Dynamic Modelling of Thermal Energy Storage for District Cooling Applications

Dr Carlos E. UGALDE-LOO

Reader in Electrical Power Systems

School of Engineering, **Cardiff University**

Based on the PhD research work from
Mr Héctor **BASTIDA**

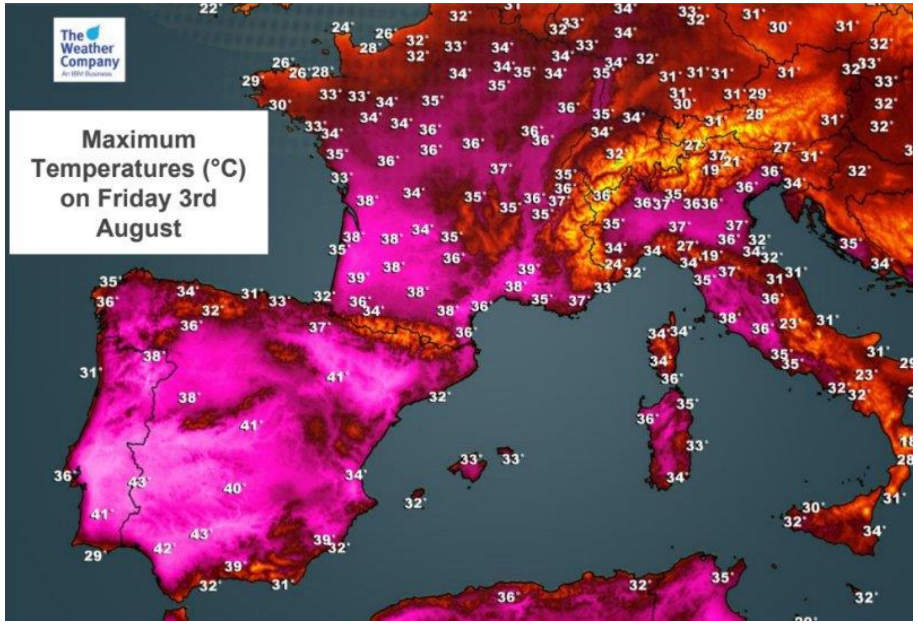
Additional credit to:
Dr M Abeysekera, Dr X Xu, Dr M Qadrdan, Prof J Wu, Prof N Jenkins

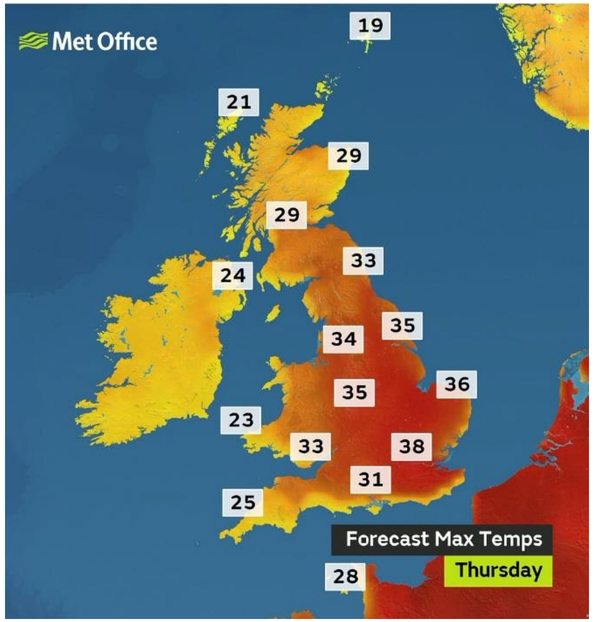
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

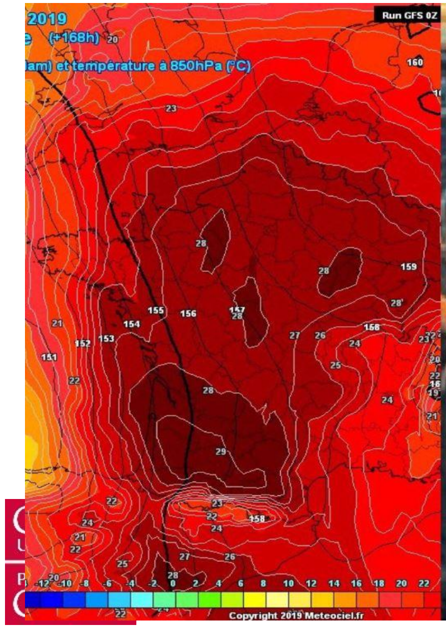
Newcastle, England, 3rd September 2019

UKES2019
UK Energy Storage Conference

Motivation







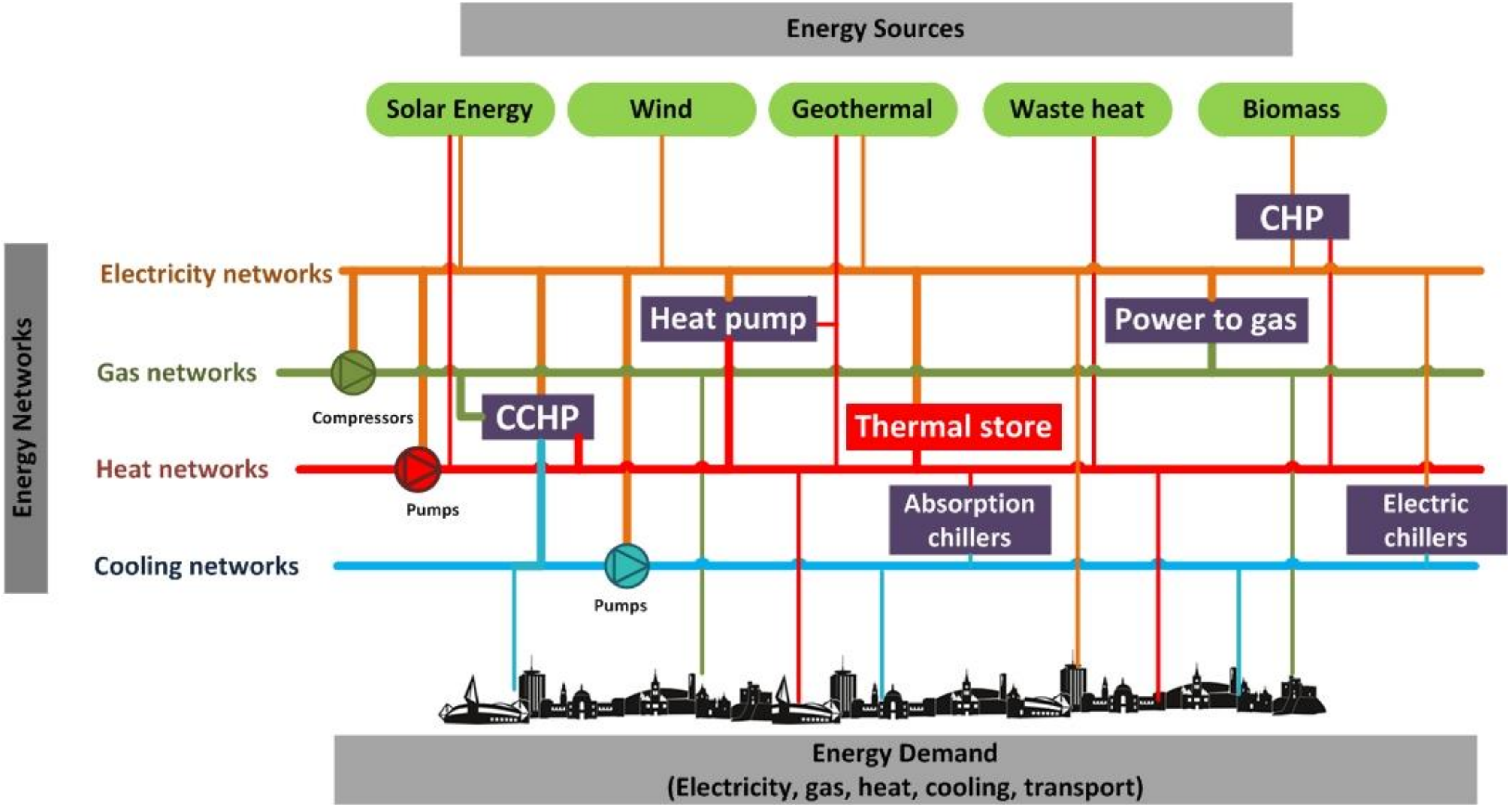
Heat waves have been **intense** and **frequent** lately, with **cooling demands** in cities **increasing** due to the **unusual weather**.

