweden

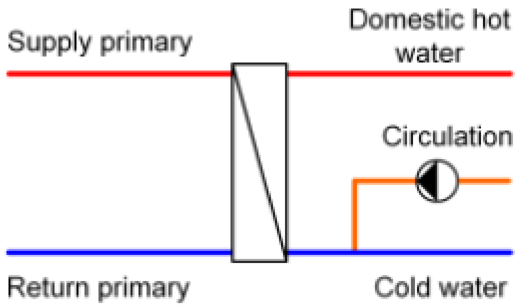
Intermediate SH circuit

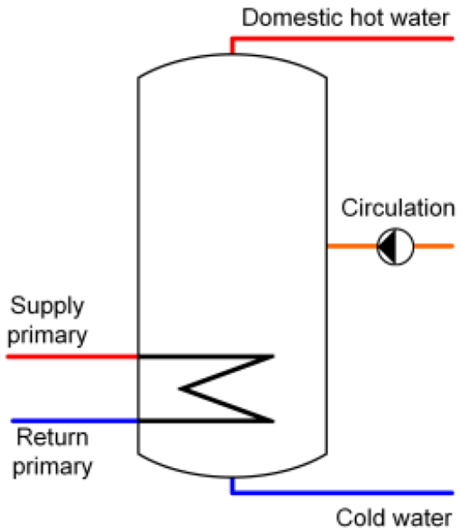


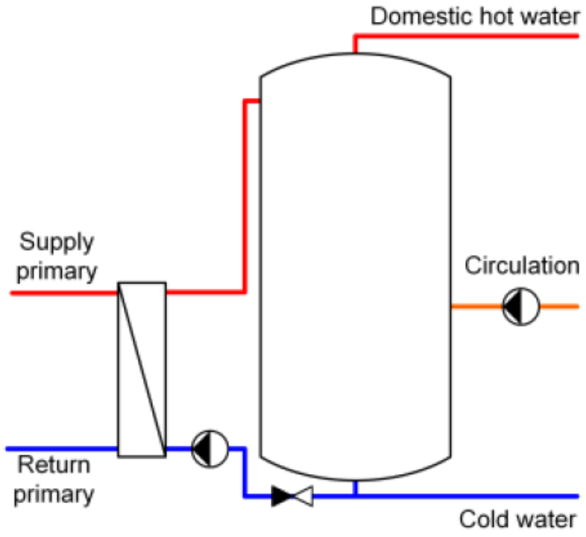

- \+ Further protected DHW system against HEX leaks with DHN water
- \- Double HEX pinch for DHW
- \- SH circuit always higher temperature than DHW temperature
- • Sometimes preferred in Germany

**Other seldom layouts:** No hydraulic separation / open hot water supply / double-walled DHW circuit separation

## Type of DHW systems



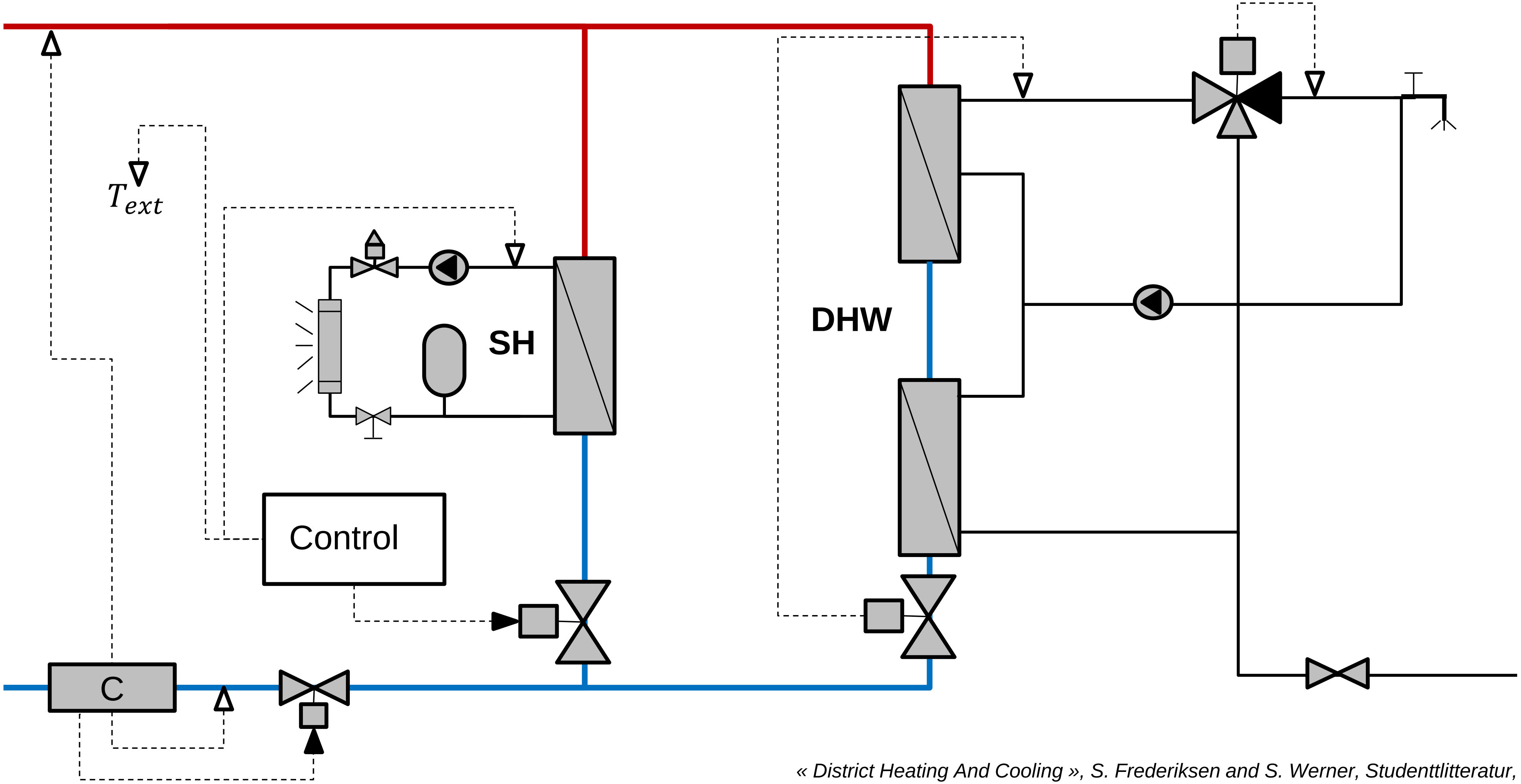




| Instantaneous DHW | Internal HEX Storage Tanks DHW | External HEX Storage Tanks DHW |
|---|---|---|
| + Even out loads (asynchronous) | + Better for small SH demand because no need to oversize service lines | + Better for small SH demand because no need to oversize service lines |
| + Few space required | + Peak loads ensured by tank | + Peak loads ensured by tank |
| + No limit of energy for a draw-offs | + Insensitive to lime scale | + Largest storage utilization |
| + Reduced legionella | - Management of legionella | - Management of legionella |
| - Demanding for the control system | - Add heat losses (but small) | - Add heat losses (but small) |

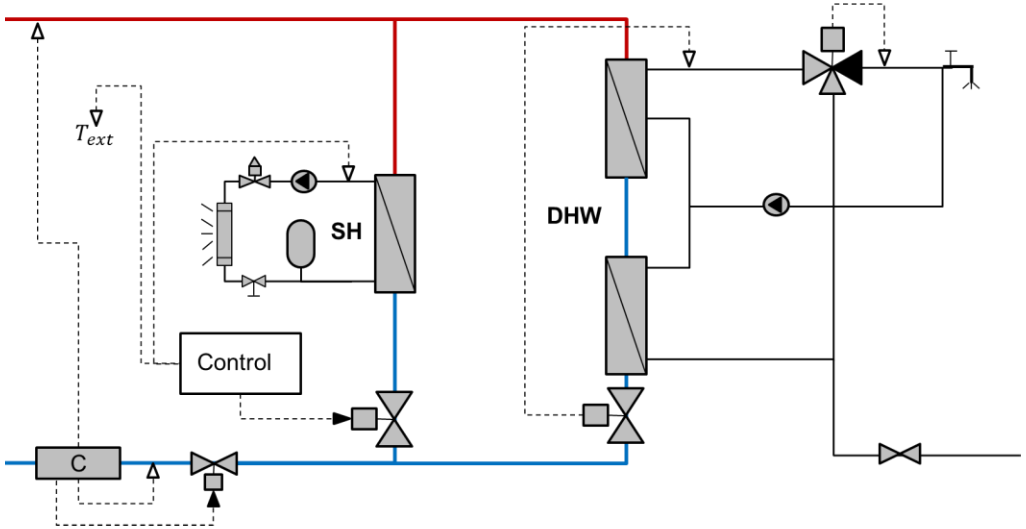
$T_{p,out} \sim 25 - 30°C$ $T_{p,out} \sim 45°C$ $T_{p,out} \sim 30 - 35°C$

Handbook on Planning of District Heating Networks, EnergieSchweiz

## Detailed type of Indirect SH and Closed instantaneous cascading DHW supply




*« District Heating And Cooling », S. Frederiksen and S. Werner, Studenttlitteratur, Sweden, 2013*




## SH loop

- Control of the valve on DHN side to satisfy a set point on the SH loop based on external temperature measurement
- Control using self-regulating thermostatic valve
- Another valve for emitter isolation or hydraulic balancing
- Variable or Fixed speed circulation pump to maintain flow
- Expansion tank necessary to:
  - set the pressure in the loop
  - compensate for thermal expansion and contraction of heat carrier fluid

## DHW loop

- Control of the valve on DHN side to satisfy a set point on the DHW loop based on legionella constraints
- Set point is generally higher than necessary and will be mixed in the 3way valve to avoid oscillations at the tap level
- Preheater / Postheater configuration to enhance DT because of recirculation sanitary loop
- Check valve on Cold Water Flow side

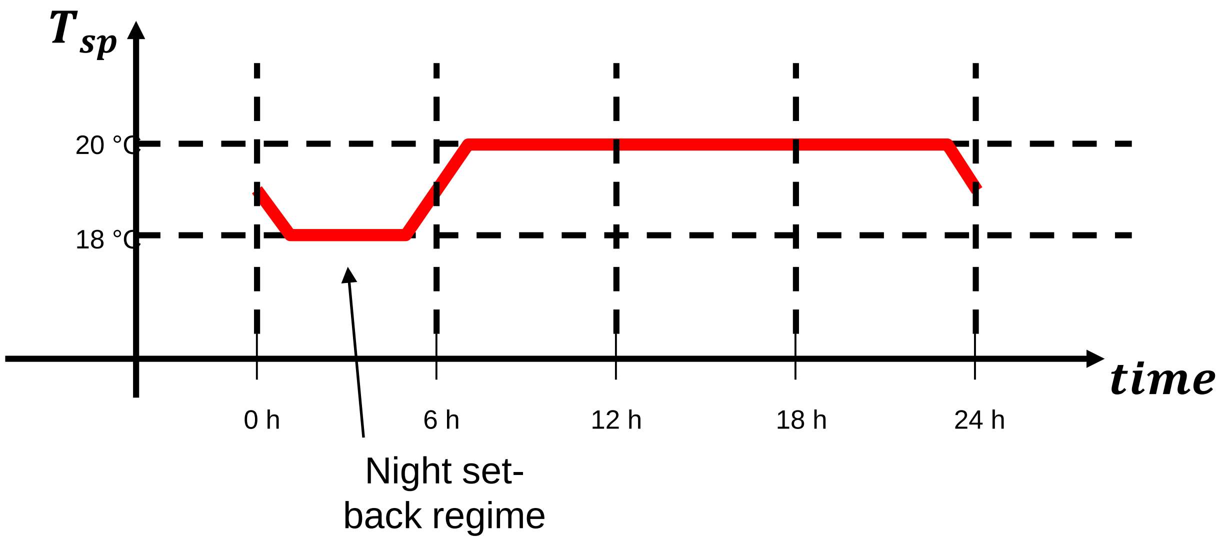
## DHN loop

- Heat Meter for billing uses 2 temperature sensors and 1 flow meter
- A flow limiter can be used depending on contract with customer to limit energy to transfer and allow more favorable situations for far customers
- Return temperature limiter also exists

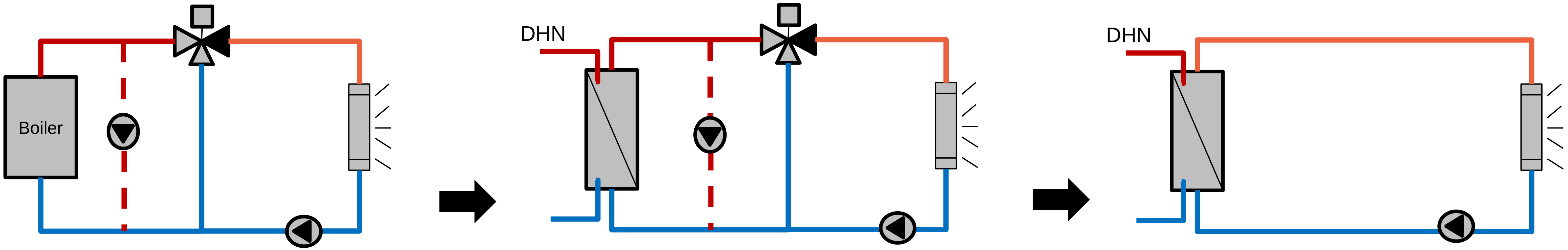
## 1) Night Setback

Save energy at night BUT
Generates high space heating loads in mornings

Flow rate increases before effect on return temperature is observed




## 2) Transition from individual production system

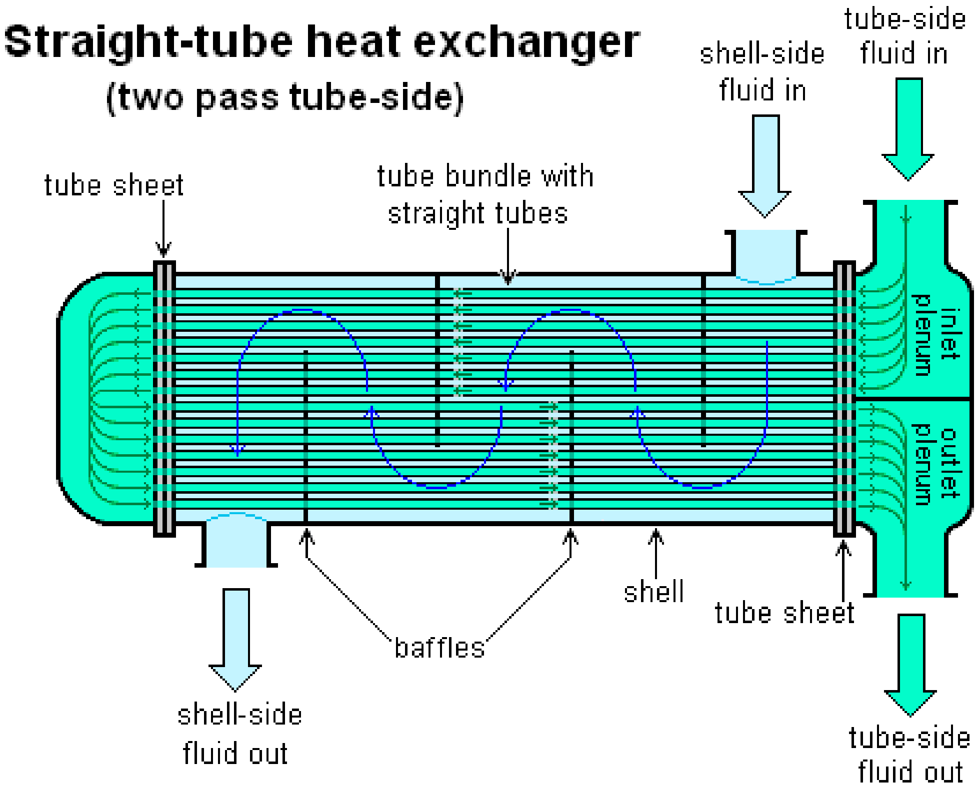



From boiler to DHN

Required secondary side adaptation

**Tube and Shell Heat Exchanger**

- For high temperature and high pressure
- For large Substations (HP network to BP network)
- For old networks
- Problem of leaking after some years