Outline

1. Integrated Energy Systems
2. Examples – District Heating and Cooling Systems
3. Thermal Energy Storage for Cooling using Ice
4. Modelling Approach
5. Simulation Results
6. On-Going Work
7. Concluding Remarks

Integrated Energy Systems

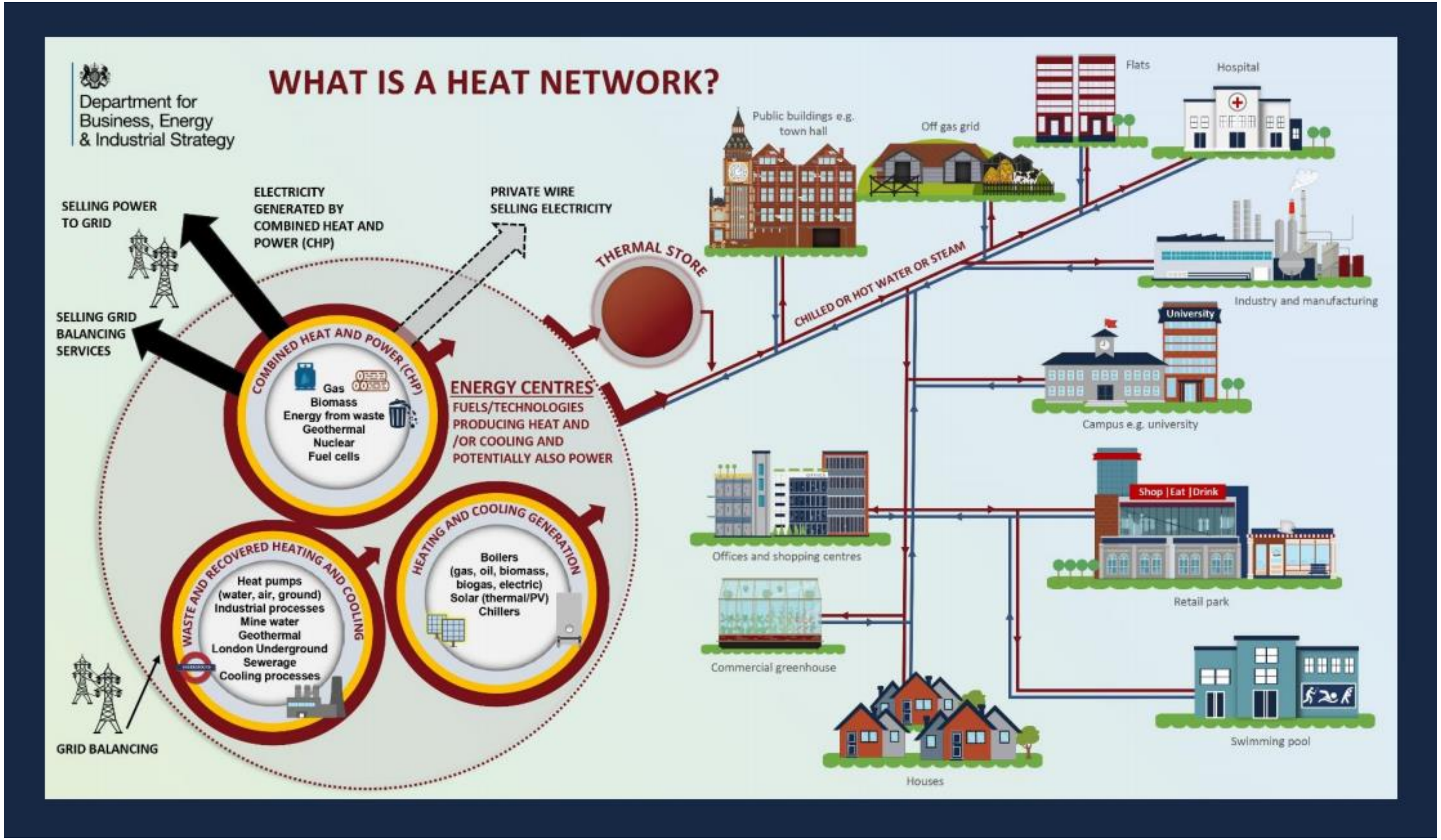
- **Also called multi-vector energy systems, multi-energy systems, multi-energy carrier, energy system integration, integrated energy networks**
  - **Interdependent** and **interacting energy sources**, **energy supply networks** and **energy demand** organised for **production, delivery and consumption** of energy.



Integrated Energy Systems (2)

- **Characteristics:**
  - Complementary advantages of various energy vectors for system design and operation.
  - Exploring and facilitating the integration of local sustainable and renewable energy resources.
  - Increasing system reliability and resilience.
  - Helping combat rural fuel poverty.
  - Improving energy efficiency and reducing energy cost.

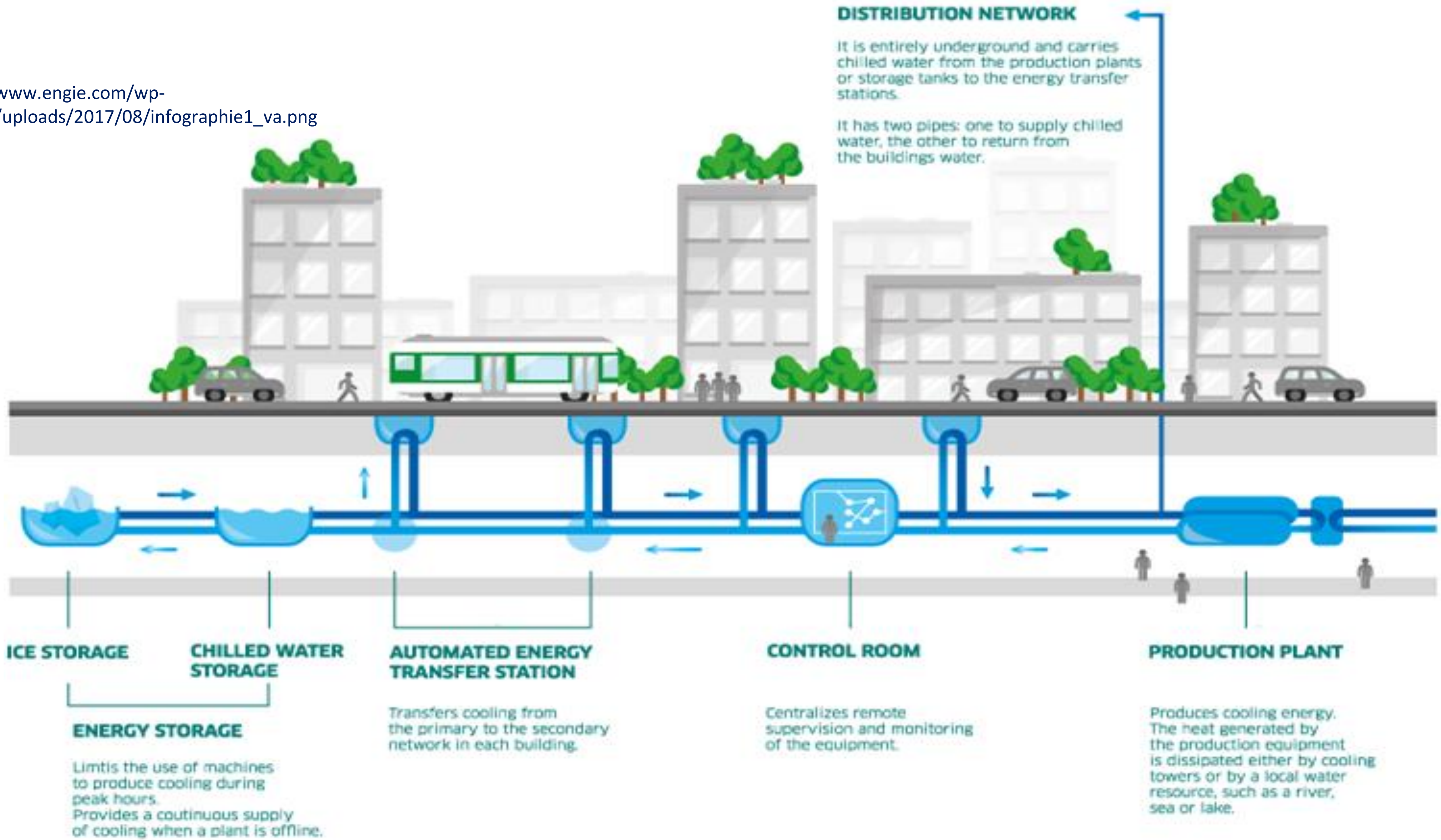
Examples – District Heating and Cooling Systems



https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/696273/HNIP_What_is_a_heat_network.pdf