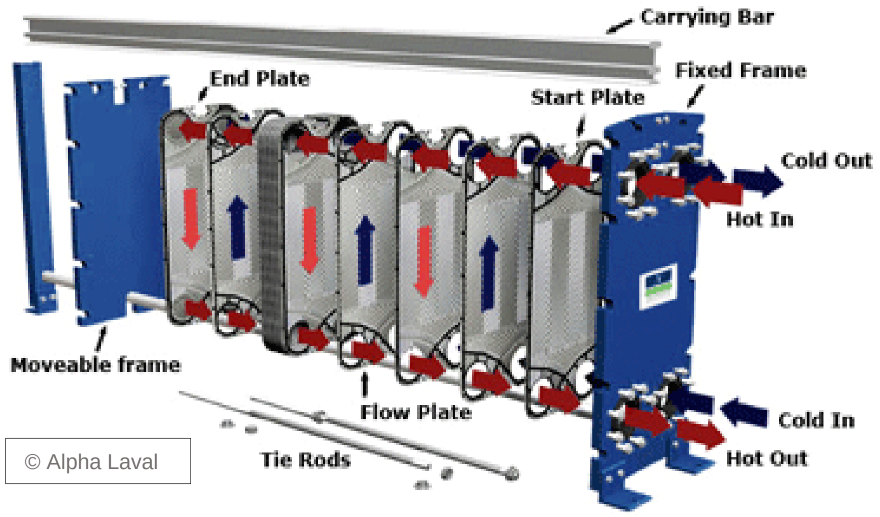



**Composed of :**

- Tubes (high pressure fluid)
- One Shell and baffles for mixing
- Cross-flow heat exchange configuration

## Plate Heat Exchanger

- Compact and high heat transfer performance
- Can be disassembled
- Number one solution in low temperature networks





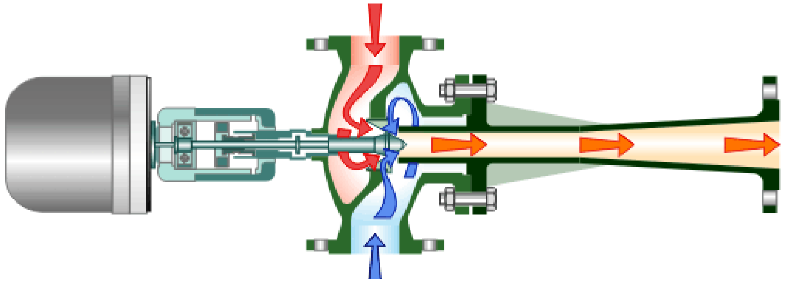
## Composed of :

- Corrugated plates and gaskets
- Counter-flow heat exchange configuration
- « Hot » fluid flows down every even channel
- « Cold » fluid flows up every odd channel
- Gasketed or Brazed

## Control Element

2way Valve

Hydro-Ejector

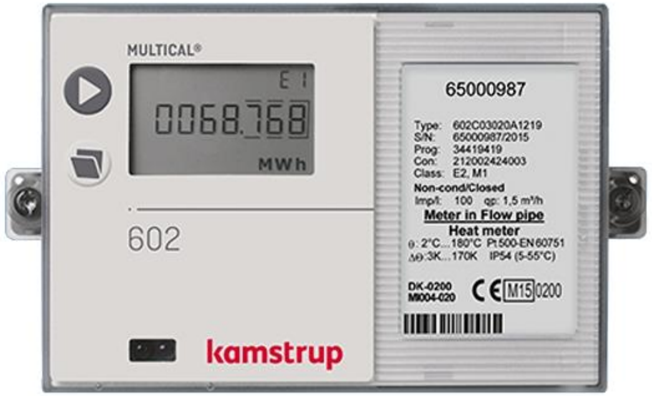


3way Valve

## Instrumentations

Pressure

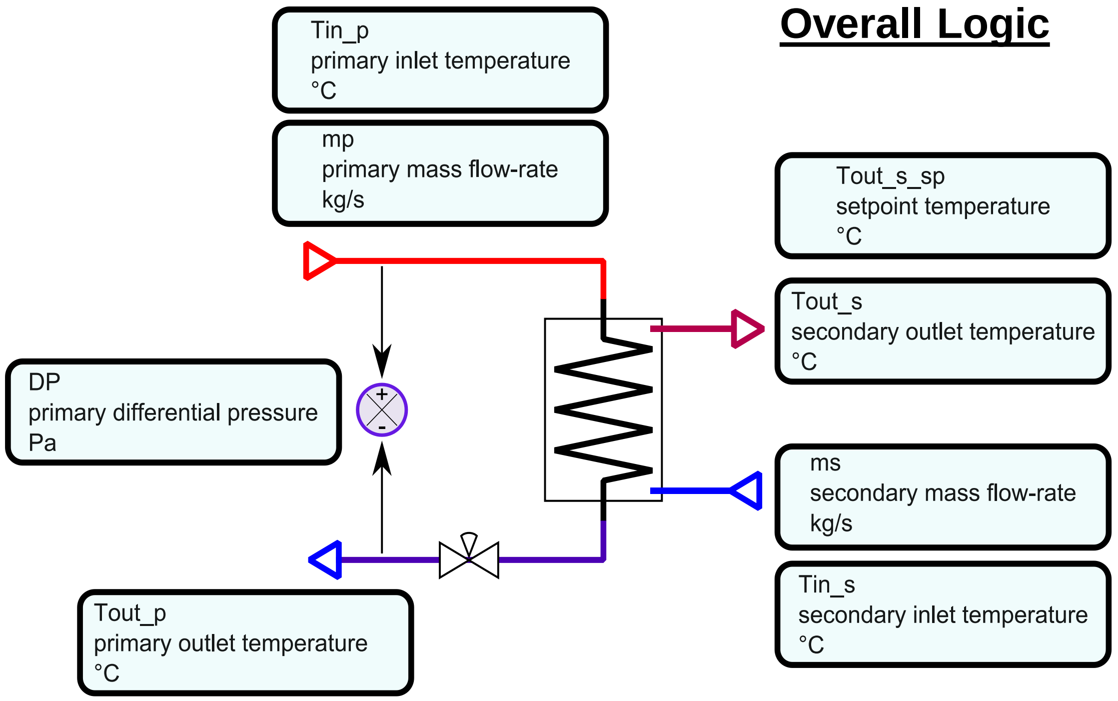
Temperature




Energy Meter

Flow Meter

## Overall Logic




## Input Nominal Data

- Secondary Temperatures: $T_{in,s,nom}$ et $T_{out,s,nom}$
- Heat Load: $Q_{dem,nom}$
- Primary Inlet Temperature: $T_{in,p,nom}$
- Primary Differential Pressure: $\Delta P_{p,nom} = 1bar$
- Desired Pinch: $\Delta T_{pp,HEX}$

1) $T_{out,p,nom} = T_{in,s,nom} + \Delta T_{pp,HEX}$

2) $\dot{m}_{p,nom} = \frac{Q_{dem,nom}}{cp\cdot(T_{out,p,nom} - T_{in,p,nom})}$

3) **Fully Open Valve Authotity**:

$$\beta = \frac{\Delta P_v}{\Delta P_{p,nom}} \geq 0.5 \quad \text{with} \quad \Delta P_v = \left(\frac{\dot{m}_{p,nom}/\rho}{K_{v,s}}\right)^2$$

4) $\dot{m}_{s,nom} = \frac{Q_{dem,nom}}{cp\cdot(T_{out,s,nom} - T_{in,s,nom})}$

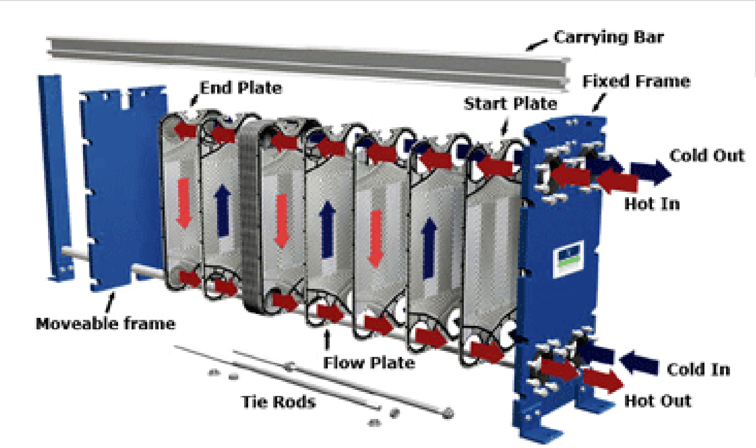
5) **Heat Exchanger Sizing**

$$UA_{HEX} = \frac{Q_{dem,nom}}{DTLM_{HEX}}$$

With $$DTLM_{HEX} = \frac{(T_{in,p,nom} - T_{out,s,nom}) - (T_{out,p,nom} - T_{in,s,nom})}{\ln\frac{(T_{in,p,nom} - T_{out,s,nom})}{(T_{out,p,nom} - T_{in,s,nom})}}$$

And $\Delta P_{HEX} \leq (1 - \beta)\cdot \Delta P_{p,nom}$

## Heat Exchanger




$$U = \left( \frac{1}{h_{conv,hot}} + \frac{1}{h_{fouling,hot}} + \frac{1}{h_{plate}} + \frac{1}{h_{fouling,cold}} + \frac{1}{h_{conv,cold}} \right)^{-1}$$

$h_{conv,hot}$: $\sim 5 kW.m^{-2}.K^{-1}$

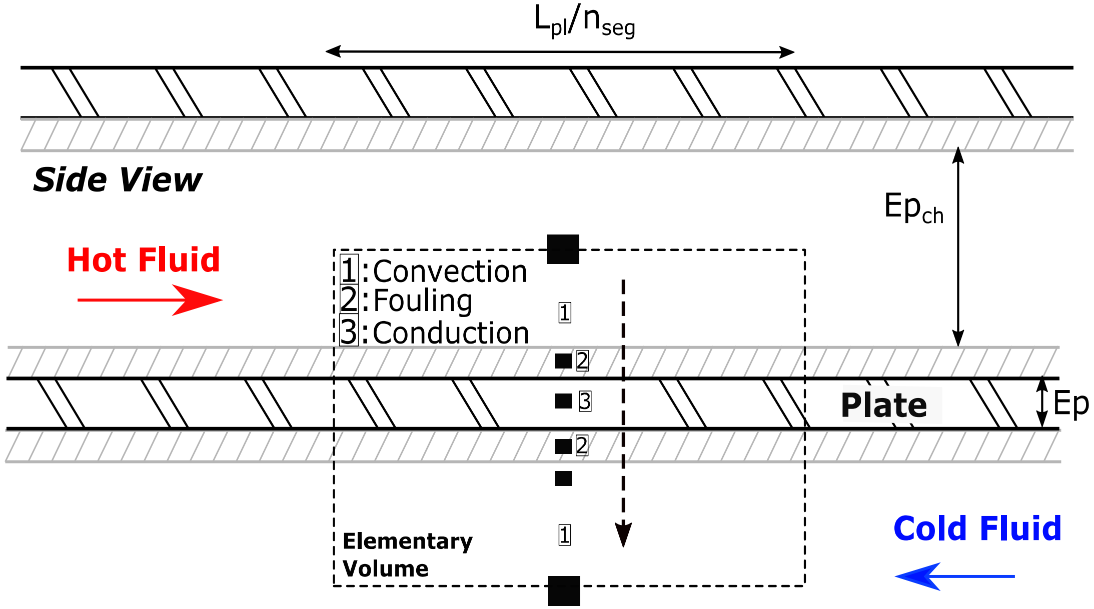
$h_{plate}$: $\sim 45 kW.m^{-2}.K^{-1}$

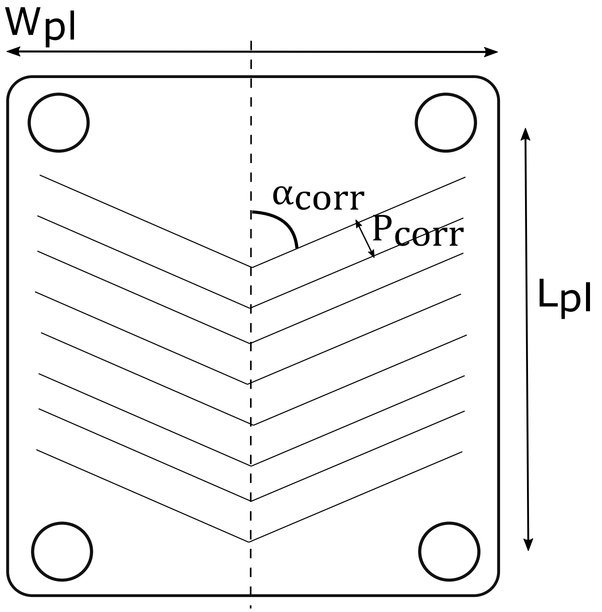
$h_{conv,cold}$: $\sim 10 kW.m^{-2}.K^{-1}$

$h_{fouling,hot}$, $h_{fouling,cold}$: $\sim 20 - 200 kW.m^{-2}.K^{-1}$

$$h_{conv} = k \cdot \frac{Nu}{d_h}$$

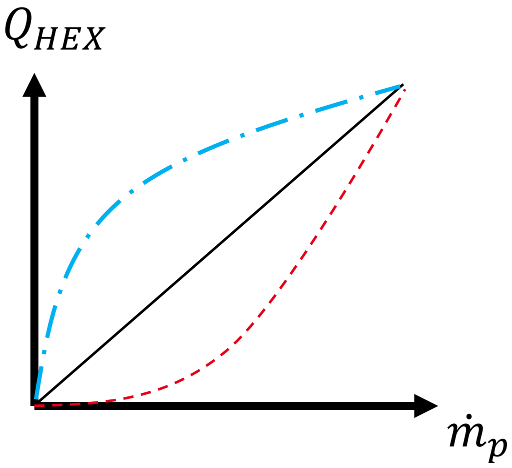
$$Nu = a \cdot Re^{b} \cdot \mathrm{Pr}^{1/3}$$



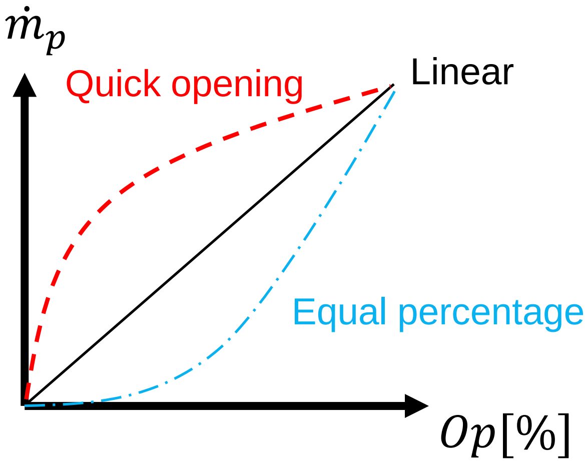



**Valve**

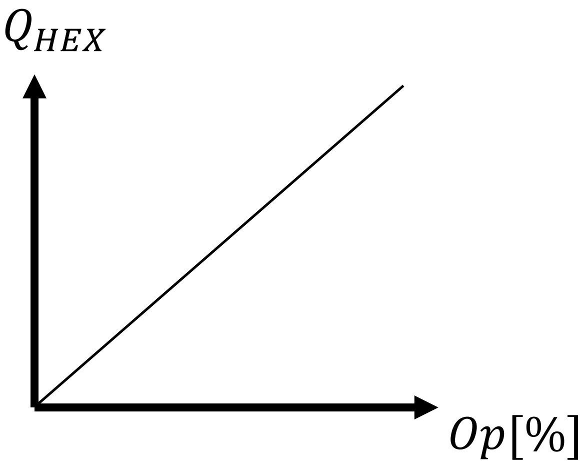
Heat Exchanger characteristics




Valve Characteristics



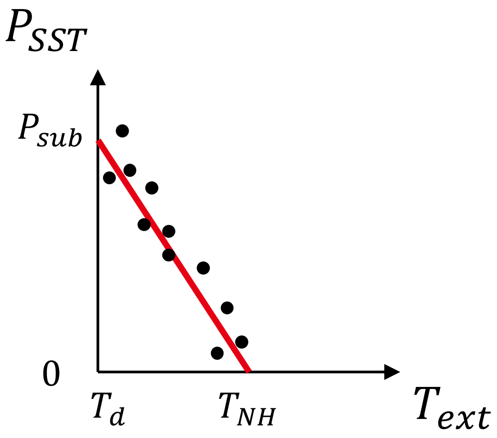

Substation characteristics




Always the same relative change in opening for equivalent relative demand variation

**Data Analysis – Physical and Sociological Influences**

Substation with SH only



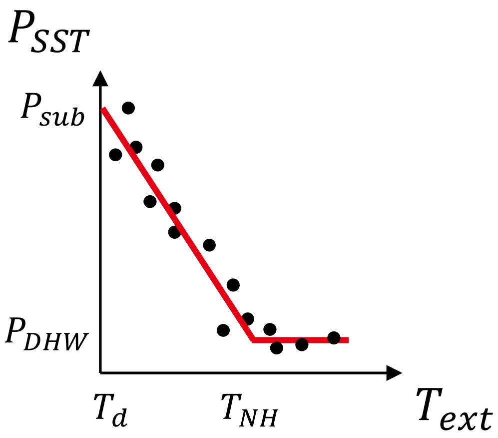

$P_{sub}$: Subscribed power

$T_d$: Design temperature

$T_{NH}$: Effective temperature

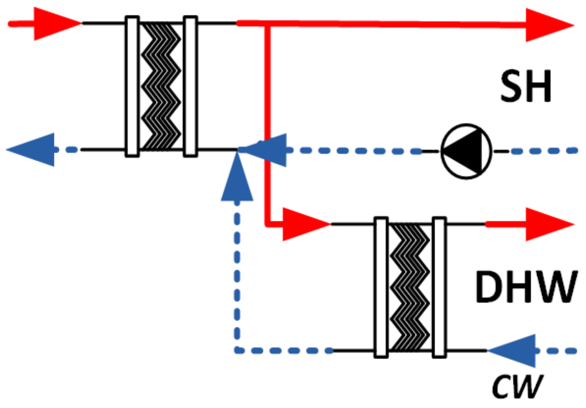
$$T_{NH} = T_{int} - \frac{Q_{internal\ gains} + Q_{solar}}{UA}$$

Substation with SH and DHW

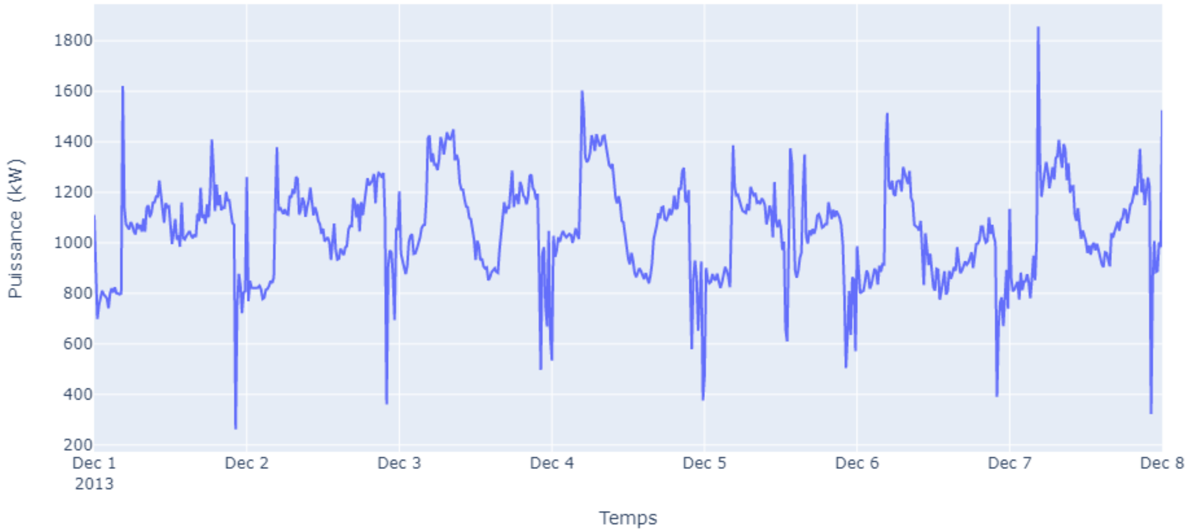


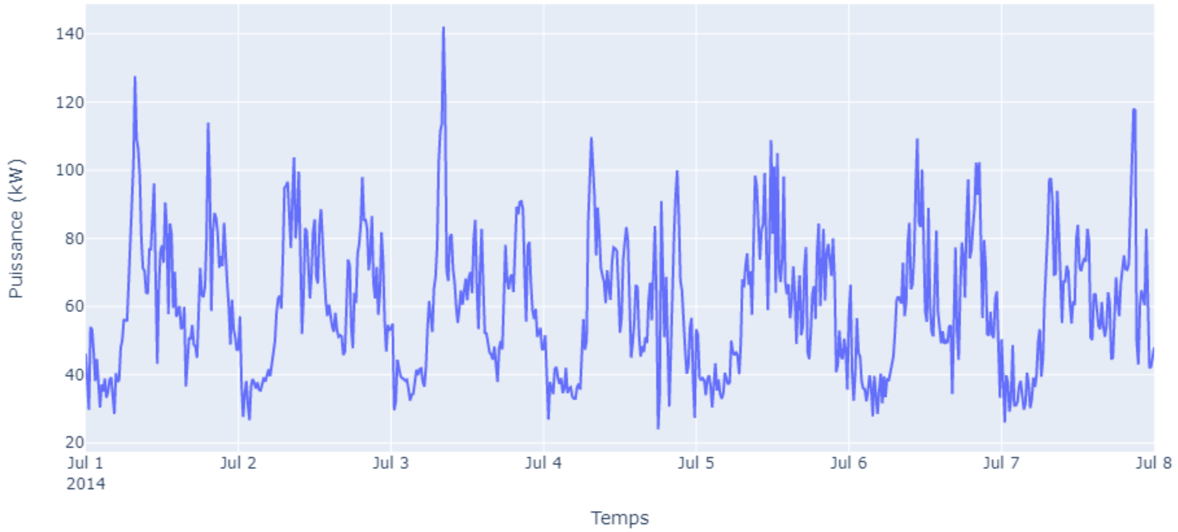

$P_{DHW}$: DHW mean power

## Data Analysis – Large Substation with SH and DHW demand

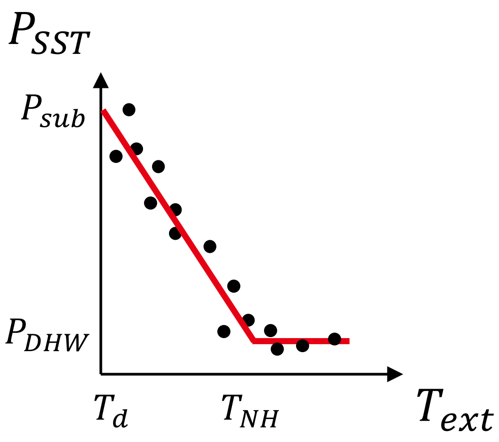



- Tubular HEX
- About 300 housings with radiators
- 20000m²
- No DHW storage



## Data Analysis – Physical and Sociological Influences




$$P_{SST} = \begin{cases} P_{DHW,m} \cdot (1 + \delta P_{DHW,n,i}) & T_{ext} > T_{NH} \\ P_{DHW,m} \cdot (1 + \delta P_{DHW,i}) + a.(T_{ext} + \delta T_{ext,i}) + b & T_{ext} < T_{NH} \end{cases}$$

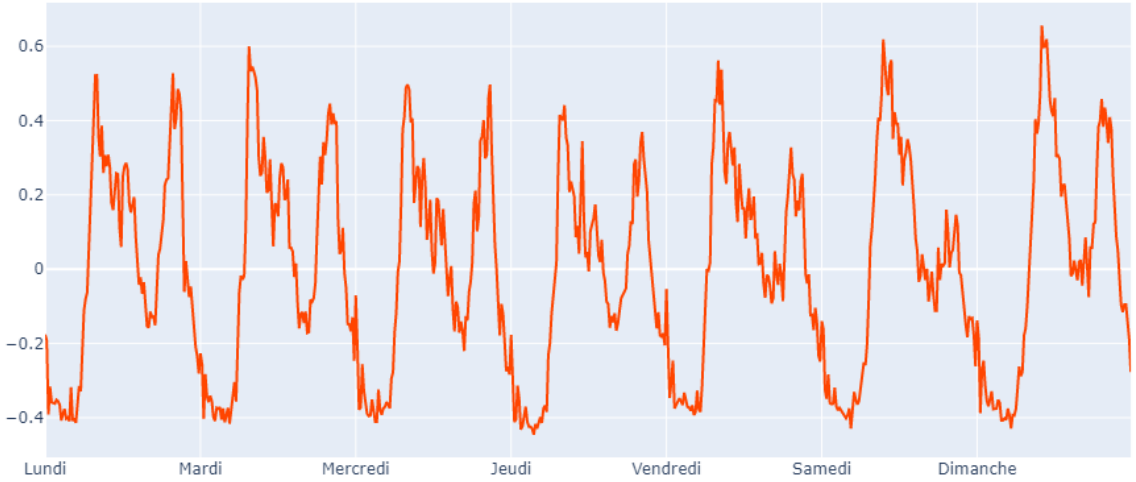
**$\delta P_{DHW,i}$ and $\delta T_{ext,i}$ are normed coefficients that can be reused as is for a similar type of customer**

- Calculation during summer time of:
  - $P_{DHW,m}$: mean summer power
  - $\delta P_{DHW,n,i}$: normed weekly coefficient for sociological DHW needs
- During winter time, the DHW part is then removed and the data are fitted with a model $a.(T_{ext}) + b$ → **Physical contribution**
- The residuals are then calculated with $P_{SST} - P_{SST,fit}$ and are normalized by $a$ to obtain residuals in °C
- These residuals represent the equivalent external temperature difference with respect to the current external temperature which would lead to the current demand
- These residuals are averaged for each time step of the week to obtain $\delta T_{ext,i}$ → **Sociologic contribution**

## SH sociologic contribution: $\delta T_{ext,i}$


- Night Setback
- Morning and Evening Peaks
- Maybe solar influence explains the peaks differences
- Less pronounced on sunday

## DHW sociologic contribution: $\delta P_{DHWn,,i}$




- Morning and Evening peaks

In 4th Generation District Heating Network, substations must face the following challenges:

- Implement at fine sampling a digital monitoring
- Reduce the return temperature
- Limit loads on the production plants
- Reinject local surplus
- Reduced cost through standardization
- Combined District Heating and Cooling Substation including heat pumps

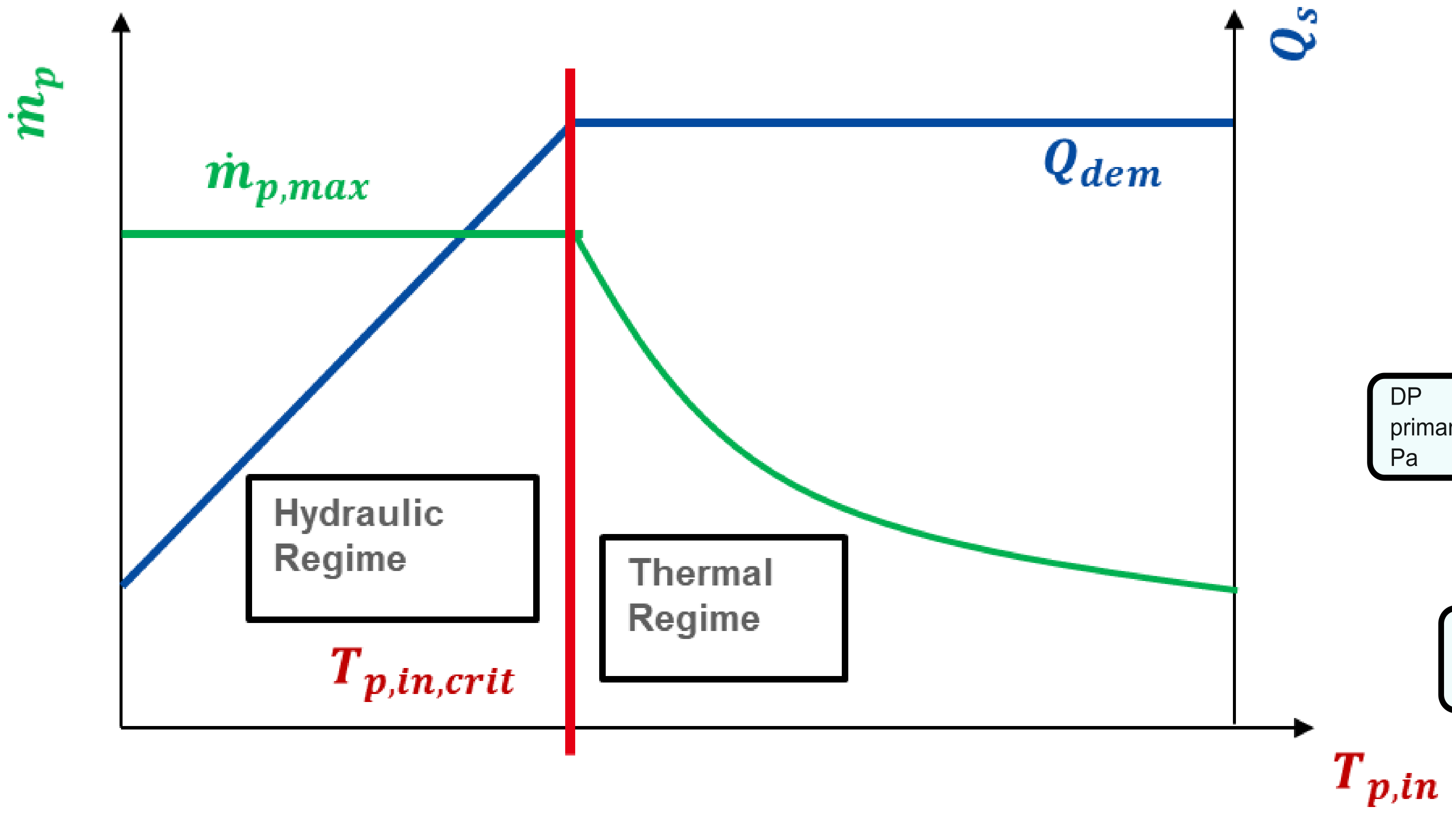
*STRATEGIC RESEARCH INNOVATION AGENDA FOR DISTRICT HEATING & COOLING AND THERMAL ENERGY STORAGE TECHNOLOGIES, Renewable Heating and Cooling (RHC), European Technology and Innovation Platform*

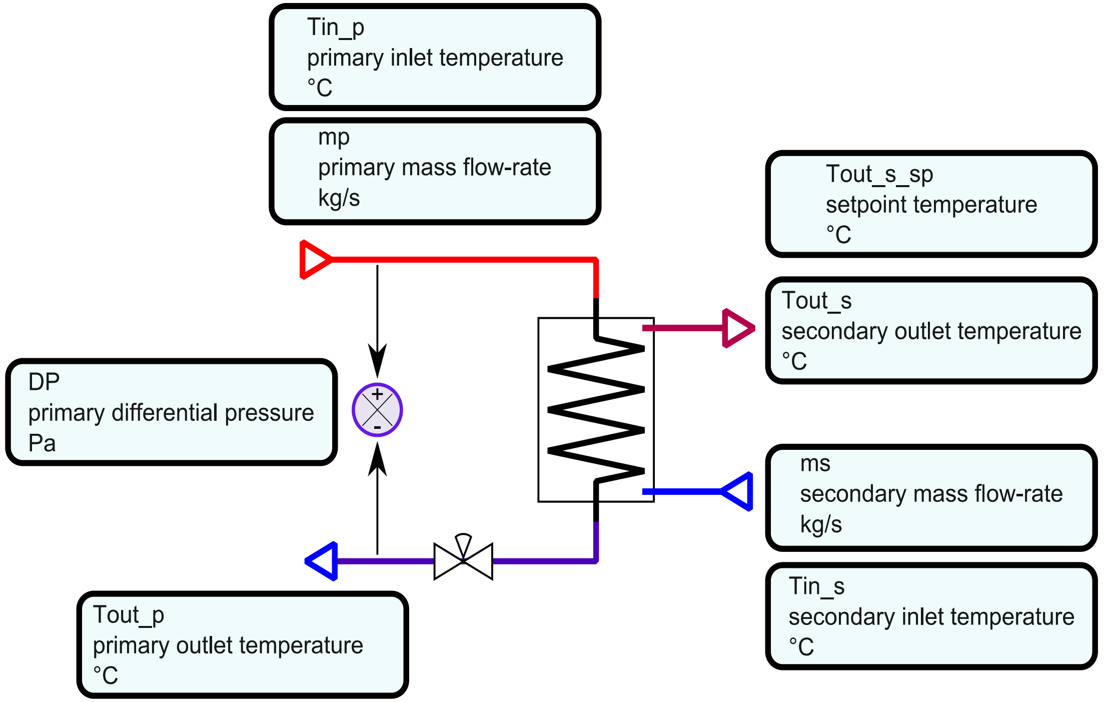
# INNOVATION

# TOPIC 1:

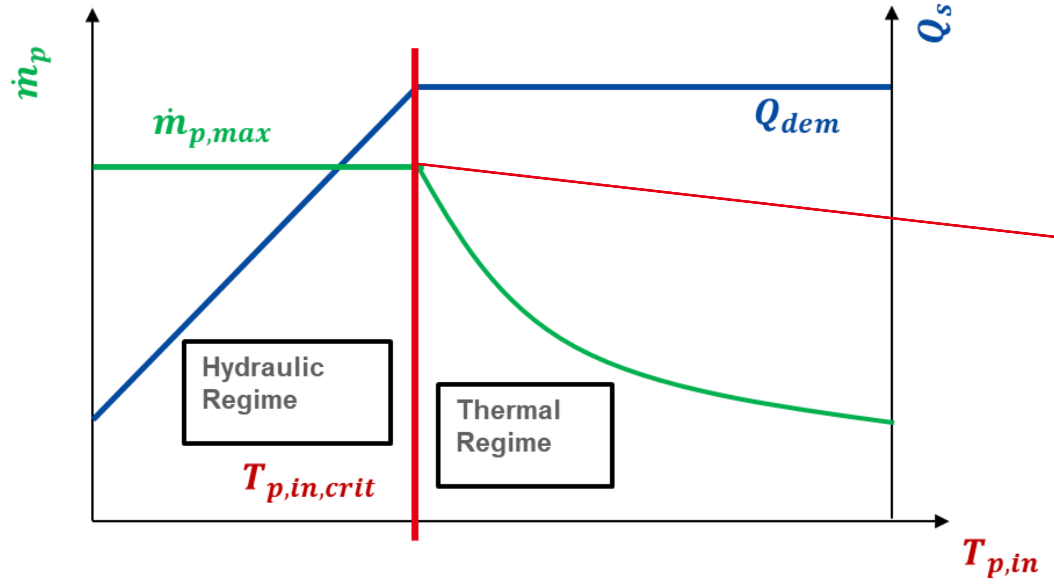
Aim for the critical temperature at the entrance of the substation for a better supply temperature management in the District Heating Network