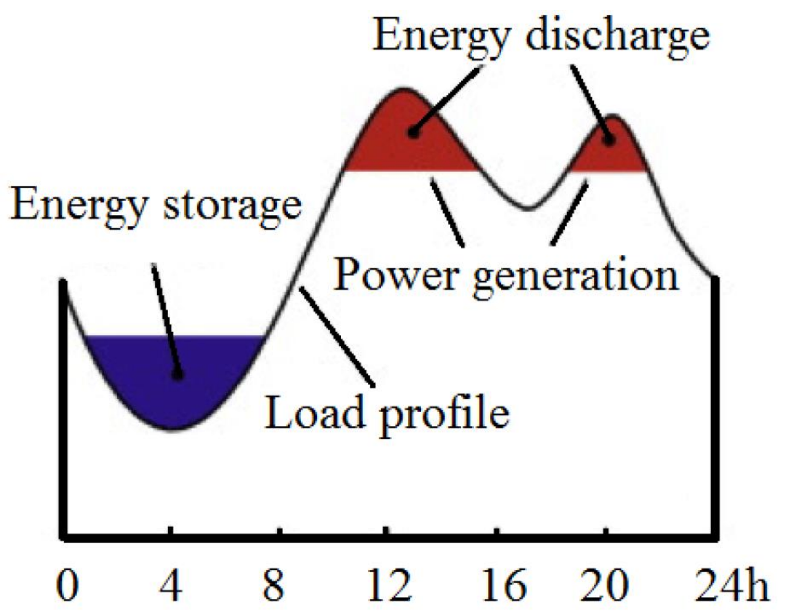
Examples – District Heating and Cooling Systems (2)

https://www.engie.com/wp-content/uploads/2017/08/infographie1_va.png

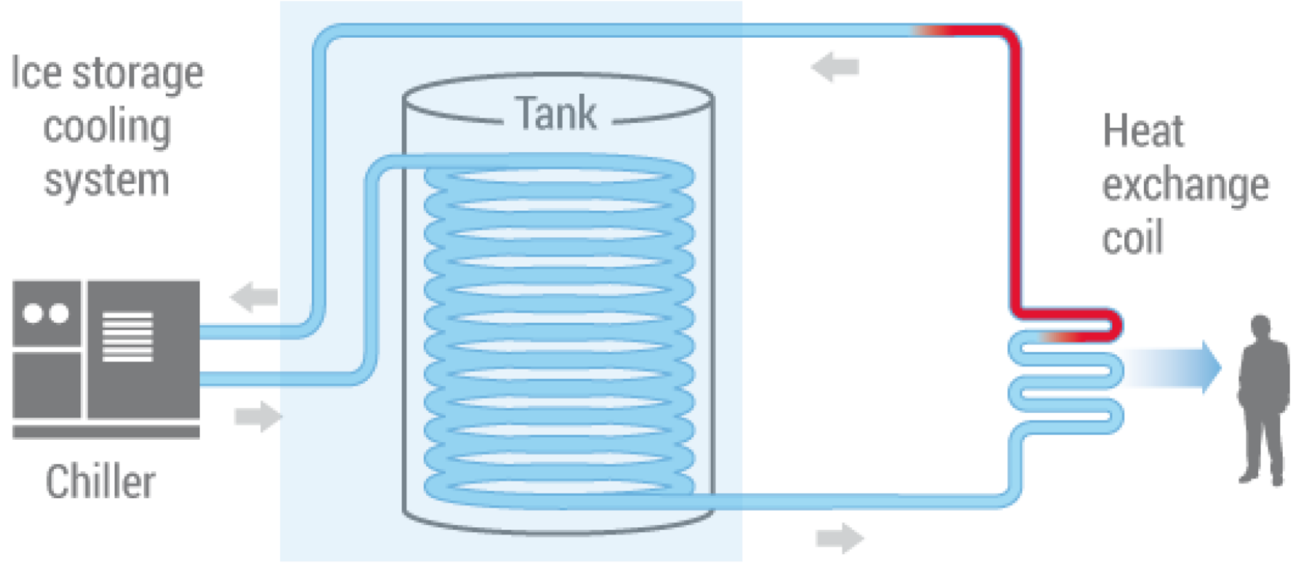


Thermal Energy Storage for Cooling using Ice

- Typical cooling systems comprise **standard cooling equipment** and an **energy storage tank**.



Shaving cooling peak demand



http://www.calmac.com/icebank-energy-storage-model-c

- **Thermal energy storage (TES)** serves as a **battery** for a cooling system.
- The **ice-based TES** can provide **flexibility** to a **district cooling system** (e.g. shifting cooling loads, peak shaving) without disruptions to the costumers.

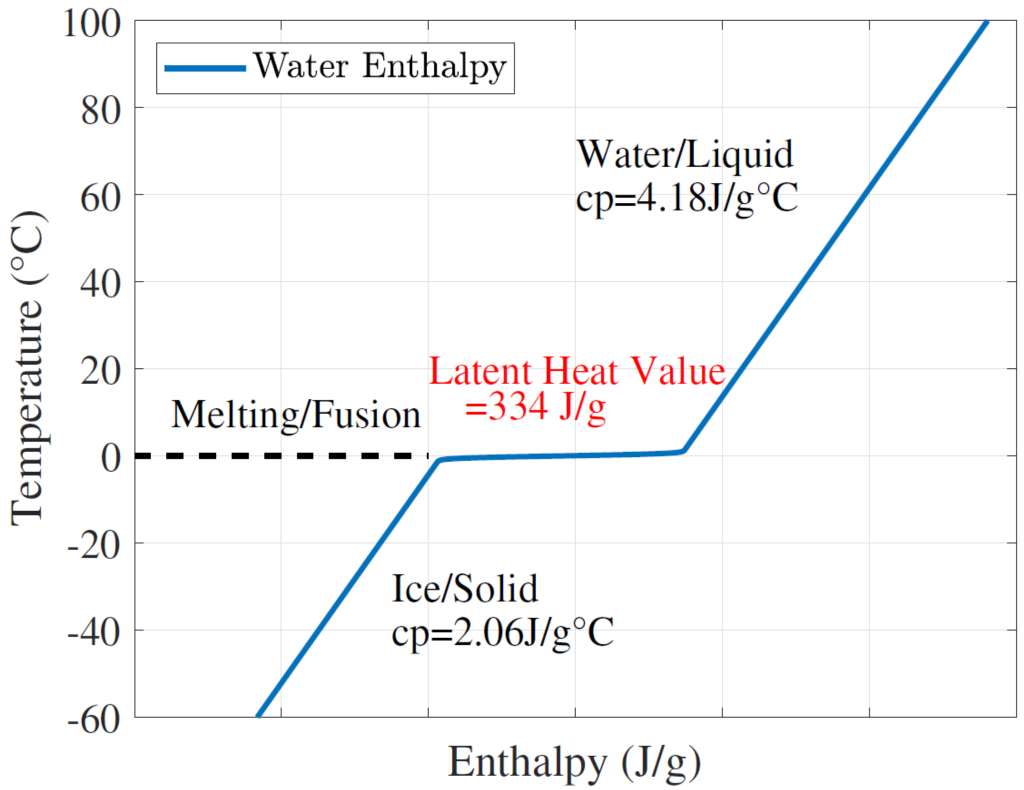
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

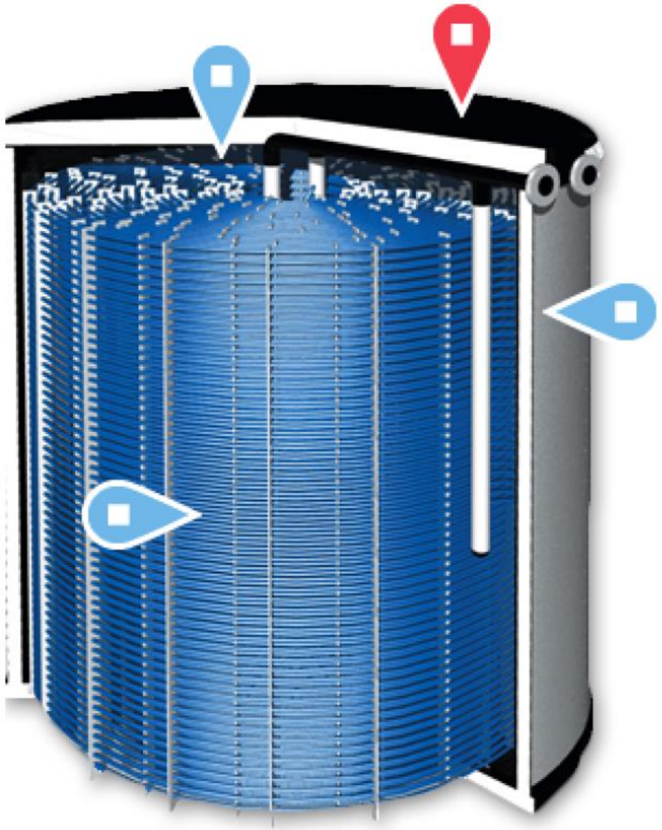
Thermal Energy Storage for Cooling using Ice (2)

➢ **Why** an **ice storage tank**?