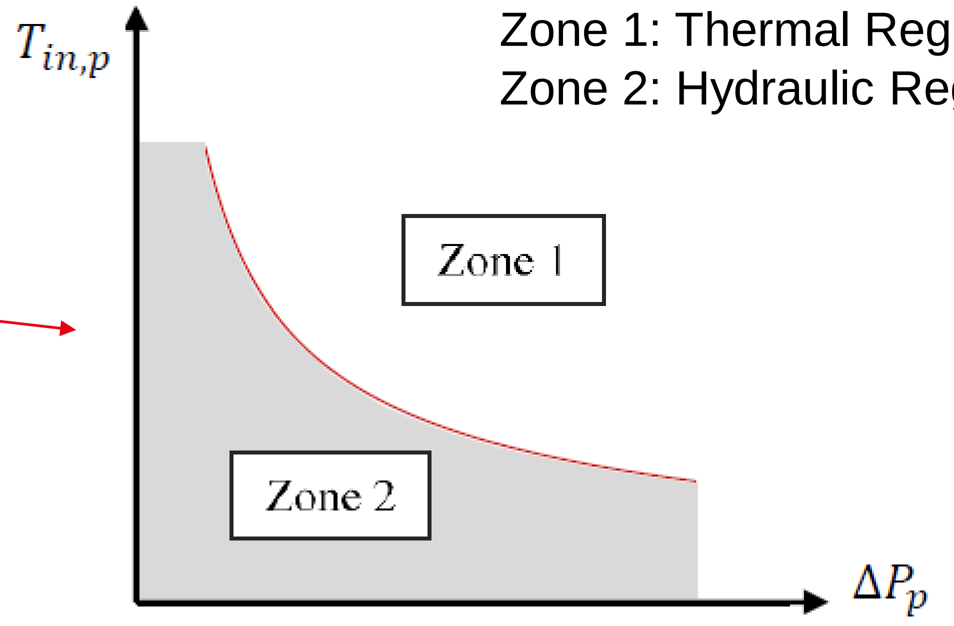
***Limit loads on the production plants***




For a given imposed differential pressure DP and a given heat demand on the secondary side, the critical temperature is the lowest possible primary inlet temperature that will satisfy the demand. In other words, it is the temperature that satisfies the demand when the valve is fully open.




Zone 1: Thermal Regime
Zone 2: Hydraulic Regime

L. Giraud, « Modélisation dynamique et gestion avancée de réseaux de chaleur », Thèse, 2016

**Maximal primary flow rate**

$$\dot{m}_{p,max} = \sqrt{\Delta P \left( \frac{\dot{m}^2_{HEX,nom} \dot{m}^2_{v,nom}}{\Delta P_{HEX,nom} \dot{m}^2_{v,nom} + \Delta P_{v,nom} \dot{m}^2_{HEX,nom}} \right)}$$

**Secondary demanded flow rate**

$$\dot{m}_{s,dem} = \frac{Q_{dem}}{cp(T_{s,out,set} - T_{s,in})}$$

**Heat Exchanger performance**

$$UA_{crit} = UA_{HEX,nom} \frac{\dot{m}^{-q}_{p,nom,HEX} + \dot{m}^{-q}_{s,nom,HEX}}{\dot{m}^{-q}_{p,max} + \dot{m}^{-q}_{s,dem}}$$

**Primary critical temperature**

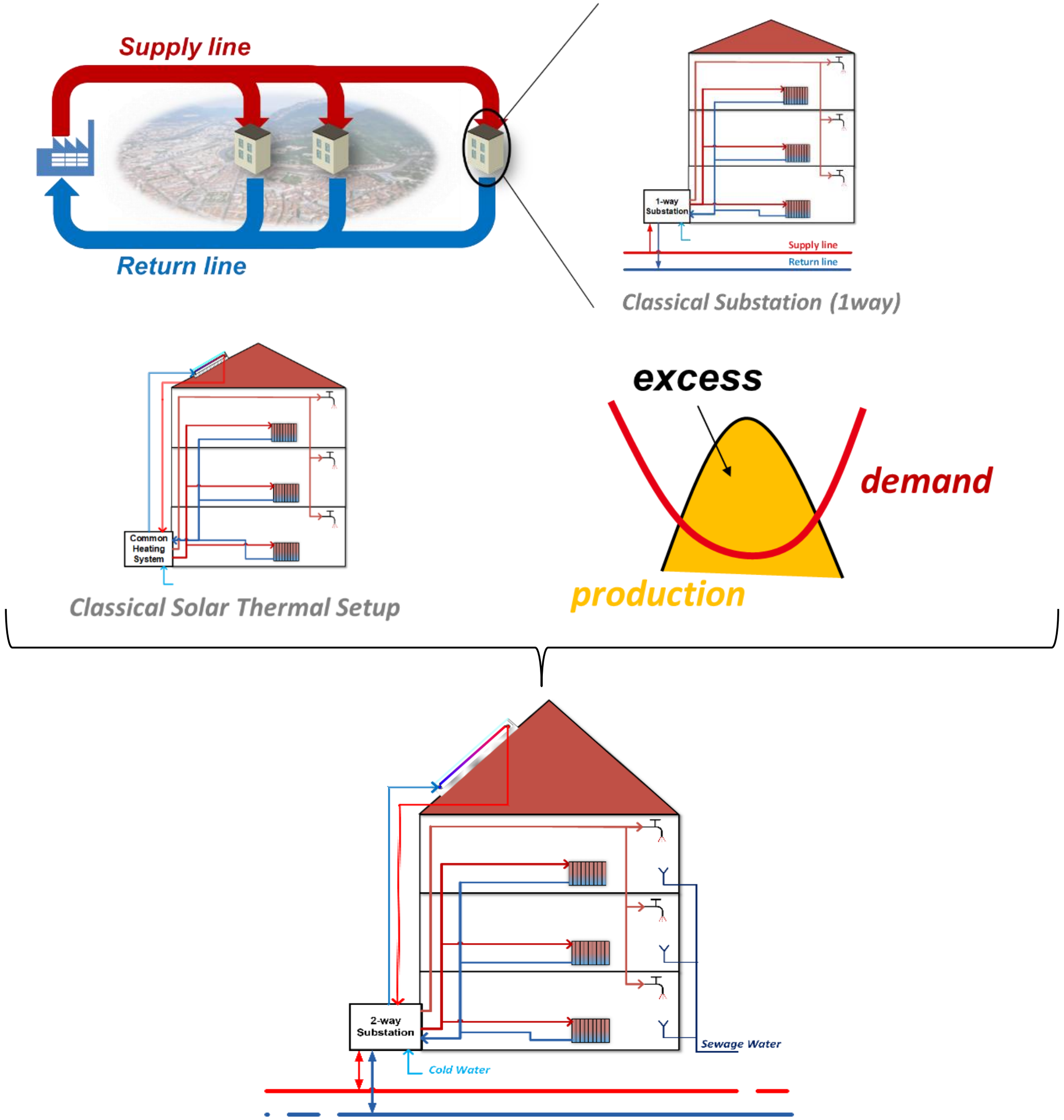
$$T_{p,in,crit} = T_{s,in} + \frac{Q_{dem}}{\dot{m}_{p,max} cp} \left[ \frac{1 - \frac{\dot{m}_{p,max}}{\dot{m}_{s,dem}} \exp(A_c)}{1 - \exp(A_c)} \right]$$

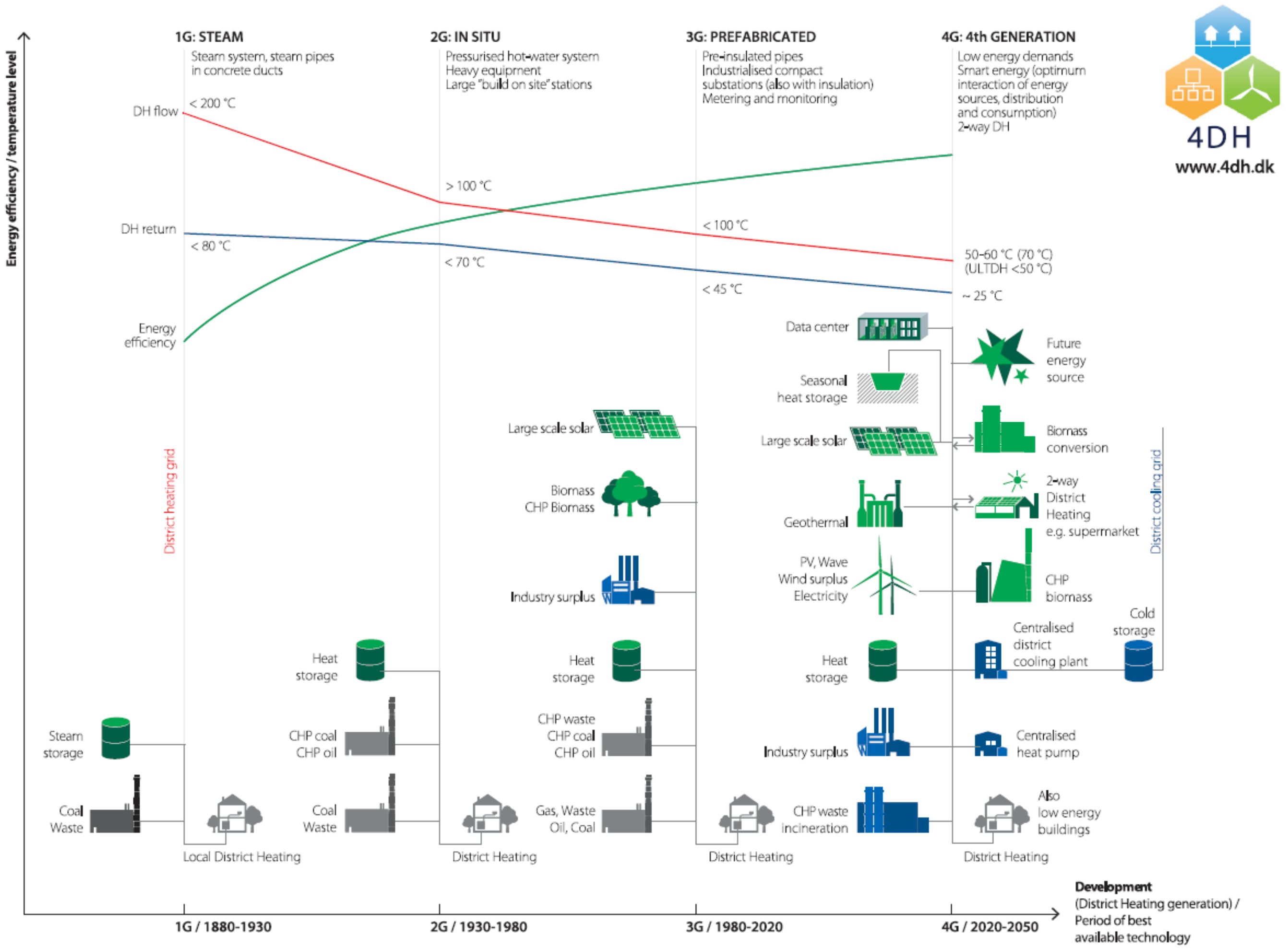
With $A_c = -\frac{UA_{crit}}{cp\, \dot{m}_{s,dem}} \left[ \frac{\dot{m}_{s,dem}}{\dot{m}_{p,max}} - 1 \right]$

# TOPIC 2:

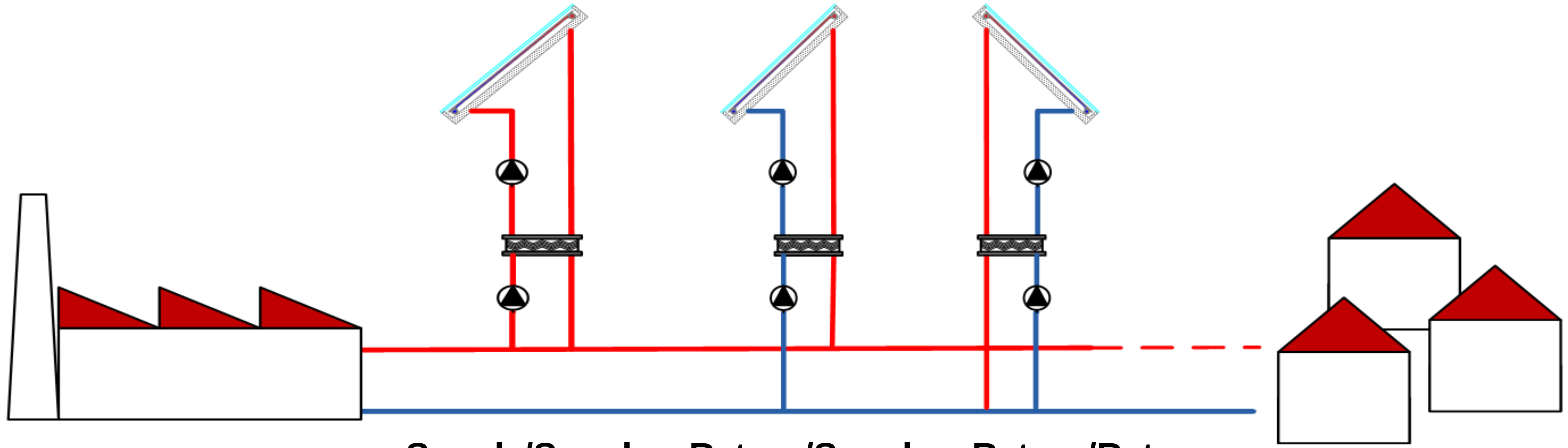
Prosumer substation

***Reinject local surplus***



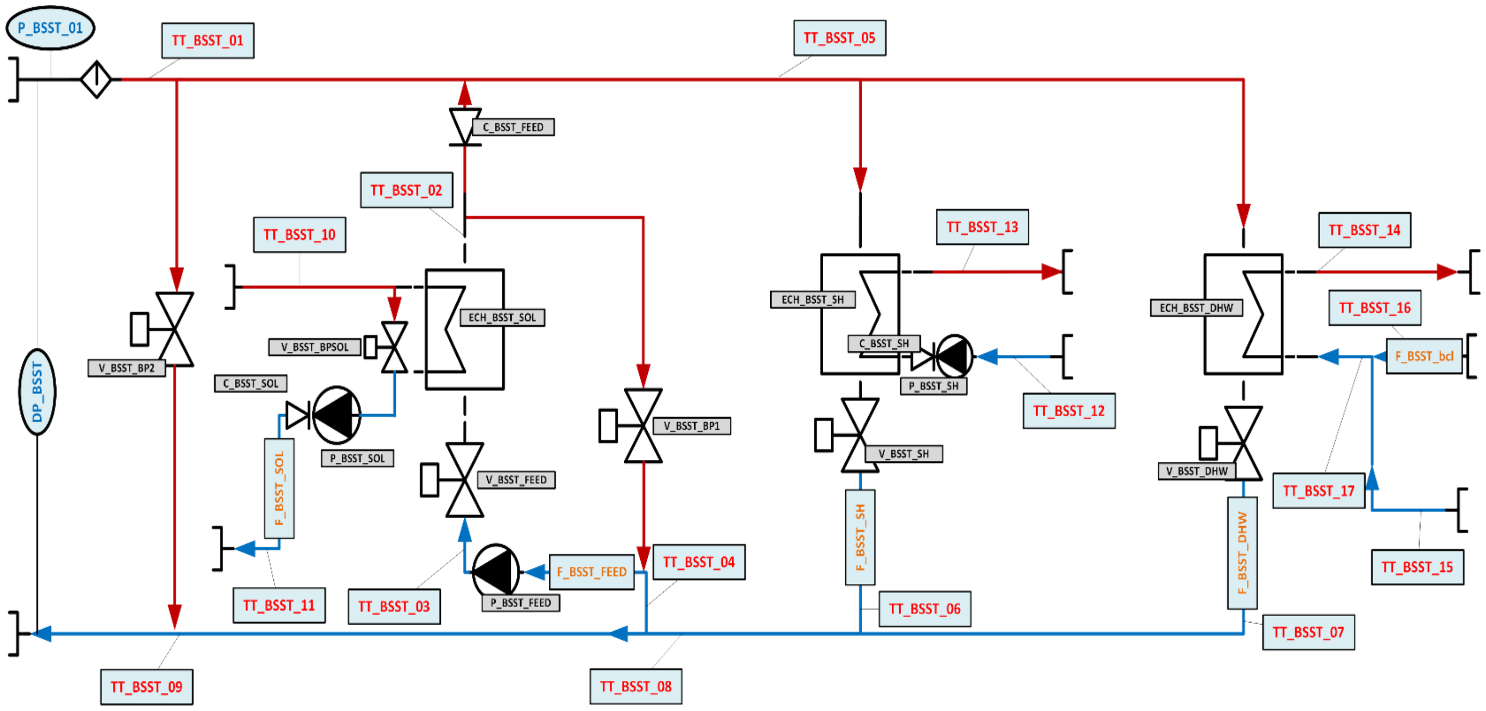

*H. Lund et al., "The status of 4th generation district heating: Research and results," Energy, vol. 164, pp. 147–159, Dec. 2018*

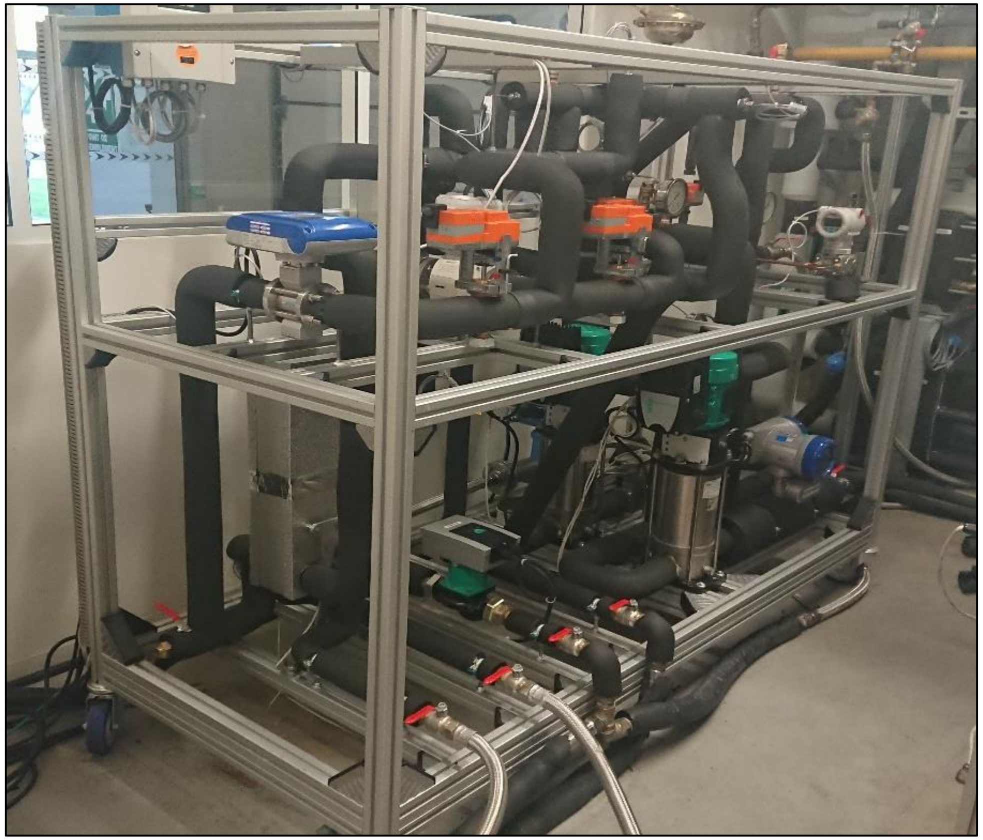



*G. Lennermo et al., "Control of decentralised solar district heating", Solar Energy, Volume 179, 2019*

| TYPE | ADVANTAGES | DISADVANTAGES | REMARKS |
|---|---|---|---|
| Supply/Supply (S/S) | • No influence on return line | • Increase supply line temperature<br>• Lowest solar field efficiency<br>• Dependent on local flow rate<br>• Requires a third pipe<br>• Temperature Cycling → Pipe Fatigue | • Generally never used |
| Return/Return (R/R) | • Highest solar field efficiency | • Increase return line temperature<br>• Lowest efficiency of centralized generators<br>• Dependent on local flow rate<br>• Requires a third pipe<br>• Temperature Cycling → Pipe Fatigue | • Seldom used<br>• Generally in combination with R/S |
| Return/Supply (R/S) | • No influence on return line<br>• Use of existing service line<br>• Do not contribute to pipe fatigue | • High feed-in pump consumption<br>• Challenging control<br>• Feed-in temperature set by network | • Preferred solution |

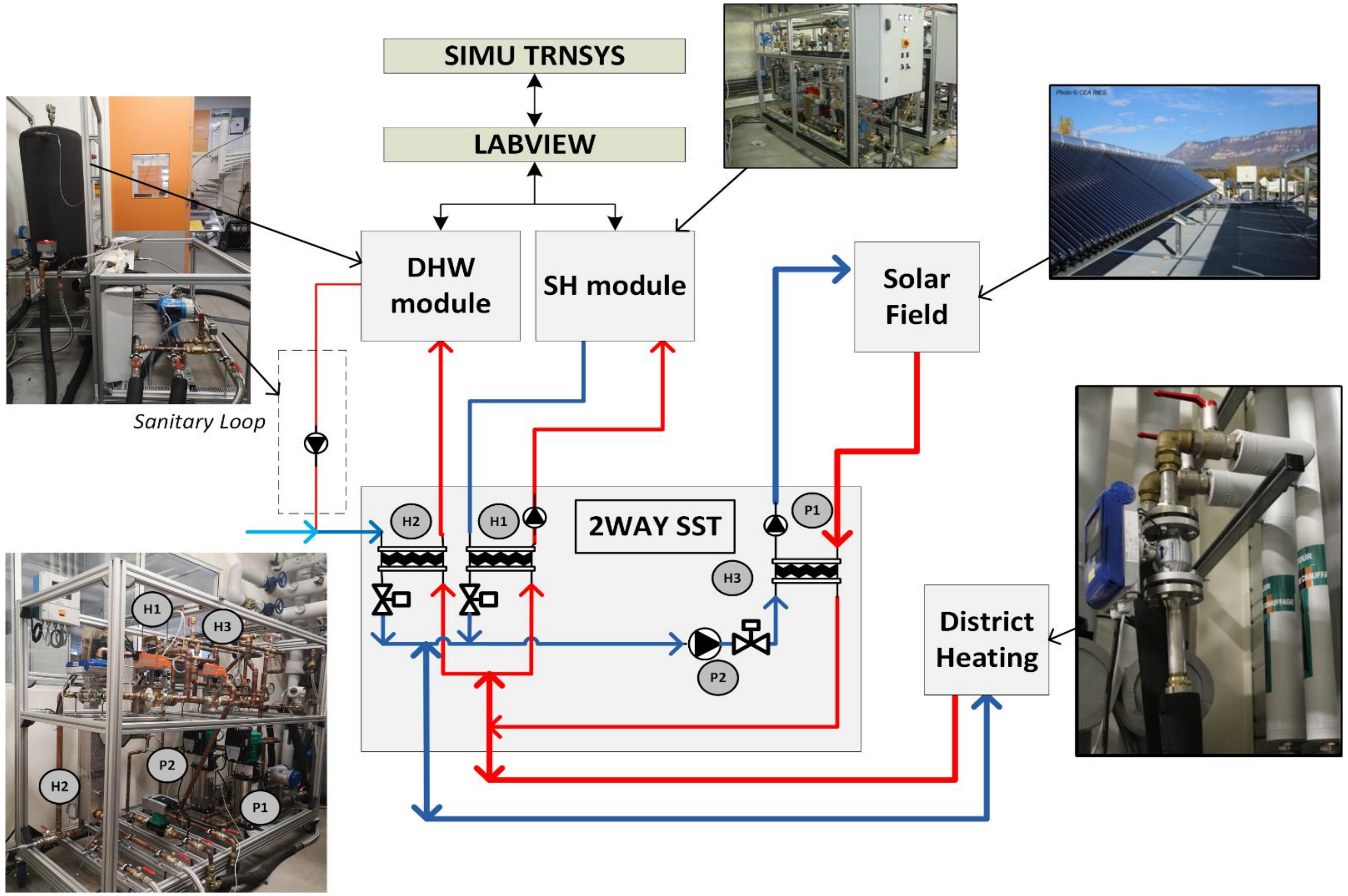
Thermoss Project
H2020 (2017 - 2020)

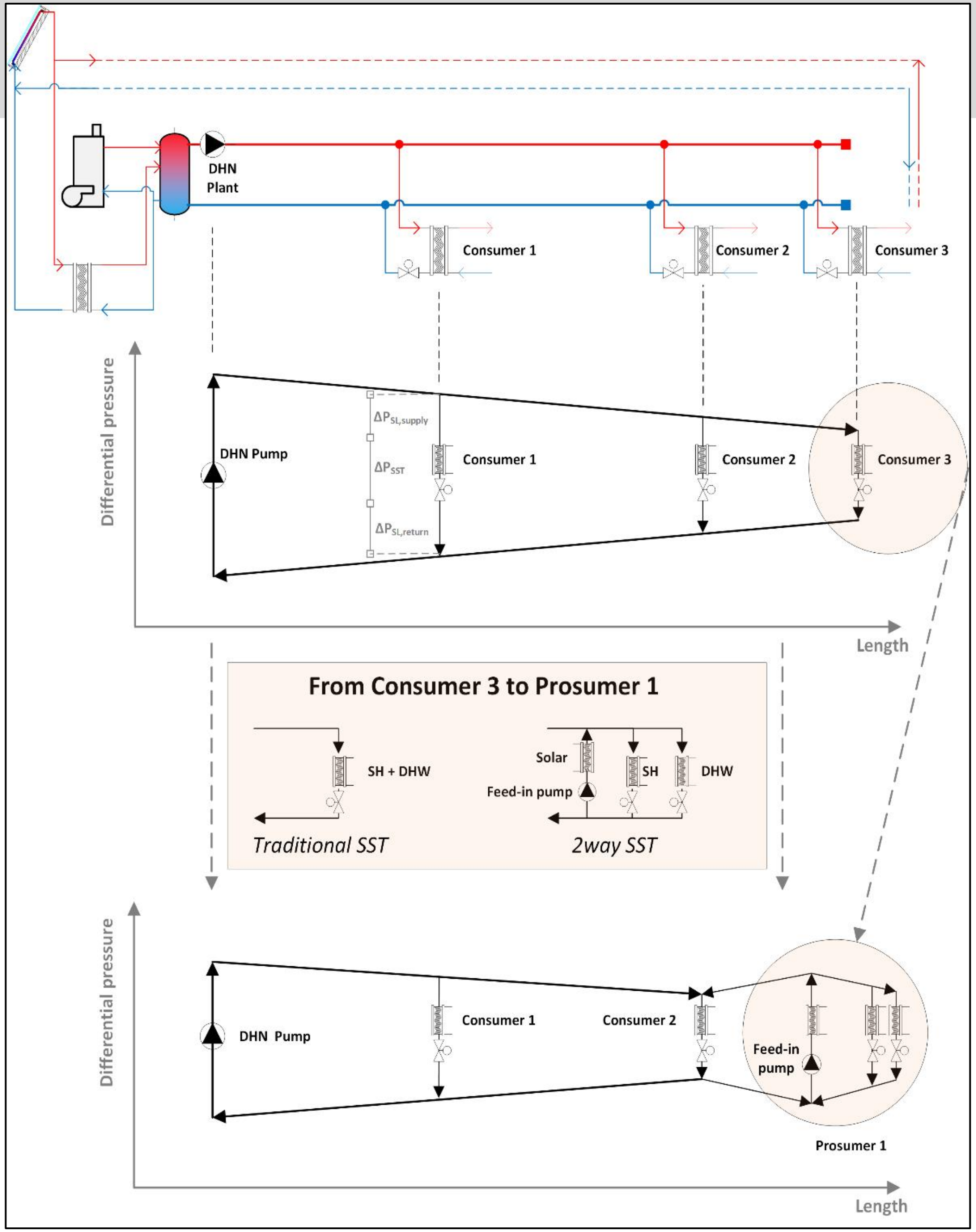


Prosumer substation = Feed-In + Consumer Substation

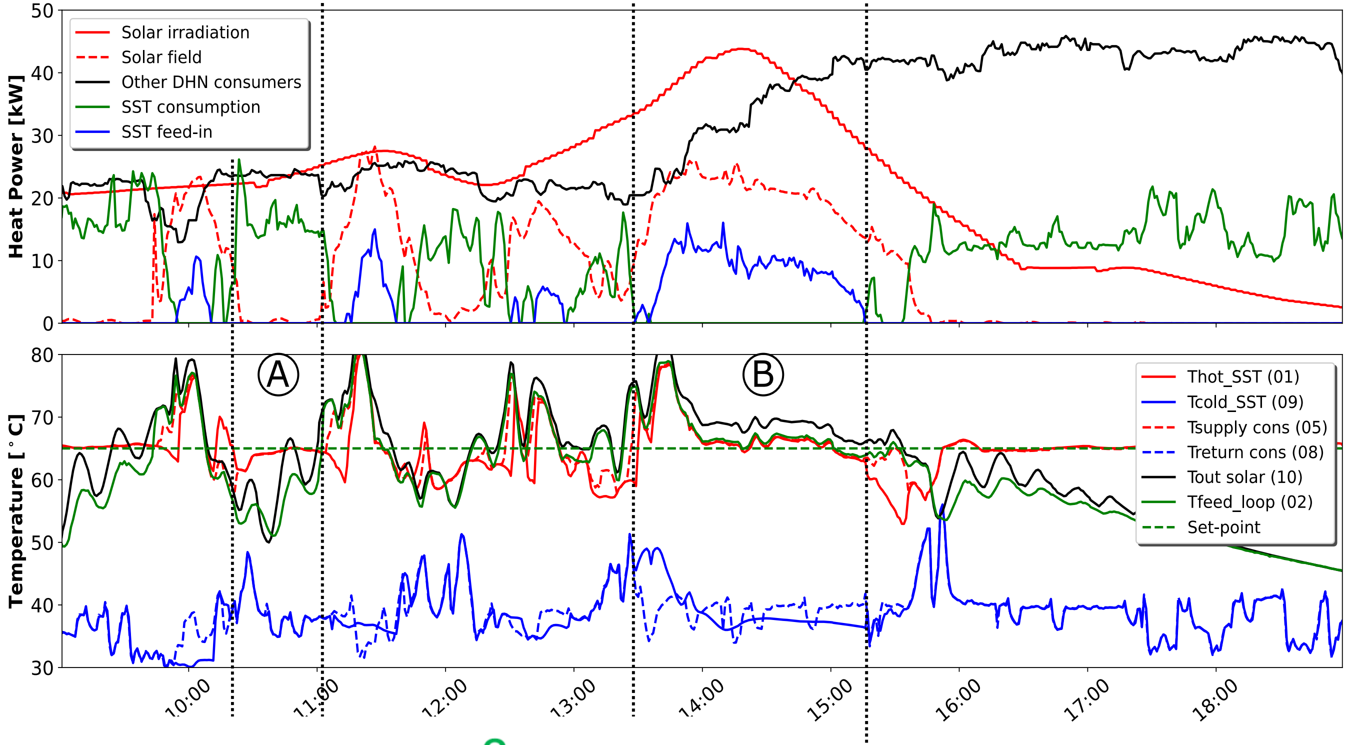
Thermoss Project
H2020 (2017 - 2020)