- Water has well-known **properties** during **phase change**.
- Employed in known **district cooling systems** (e.g. **University campus**).
- The **energy storage** in this work is based on an **ice bank tank**.



http://www.calmac.com/icebank-energy-storage-model-c

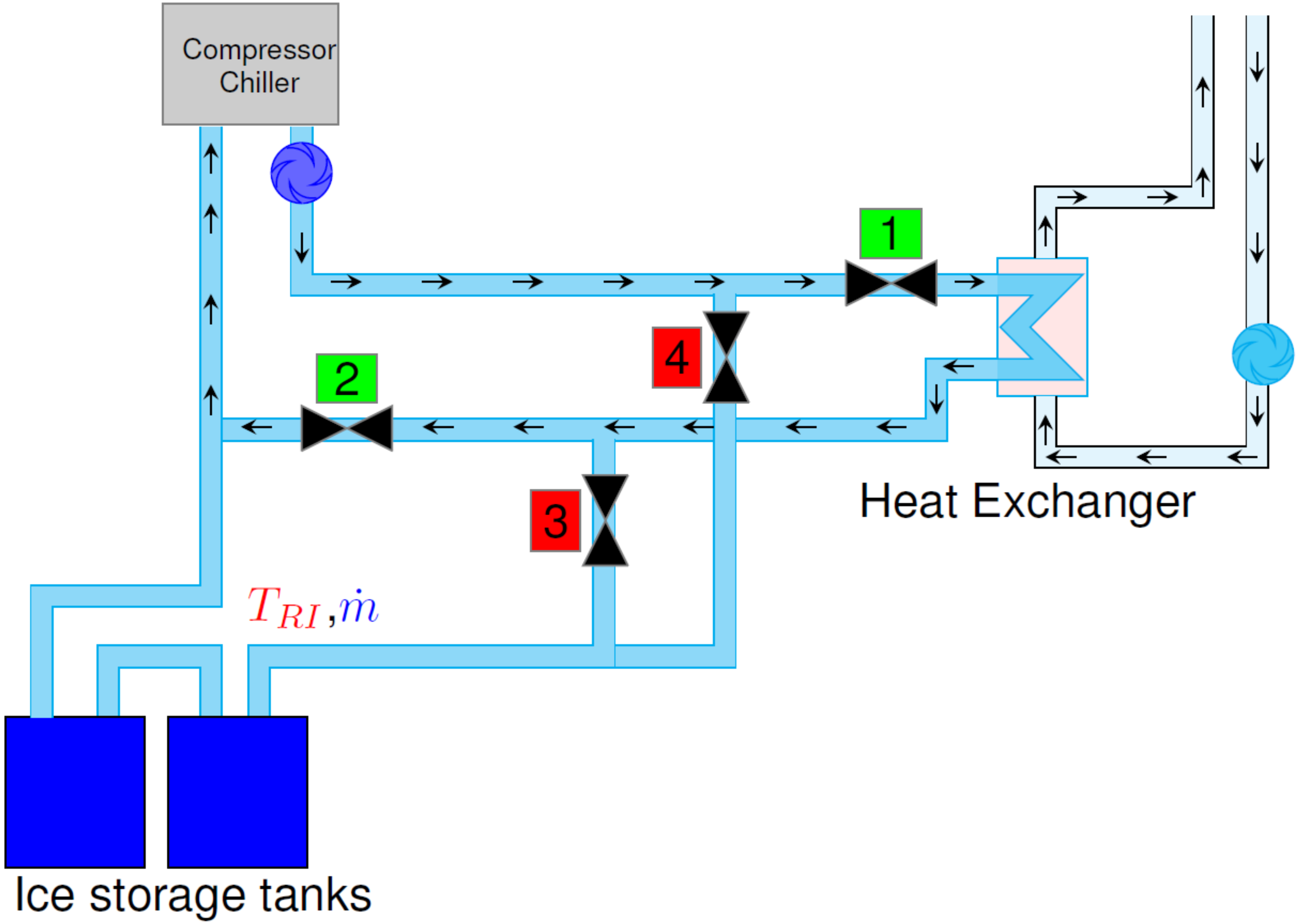


CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

Thermal Energy Storage for Cooling using Ice (3)

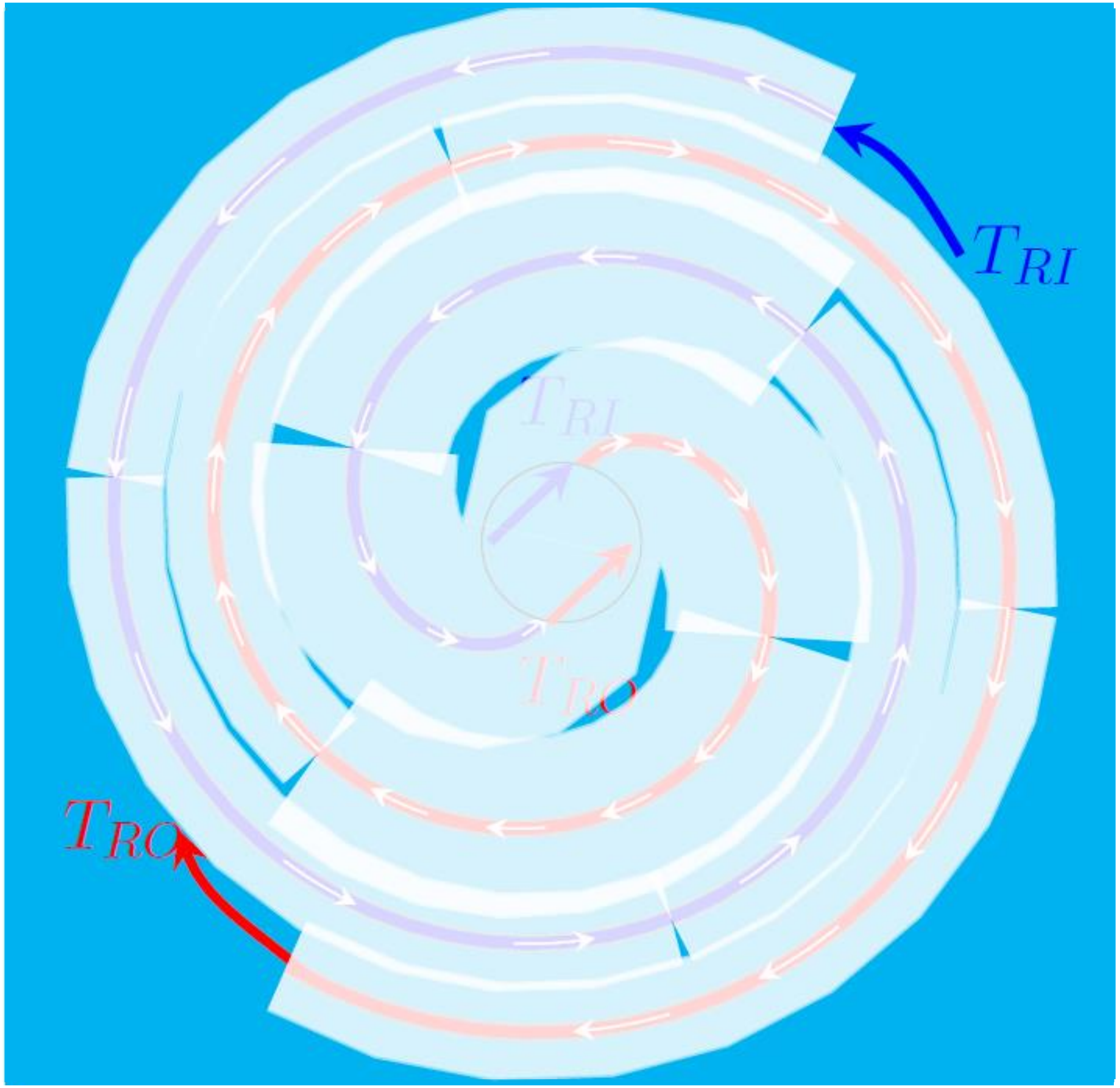
- **System operation.** There are **three** operating modes.
  - **Stand-by mode:**



Modelling Approach

- To understand the **interactions** between **energy vectors** in an **integrated energy system** and to design **effective control strategies**, **dynamic models** are required.