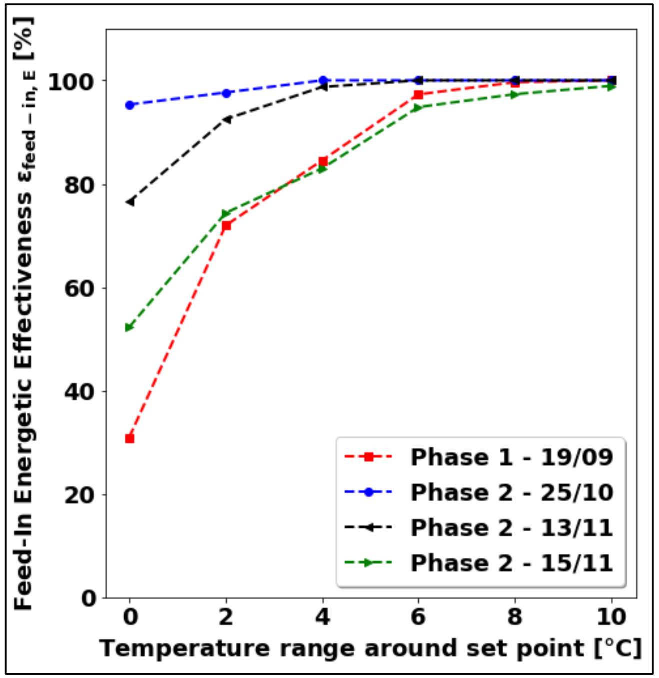


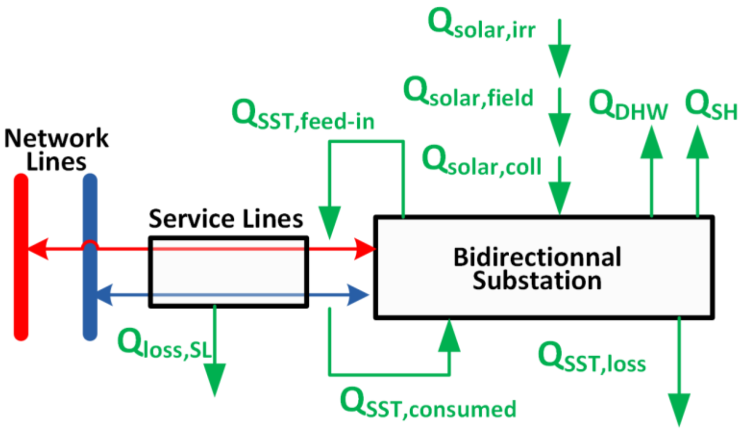



# SOLAR FEED-IN SUBSTATION

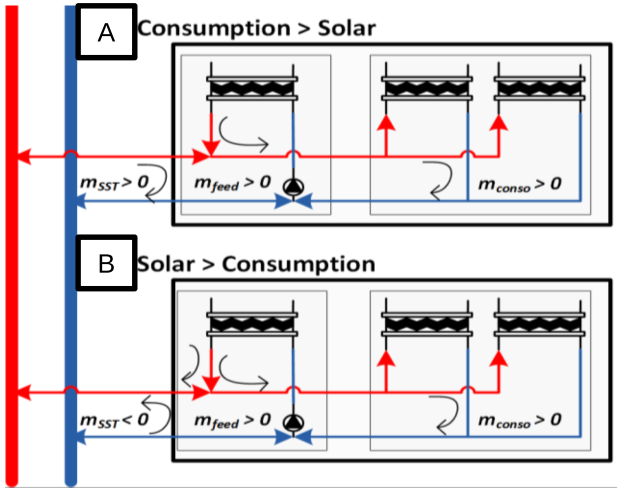
$$\varepsilon_{\text{feed-in,E,i}} = \frac{\sum P_{feed,in}.\Delta t|_{F_{BSST\_DHN}<0\ \&\ TT01>T_{sp,TT01}-2K}}{\sum P_{feed,in}.\Delta t|_{F_{BSST\_DHN}<0}}$$




$$SF_{tot} = \frac{E_{SST,feed-in} + E_{SH} + E_{DHW} - E_{SST,consumed}}{E_{SH} + E_{DHW}} = 25.5\%$$



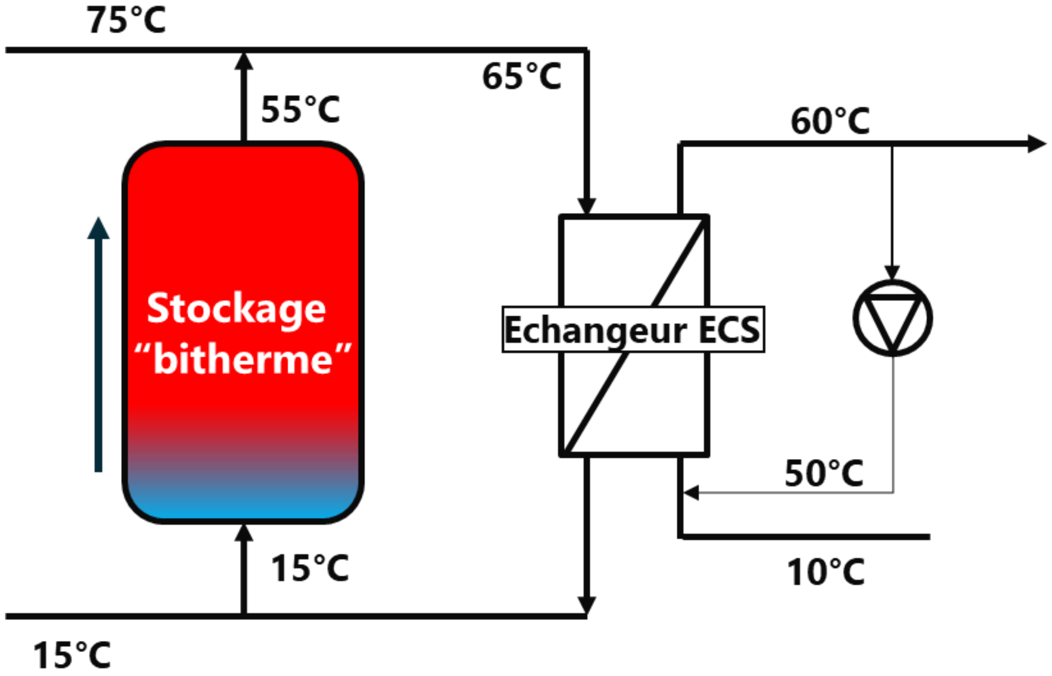
# TOPIC 3:

Innovative design with primary storage

***Limit loads on the production plants***

***Reduce the return temperature***

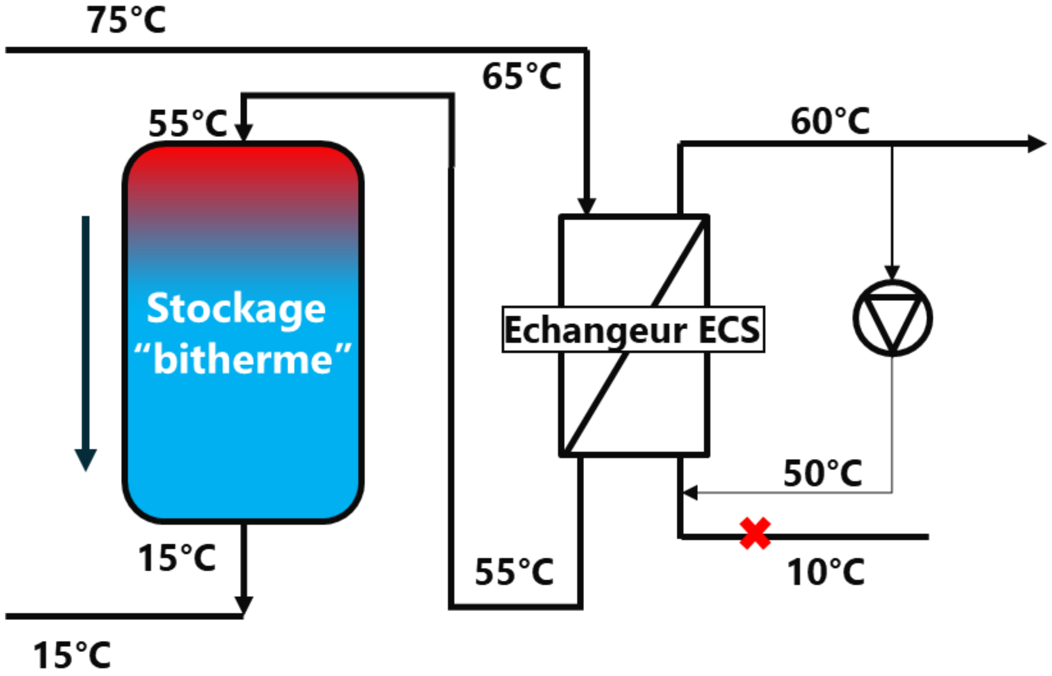
## Mode Production ECS




- Vidange du chaud à 55°C du ballon
- Remplissage de froid à 15°C du ballon

➡ **Lissage de l'appel de puissance**

## Mode Bouclage sanitaire seul

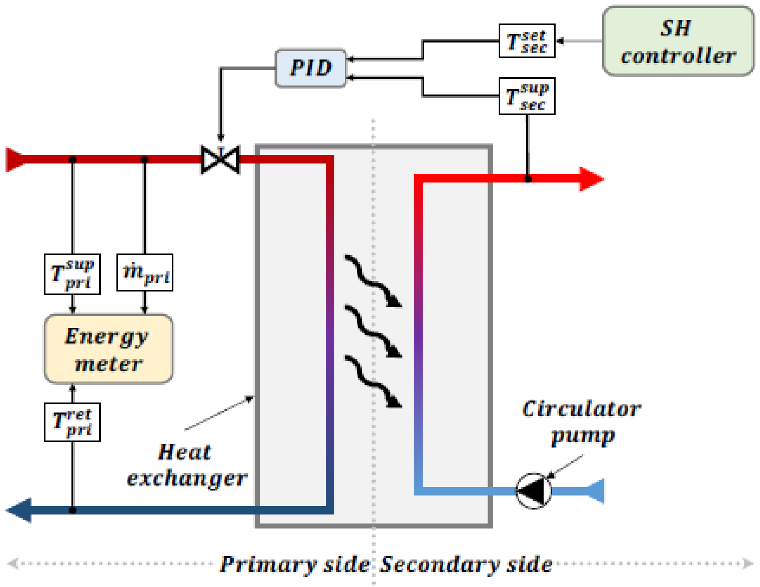



- Vidange du froid à 15°C du ballon
- Remplissage de chaud à 55°C

➡ **Diminution température de retour**

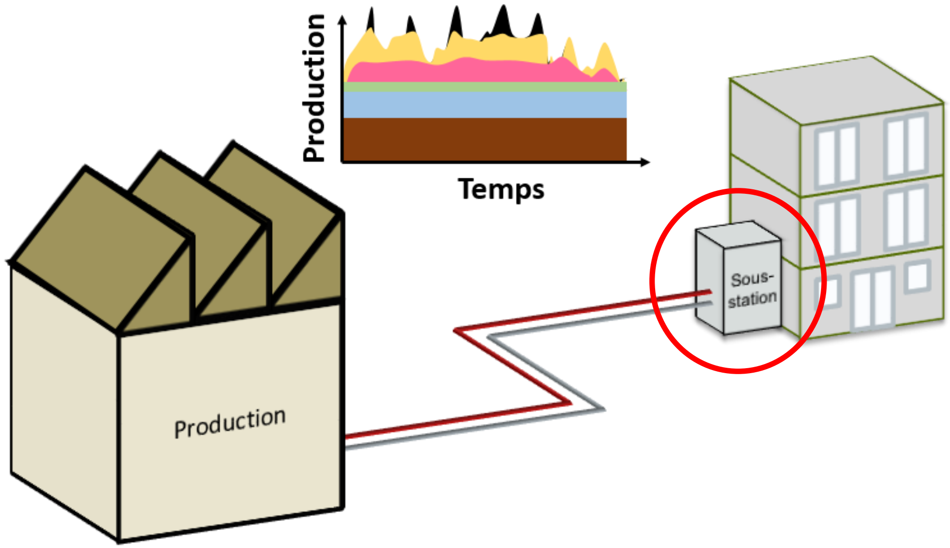
# TOPIC 4:

Advanced Control




***Limit loads on the production plants***

## Demand-Side Management

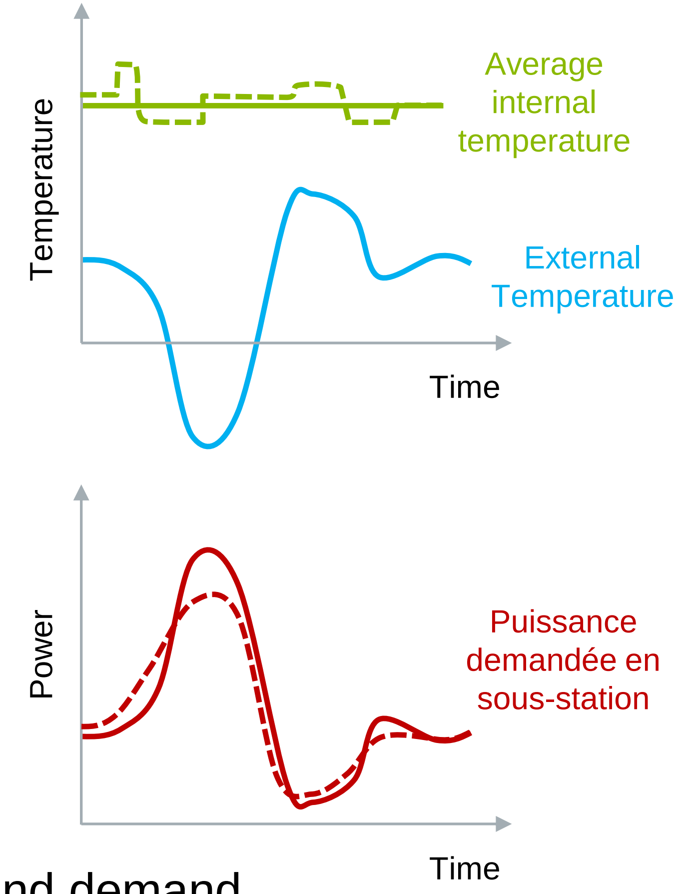



Advanced management (Predictive control)

Prediction of consumption on the horizon

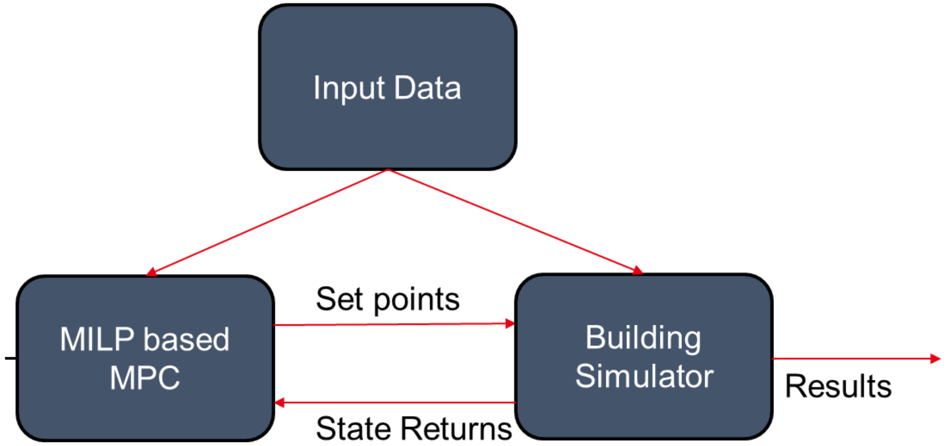
Optimization of the load under internal temperature constraints

Advanced Control

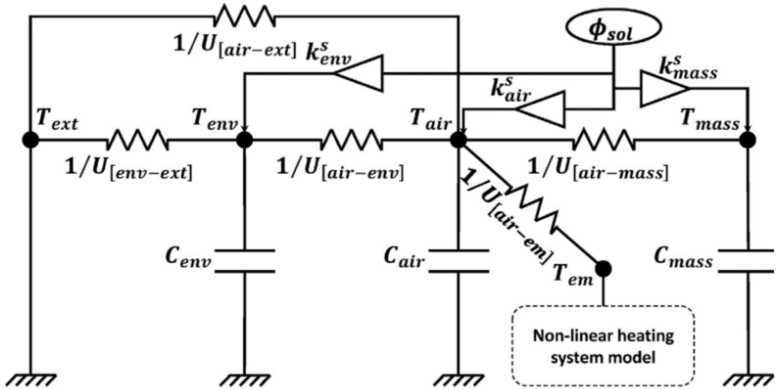



➡ Towards combined optimization of production, distribution and demand

- MILP based MPC for SH demand
- Use of Heating circuit and internal mass for flexibility
- Replacement of WC with demand-side management



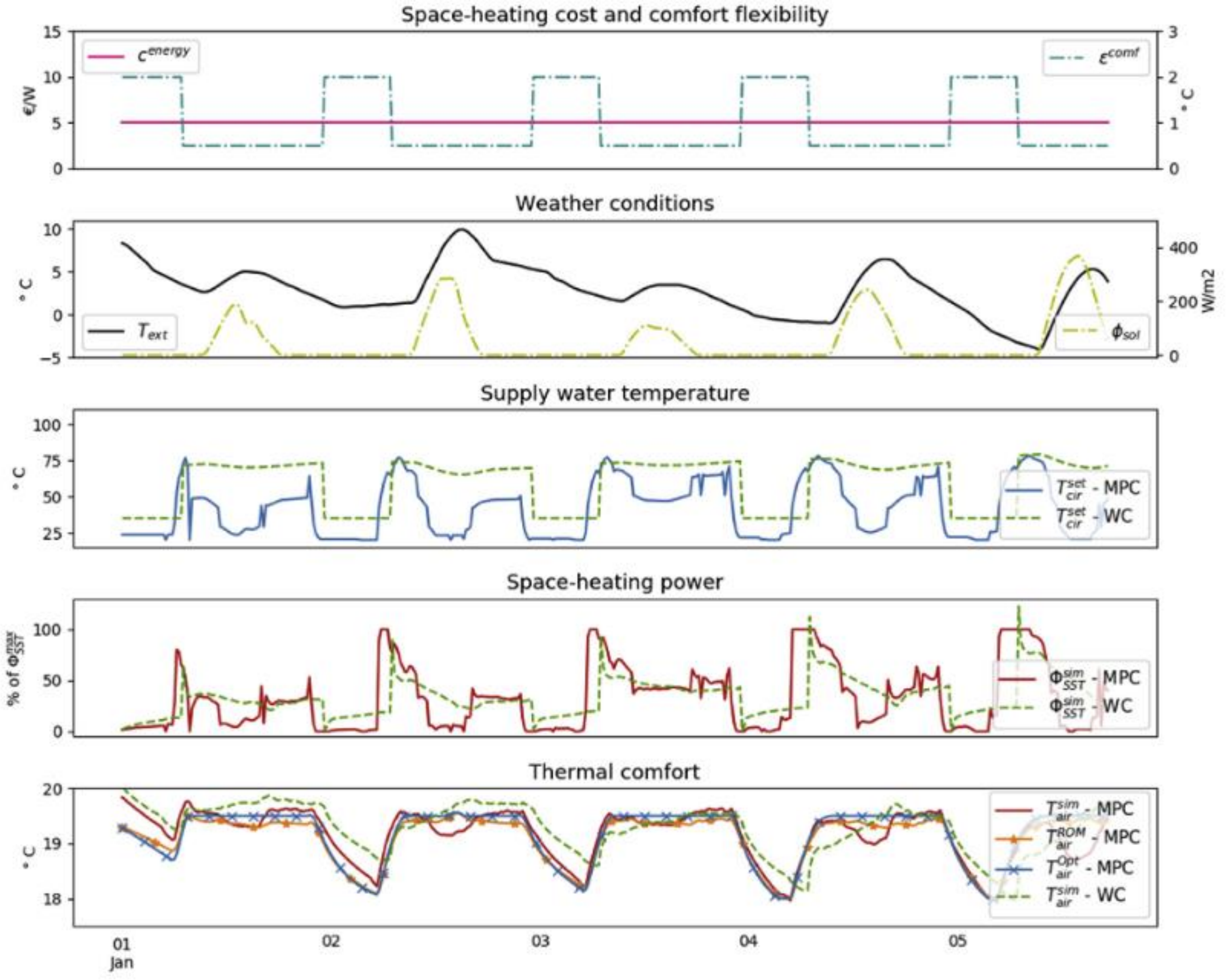

3rd order ROM model
Non linear heating circuit model → linearized for MPC
16 parameters identified with detailed model
Identification use data available at the SST (power, flow, T setpoint)




$$f_{obj} = \sum_{n=1}^{N} \begin{pmatrix} p^{energie}[n] \cdot Q_{SST}[n] \cdot \Delta t \\ +p^{sur-chauffe}[n] \cdot \Delta T_{air}^{sur-chauffe}[n] \cdot \Delta t \\ +p^{sous-chauffe}[n] \cdot \Delta T_{air}^{sous-chauffe}[n] \cdot \Delta t \\ +p^{pertes}[n] \cdot \Delta T_{cir}^{pertes}[n] \cdot \Delta t \end{pmatrix}$$

MODELICA
Dymola

Aoun et al. Modelling and flexible predictive control of buildings space-heating demand in district heating systems, Energy, 2019




Standard WC control using a static heating curve with a night-time set-back limiting $T_{set,cir}$ to 35°C from 11:00 p.m. to 6:45 a.m., $T_{set,air}$ =19.5°C

**VS**

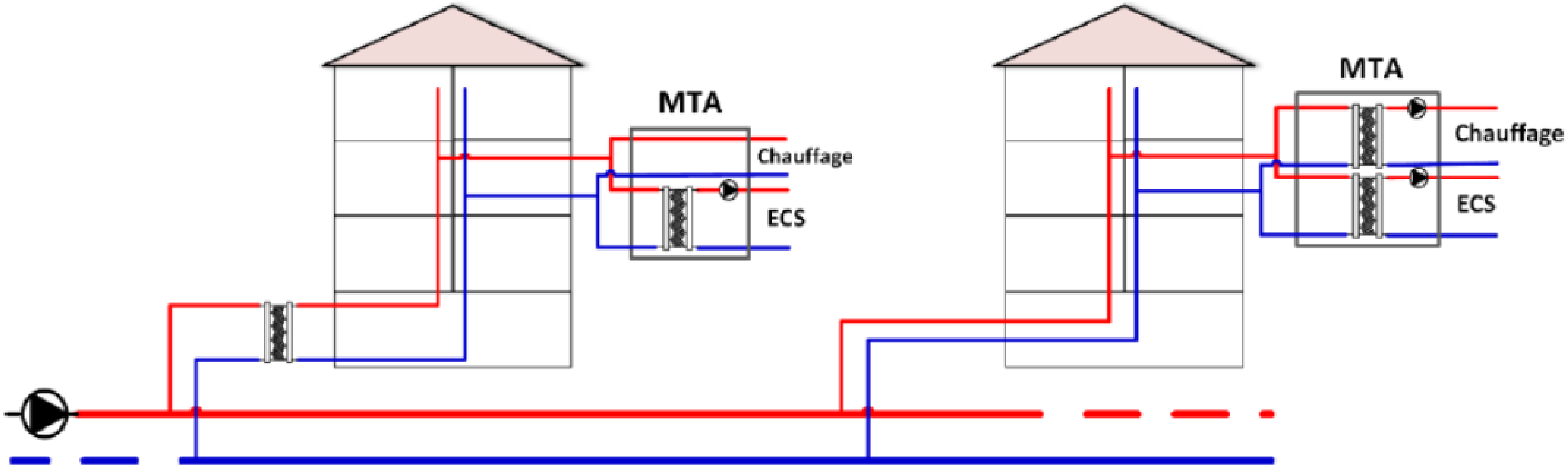
MILP-based MPC considering fixed energy cost with $\varepsilon_{comf} = 0.5°C$ during the day and $\varepsilon_{comf} = 2°C$ from 11:00 p.m. to 6:45 a.m.,

## RESULTS

- Reduced supplied water temperature exploiting at best the 2°C flexibility and anticipates solar gains
- MPC launches and exists set back period ahead because anticipation of thermal inertia
- Peak-shaving not achieved with constant energy cost

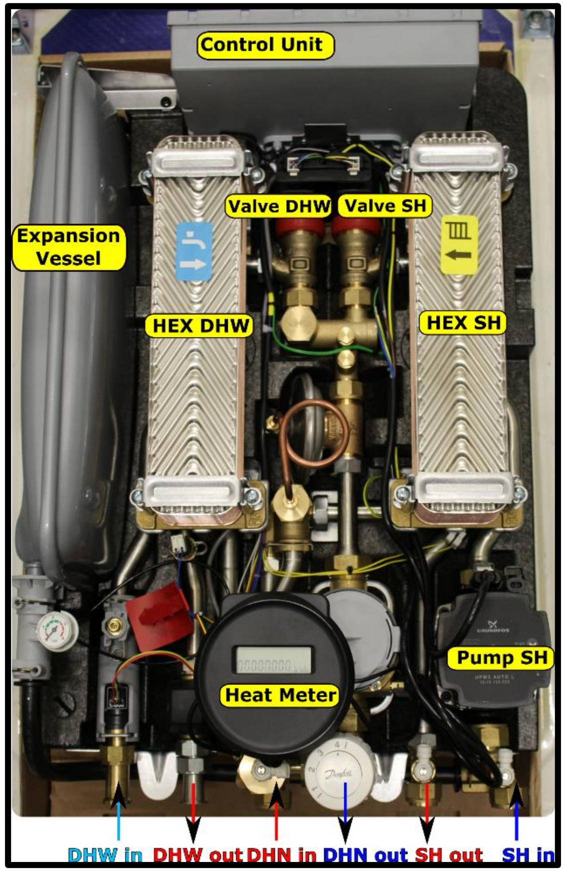
# TOPIC 5:

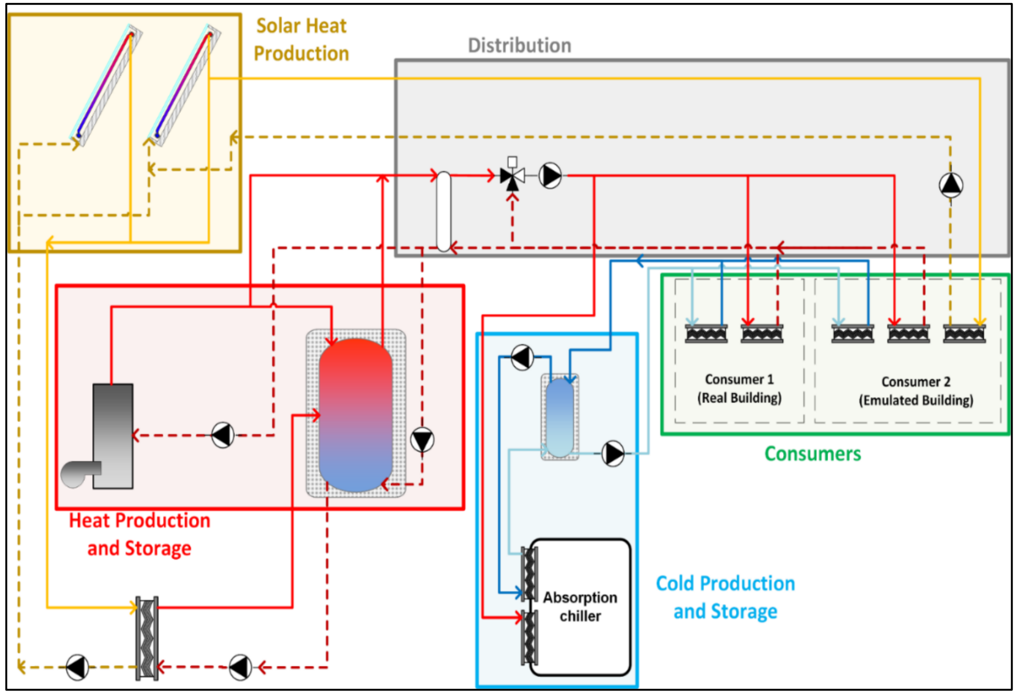
Apartment Substation

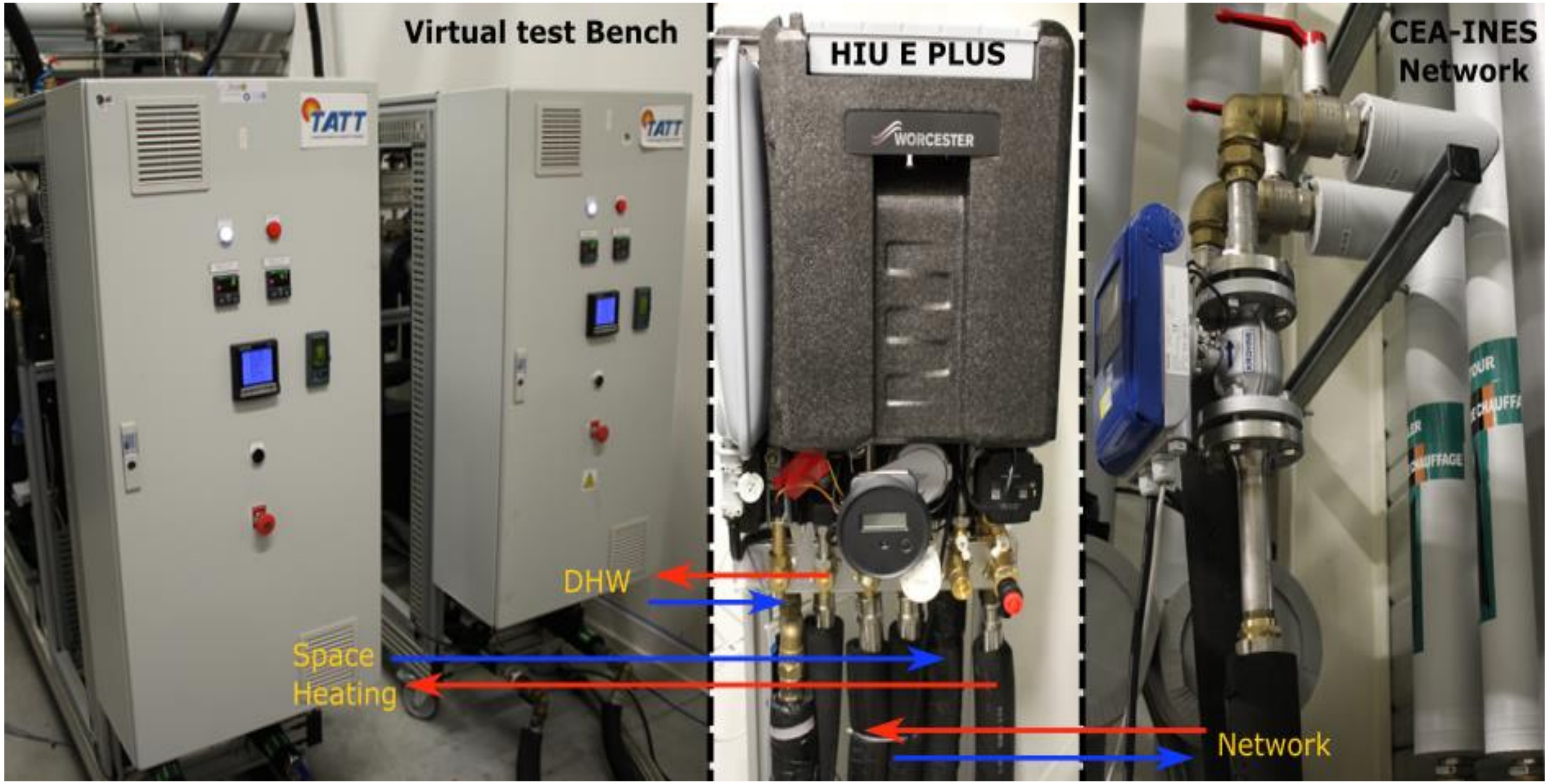



With an individual substation, the secondary side return temperature is the smallest as possible because component sized for a single user.

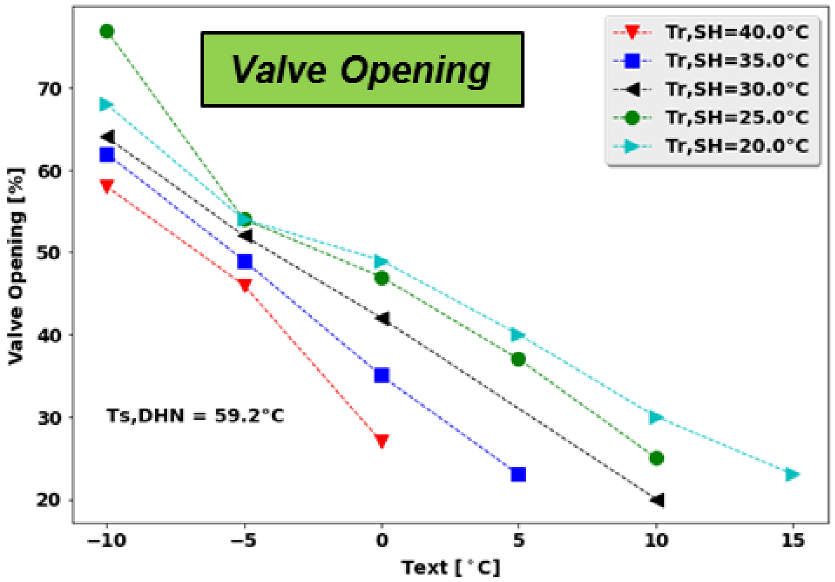
DHN return temperature is thus further reduced

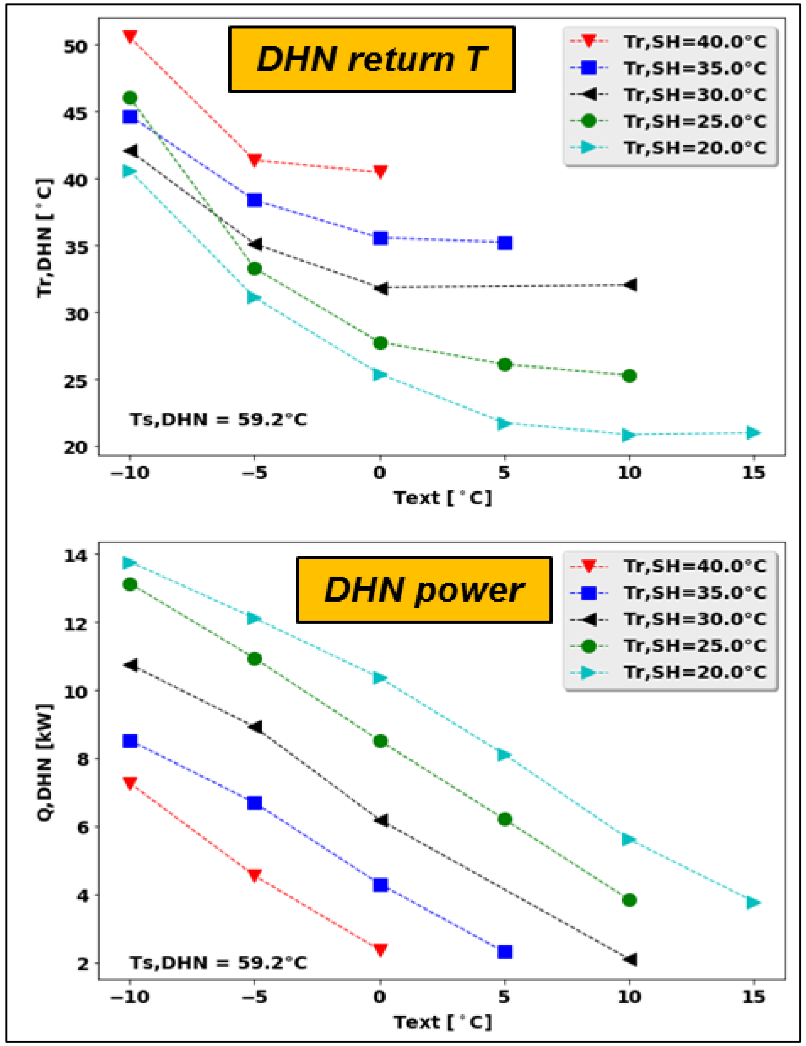

Control Unit
Valve DHW
Valve SH
Expansion Vessel
HEX DHW
HEX SH
Pump SH
Heat Meter
DHW in
DHW out
DHN in
DHN out
SH out
SH in