- The animation shows how the **ice storage tank** works.
  - **Two tubes** are rolled-up in a **spiral**.
  - **Flows** in the tubes are in a **counter-flow** direction.
  - This forms a **heat exchanger per horizontal level**.



CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

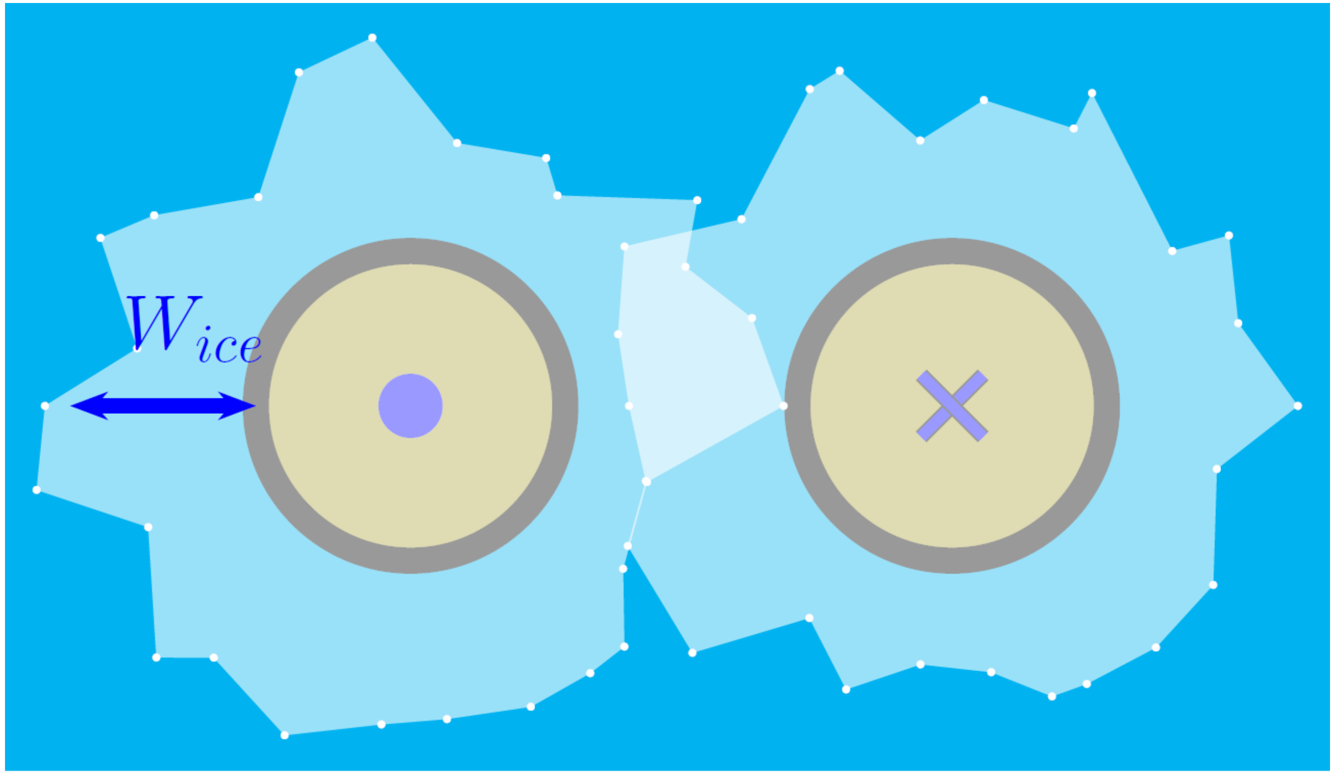
UKES2019 UK Energy Storage Conference

Modelling Approach (2)

➢ **Energy balance:** A set of **differential equations** describe the **thermal behaviour** of **water** and the **refrigerant.**

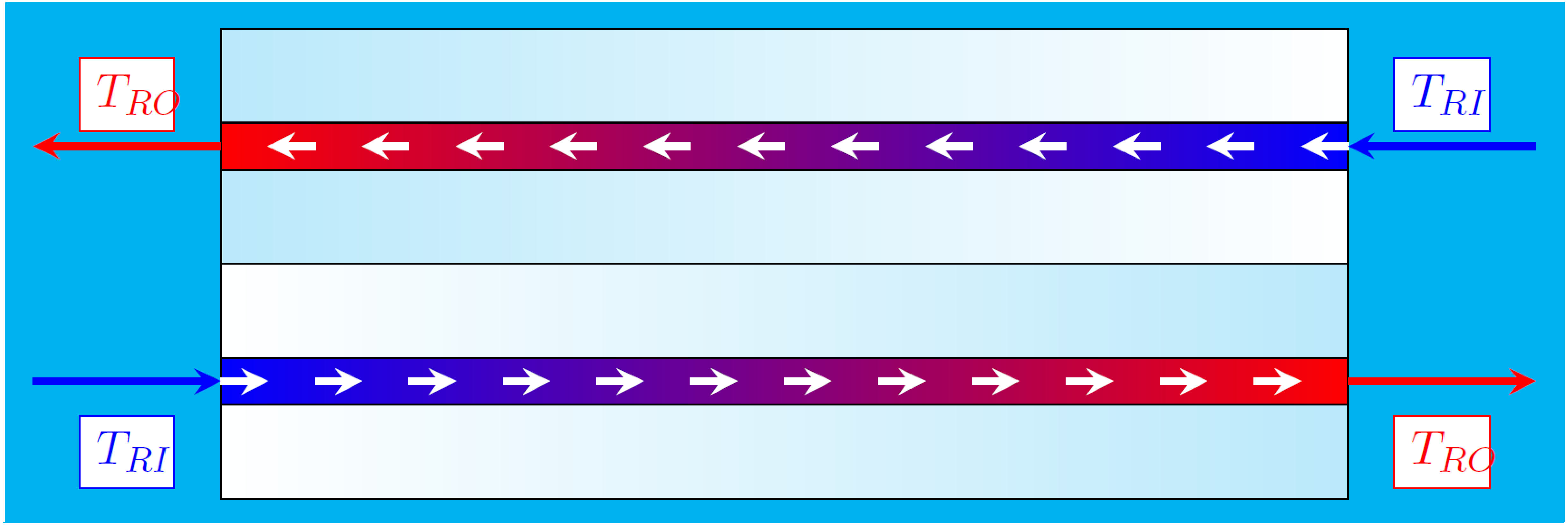
➢ **Knowledge** of the following is required:

- **Dimensions** of the tank, water **mass**, pipe **length** and **diameter**.
- **Thermophysical properties** involved in the **heat transfer process**: **thermal conductivity** (k), **specific heat** (c_p), **density** (ρ), **viscosity** (ν).



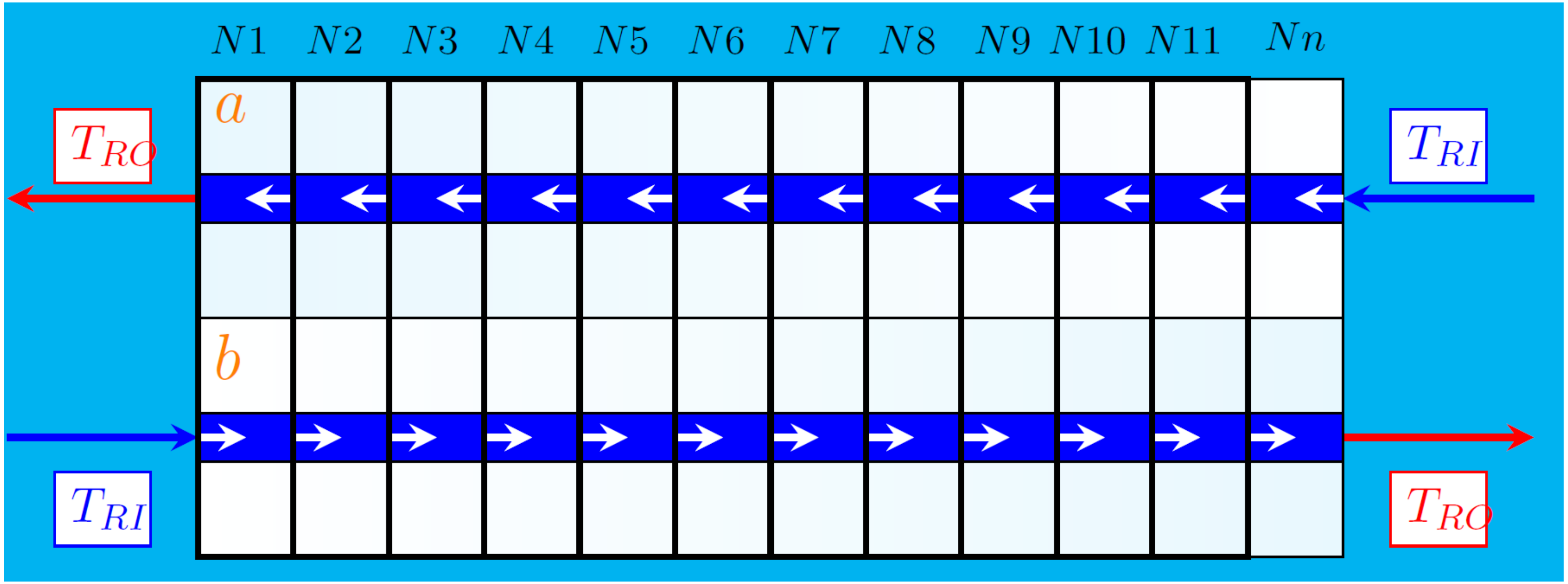
- The **heat transfer coefficient** (U) can be calculated using the **mass flow rate** and the **temperatures** of water/ice and the refrigerant.

Modelling Approach (3)



Modelling Approach (4)

- **'Splitting (Stratification) Approach'.** Each **node** considers:



- **Parameters.**
- **Thermophysical properties.**
- **Dynamic properties.**

$$V_W \rho_W c_{P,W} \frac{dT_{Wai}}{dt} = A_t U\left(t, \nu, k, \rho, \Pr, \mathrm{Nu}, D_H\right)\left(T_R - T_W\right)$$

$$V_R \rho_R c_{P,R} \frac{dT_{Rbi}}{dt} = \dot{m}_R c_{P,R}\left(T_W - T_R\right) + A_t U\left(t, \nu, k, \rho, \Pr, \mathrm{Nu}, D_H\right)\left(T_W - T_R\right)$$

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

Modelling Approach (5)

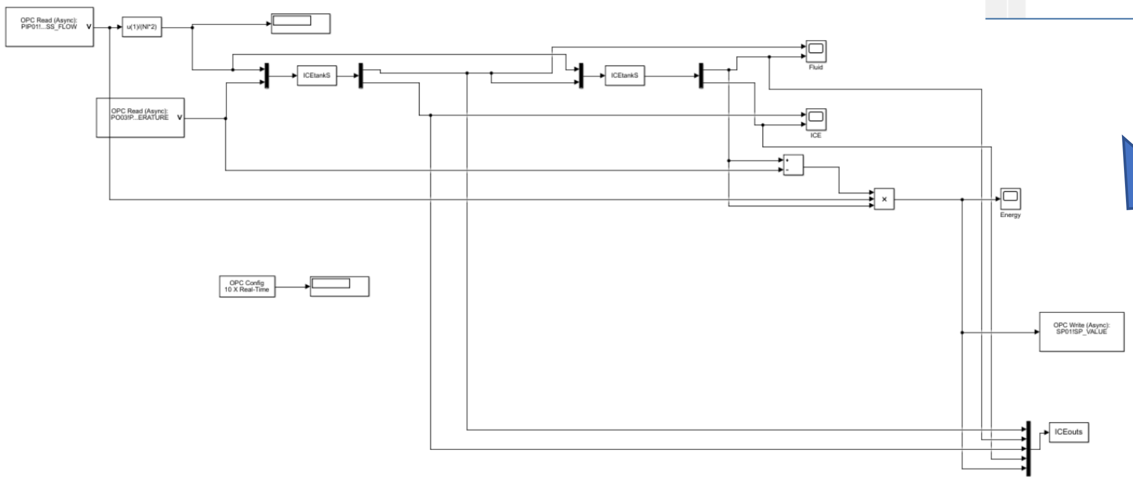
- The set of **non-linear differential equations** describing the **thermal behaviour of the TES** is coded in **MATLAB** (as an **S-function**). The script is used as a block in **Simulink**.

$$
\begin{bmatrix} \dot{T}_{Ra1} \\ \dot{T}_{Wa1} \\ \dot{T}_{Rb1} \\ \dot{T}_{Wb1} \\ \vdots \\ \dot{T}_{Rai} \\ \dot{T}_{Wai} \\ \dot{T}_{Rbi} \\ \dot{T}_{Wbi} \\ \vdots \\ \dot{T}_{Ran} \\ \dot{T}_{Wan} \\ \dot{T}_{Rbn} \\ \dot{T}_{Wbn} \end{bmatrix} = \begin{bmatrix} \dot{m}c_p\Delta T_{1-2} + A_tU\Delta T_{1-2}/V_{Ra1}\rho_{Ra1}c_p \\ A_tU\Delta T_{1-2}/V_{Wa1}\rho_{Wa1}c_p \\ \dot{m}c_p\delta T_{1-2} + A_tU\Delta T_{1-2}/V_{Rb1}\rho_{Rb1}c_p \\ A_tU\Delta T_{1-2}/V_{Wb1}\rho_{Wb1}c_p \\ \vdots \\ \dot{m}c_p\Delta T_{i-i+1} + A_tU\Delta T_{i-i+1}/V_{Rai}\rho_{Rai}c_p \\ A_tU\Delta T_{i-i+1}/V_{Wa1}\rho_{Wai}c_p \\ \dot{m}c_p\delta T_{i-i+1} + A_tU\Delta T_{i-i+1}/V_{Rb1}\rho_{Rbi}c_p \\ A_tU\Delta T_{i-i+1}/V_{Wbi}\rho_{Wbi}c_p \\ \vdots \\ \dot{m}c_p\Delta T_{n-1-n} + A_tU\Delta T_{n-1-n}/V_{Ran}\rho_{Ran}c_p \\ A_tU\Delta T_{n-1-n}/V_{Wan}\rho_{Wan}c_p \\ \dot{m}c_p\delta T_{n-1-n} + A_tU\Delta T_{n-1-n}/V_{Rbn}\rho_{Rbn}c_p \\ A_tU\Delta T_{n-1-n}/V_{Wbn}\rho_{Wbn}c_p \end{bmatrix}
$$

icebank1.m

```
function xdot = icebank1(t,x,N,mf,TrI)
%Volume total water is divided by 2 for each heat exchanger pipe
Vwa = Vw/(2*N);
%pipe Longitudinal area
Alp = P(4)/N;
wp = P(3);
Vr = P(6)/N;
Ac = P(2);
Dh = P(1);
kp = P(7);


%%%Ice width
xdot(:,1) =((mf*cp*(TrI-x(1)))+(Alp*U)/(Vr*cp*rho);
xdot(:,2) =((Alp*U*(x(1)-x(2)))+(Ai*Uiw)/(Vwa*cp*rho);
xdot(:,3) =((mf*cp*(x(i+1)-x(1)))+(Alp*U)/(Vr*cp*rho);
xdot(:,4) =((Alp*U*(x(3)-x(4)))+(Ai*Uiw)/(Vwa*cp*rho);
i =5:4:N;
xdot(:,i) = ((mf*cp*(x(i-1)-x(1)))+(Alp*U)/(Vr*cp*rho);
xdot(:,i+1) =((Alp*U*(x(i)-x(i+1)))+(Ai*Uiw)/(Vwa*cp*rho);
xdot(:,i+2) = ((mf*cp*(x(i+6)-x(i+2)))+(Alp*U)/(Vr*cp*rho);
xdot(:,i+3) = ((Alp*U*(x(1+2)-x(i+3)))+(Ai*Uiw)/(Vwa*cp*rho);
xdot = xdot(:);
```