Solar Heat Production
Distribution
Heat Production and Storage
Consumer 1 (Real Building)
Consumer 2 (Emulated Building)
Consumers
Absorption chiller
Cold Production and Storage

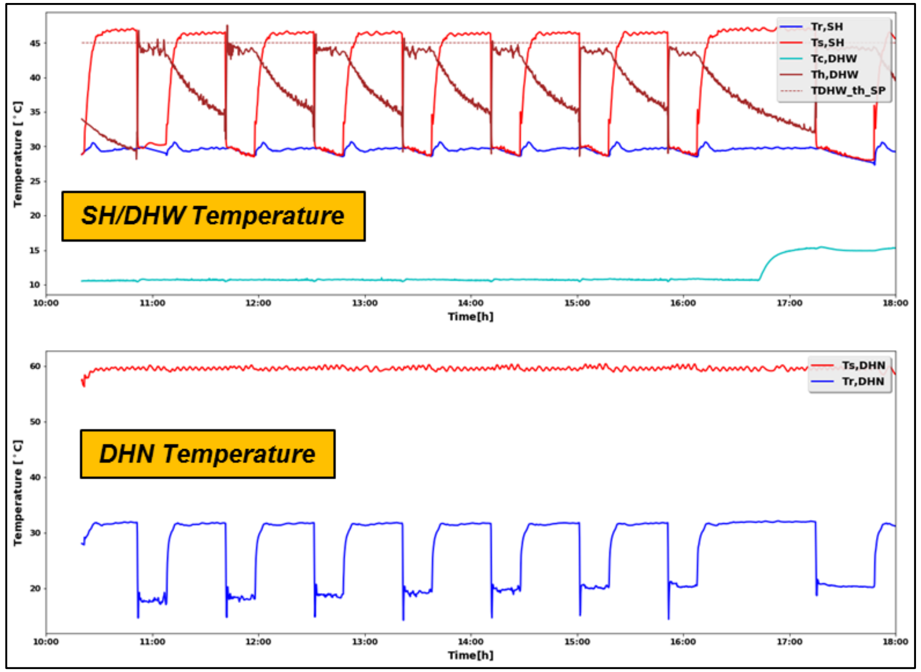

Virtual test Bench
HIU E PLUS
CEA-INES
Network
TATT
WORCESTER
DHW
Space
Heating
Network

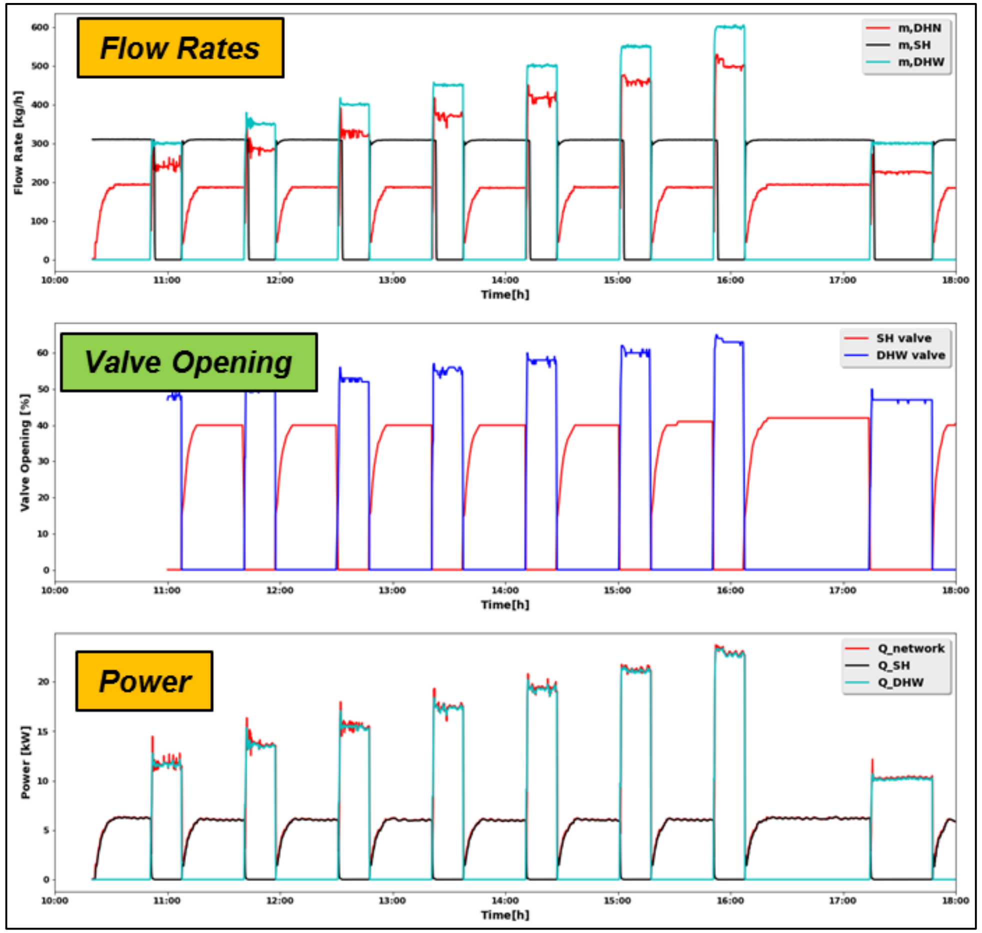
# Validation TESTS
# Space Heating Only (STEADY)



# Validation TESTS - Dynamic




- Sudden change of return T at each draw-off
- Very fast DHW response time (less than 1 minute with only a slight overshoot)
- DHW priority

# **TOPIC 6:**

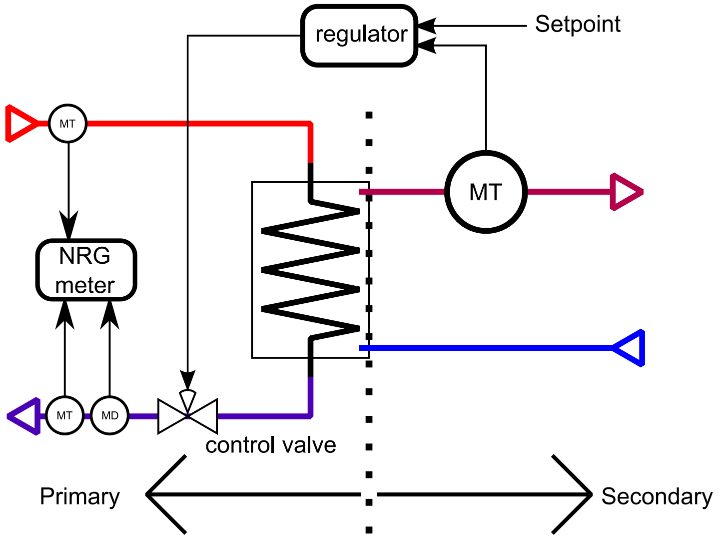
Faults in Substation

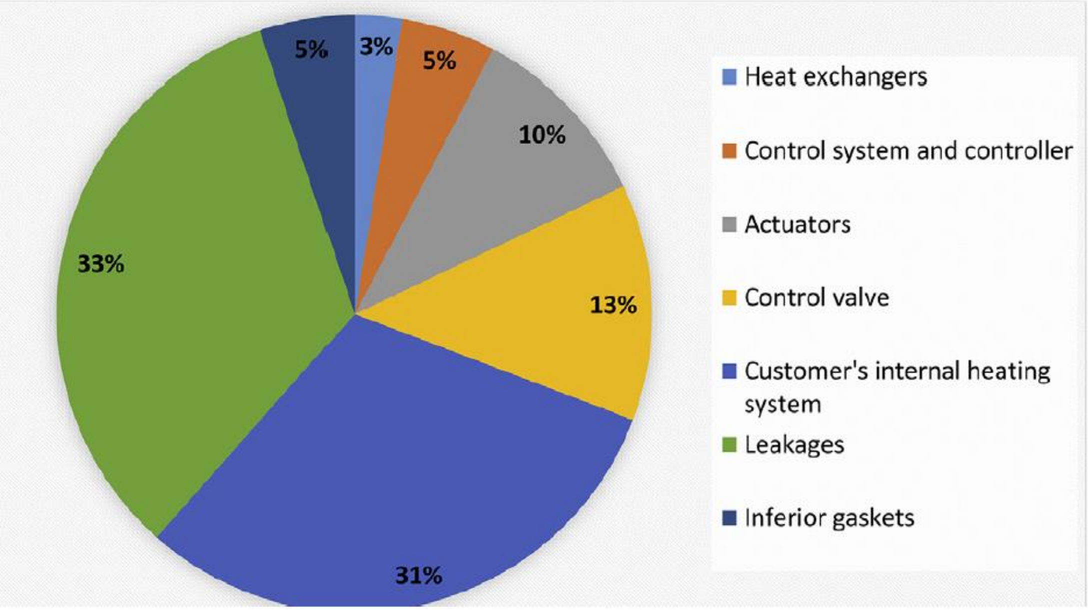
***Implement at fine sampling a digital monitoring***

Focus is on the problem of high return temperature:
- Short circuit flows (intentional and non-intentional)
- Too low supply temperatures in peripheral substations
- Errors in substation
- Errors in customer heating system

→ Detection and priority set using overflow indicator

*« District Heating And Cooling », S. Frederiksen and S. Werner, Studenttlitteratur, Sweden, 2013*




*Mansson et al., Faults in district heating customer installations and ways to approach them: Experiences from Swedish utilities, Energy, 2019*

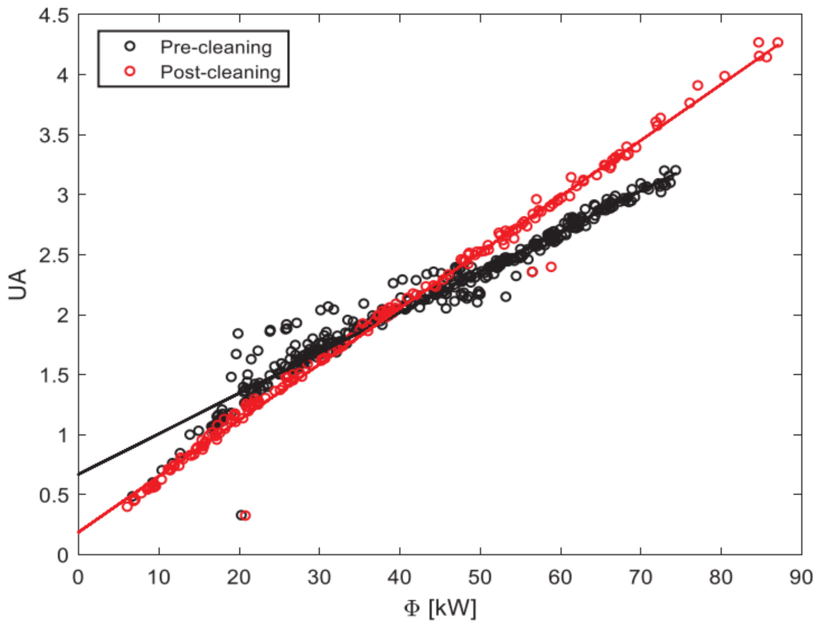
<u>3 different fault groups:</u>
- Unsuitable heat load patterns
- Low average return temperature
- Poor substation control

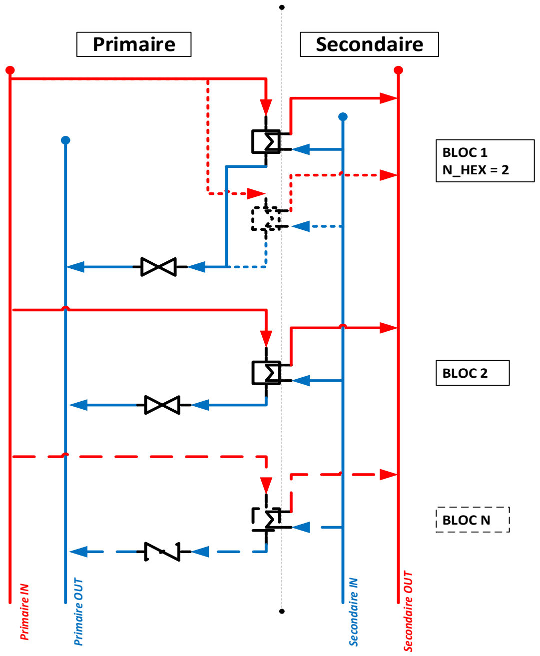
→ Use of automatic data collection is necessary

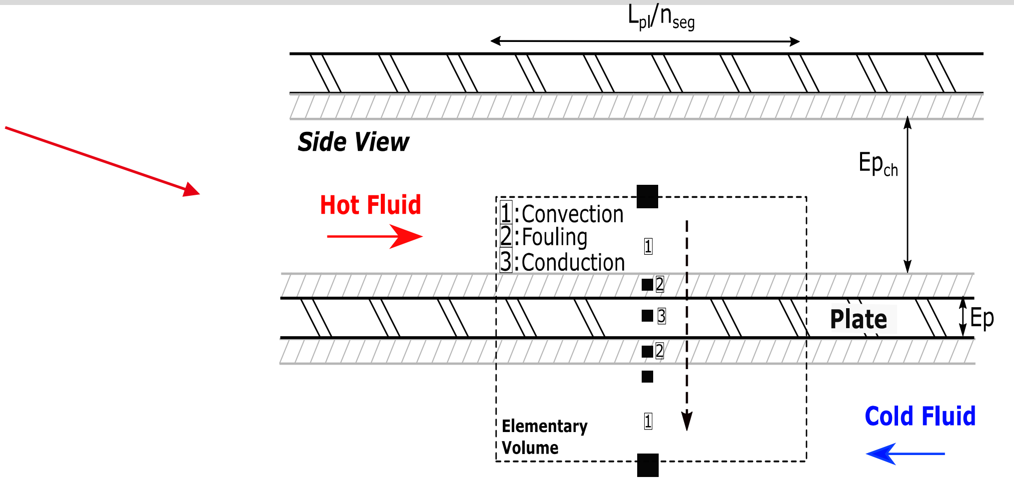
*Gadd and Werner, "Fault detection in district heating substations", Applied Energy, 2015*

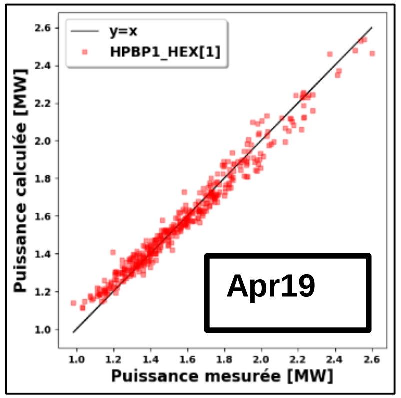
Fouling detection using:

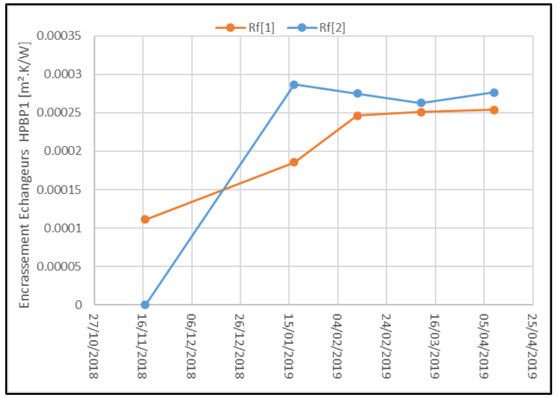
- full substation model and identification of the fouling parameter
- steady state detection and linear fit of Q as a function of UA: assumption of constant DTLM




→ **If slope increases, HEX is fouled**

*Guelpa et al., Automatic fouling detection in district heating substations: Methodology and tests, Applied Energy, 2020*

# THANKS FOR YOUR ATTENTION

Commissariat à l'énergie atomique et aux énergies alternatives
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