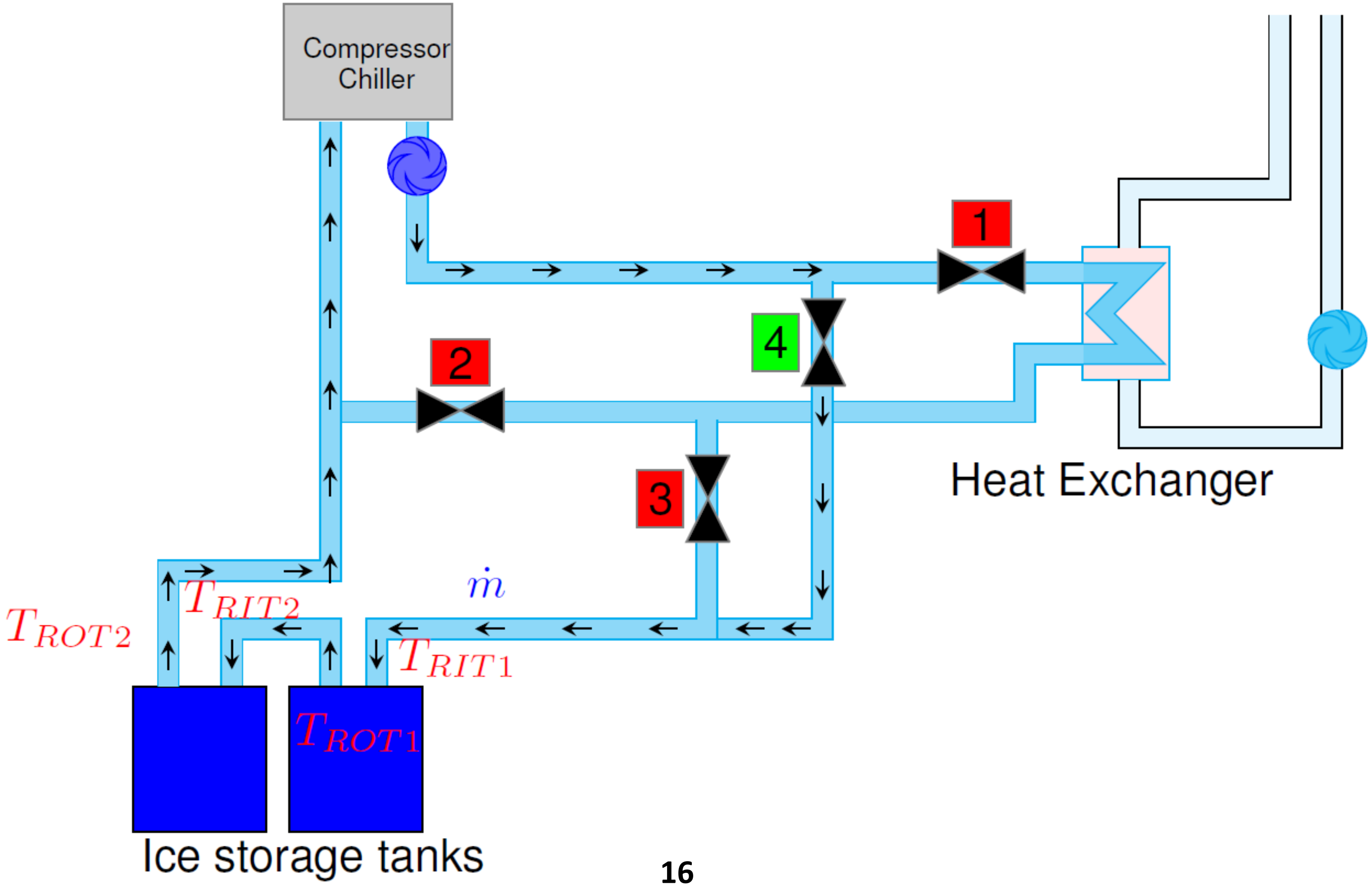


CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

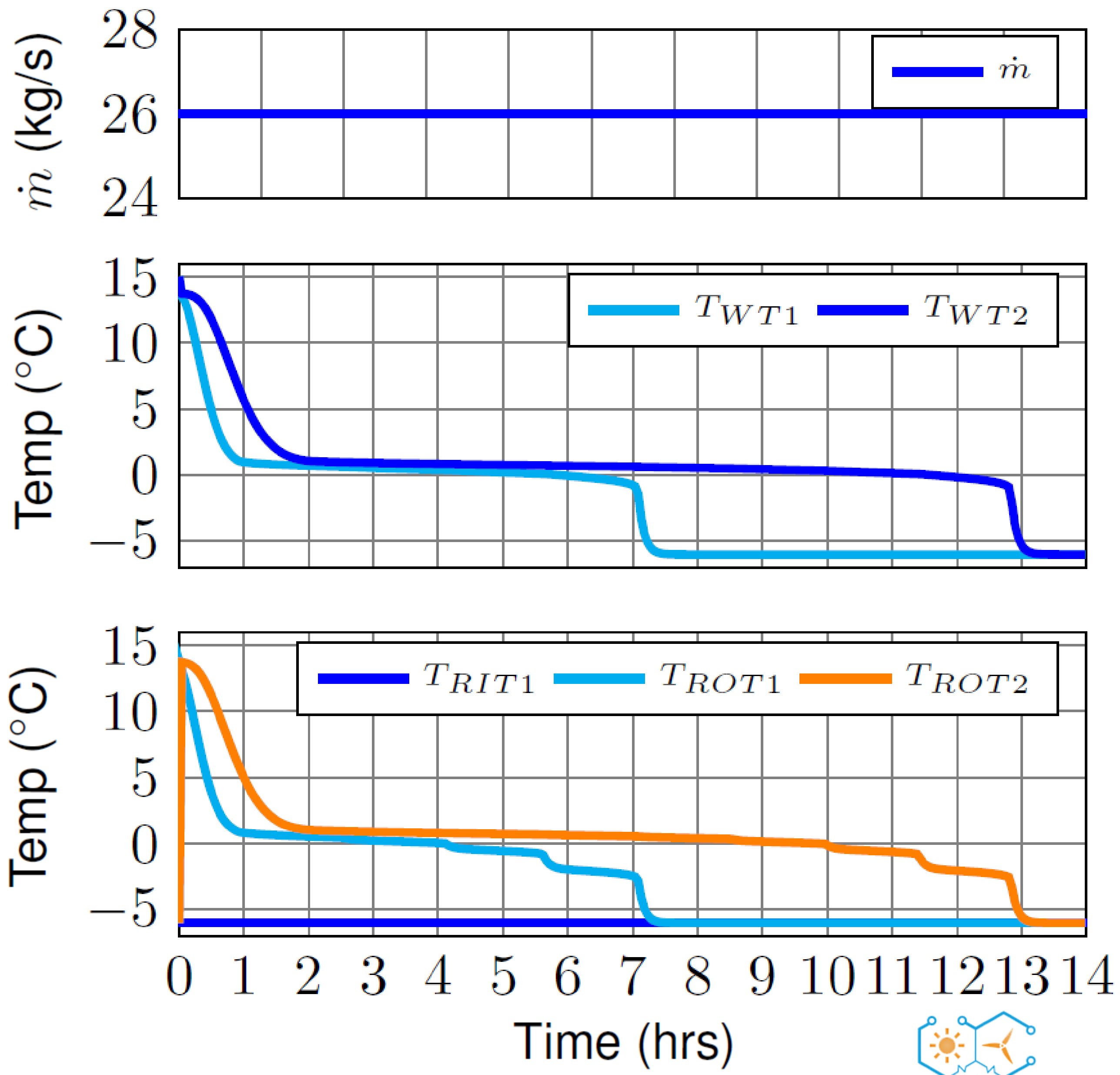
Simulation Results

- The suitability of the model is assessed through **time-domain simulations** conducted in **MATLAB**. Only the **TES** tank is simulated.
- **Charging** and **discharging** processes are examined.



Simulation Results (2)

- **Charging** process:
  - The **mass flow rate** of the **refrigerant** is kept at a value of $\dot{m}_R = 26\ \mathrm{kg/s}$.
  - The **initial temperature** of the **water** is $15°\mathrm{C}$.
  - The **input temperature** of the **refrigerant** is $-6°\mathrm{C}$.
  - The behaviour of **water/ ice** is shown for the **last heat exchanger node** (both tanks).
  - The behaviour of the **refrigerant** is shown at the bottom (both tanks).



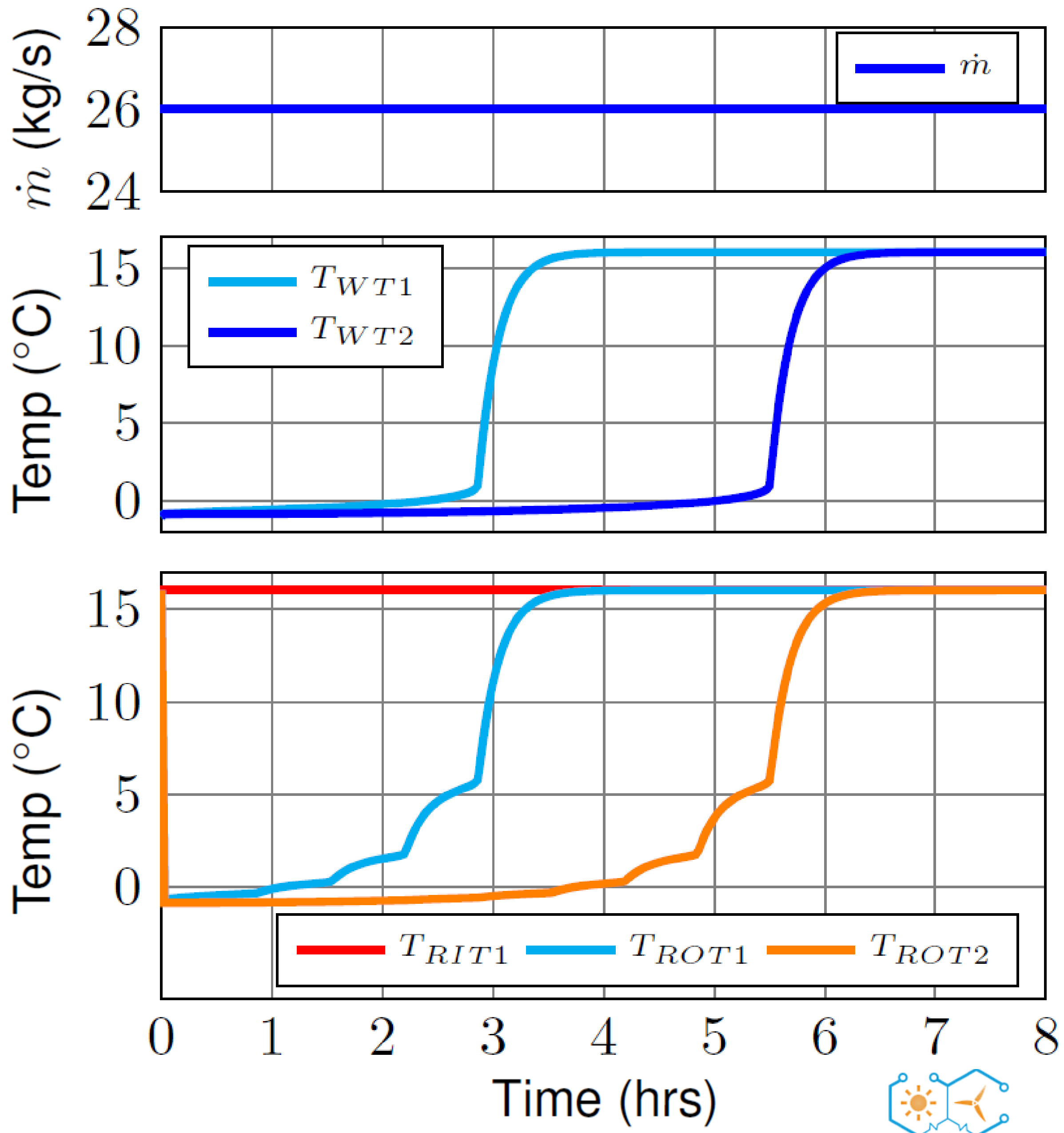
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

Simulation Results (3)

➢ **Discharging** process:

- The **mass flow rate** of the **refrigerant** is kept at a value of $\dot{m}_R = 26$ kg/s.
- The **initial temperature** of the **ice** is $-1°C$.
- The **input temperature** of the **refrigerant** is $16°C$.
- The behaviour of **water/ ice** is shown for the **last heat exchanger node** (both tanks).
- The behaviour of the **refrigerant** is shown at the bottom (both tanks).



CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UKES2019 UK Energy Storage Conference

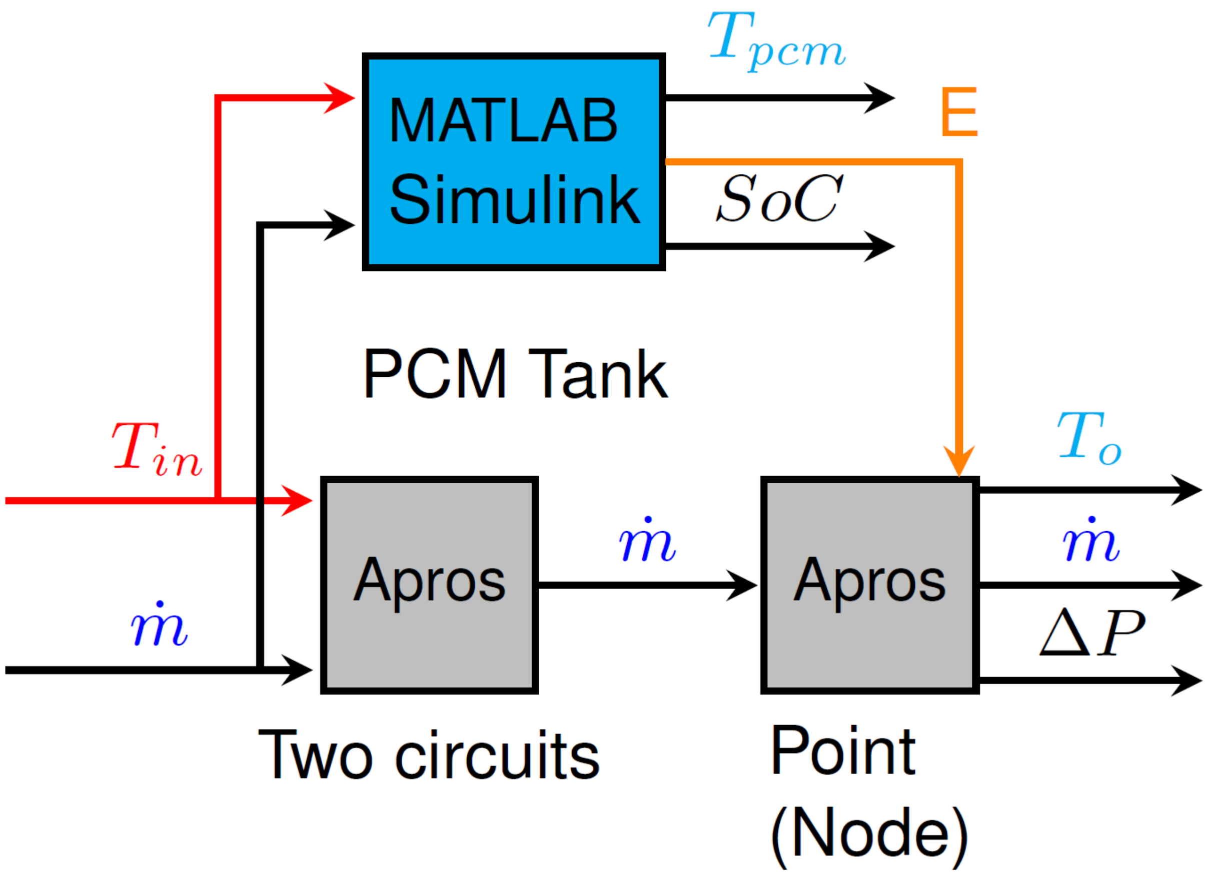
On-Going Work

➢ Next Steps

- The **performance** of the **ice store model** will be verified through some **experimental data** available from a **University campus**.

- The **hydraulic performance** of the **complete cooling system**, including the **ice-based TES**, **piping**, **valves**, **pumps**, and heat exchangers will be assessed in **Apros** (a commercial software to simulate processes). **Experimental data** will be used for comparison purposes.

- The **thermal performance** will be incorporated from the **MATLAB model**.



Concluding Remarks

- Modelling of **TES** and **PCM (ice)** has enabled us to **gain knowledge and understanding** of **heat transfer for district cooling applications**.

- The **modelling approach** is based on **thermodynamic processes** reported in the **open literature**.

- The **'stratification approach'** has been used to model **hot water storage tanks**. This work has been published (ICAE/Energy Procedia).

- The **research ambition** is to carry on developing our models:
  - The work linking **thermal storage (MATLAB)** with **Apros** was presented in Finland (May 2019).
  - The **modelling methodology** will be submitted to a journal soon.
  - A **case study with experimental results from a University campus** will be submitted to a journal. Work is in progress.

Questions?

Dr Carlos UGALDE

Ugalde-LooC@cardiff.ac.uk

Cardiff University, Wales, UK