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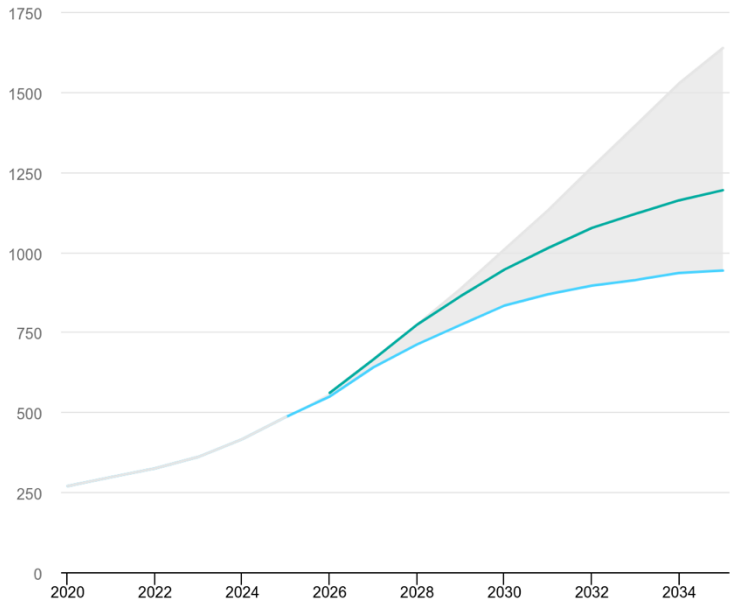
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A Mixed H_∞-Passivity Approach for Leveraging District Heating Systems as Frequency Ancillary Service in Electric Power Systems

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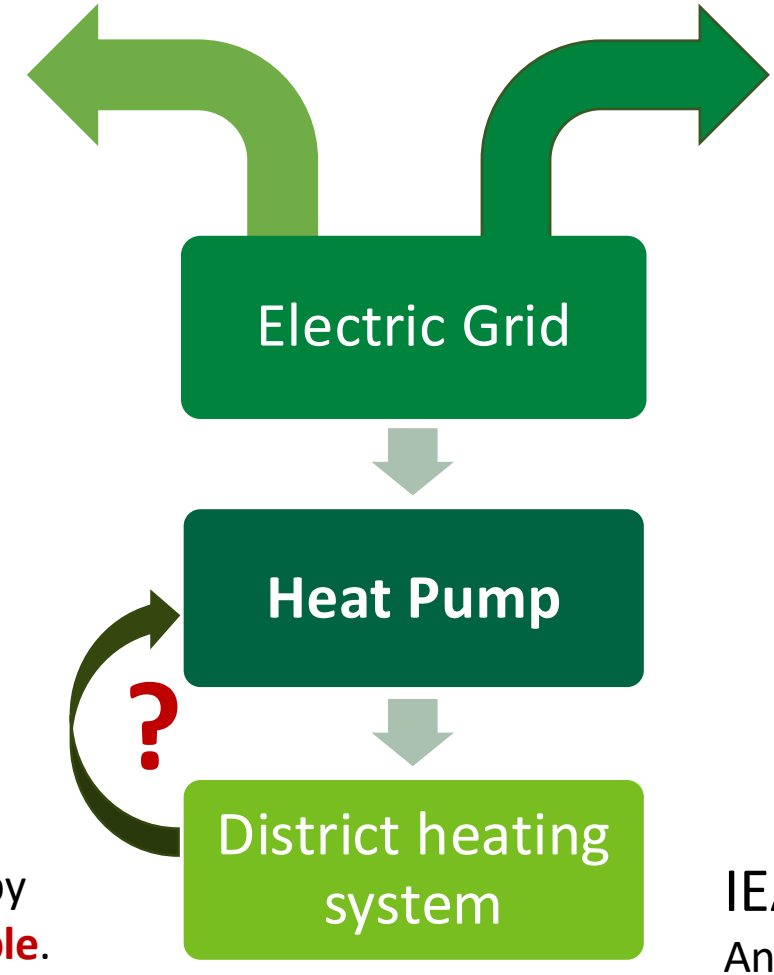
District Heating Systems with Heat Pumps as Reliable Ancillary Services for Electric Power Systems

Background

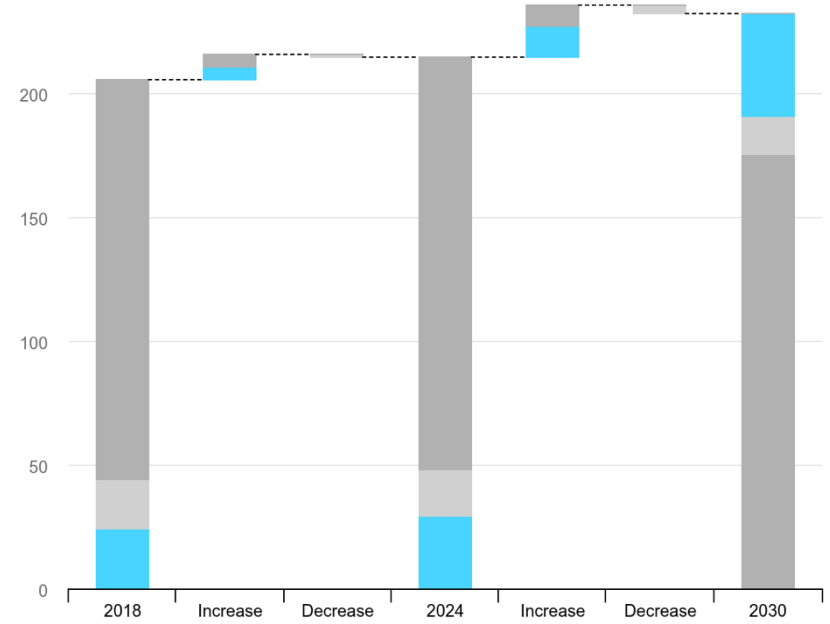


IEA (2026), Electricity consumption by data centers

Data-center demand is set to **double** by 2030 and AI-focused power use to **triple**.



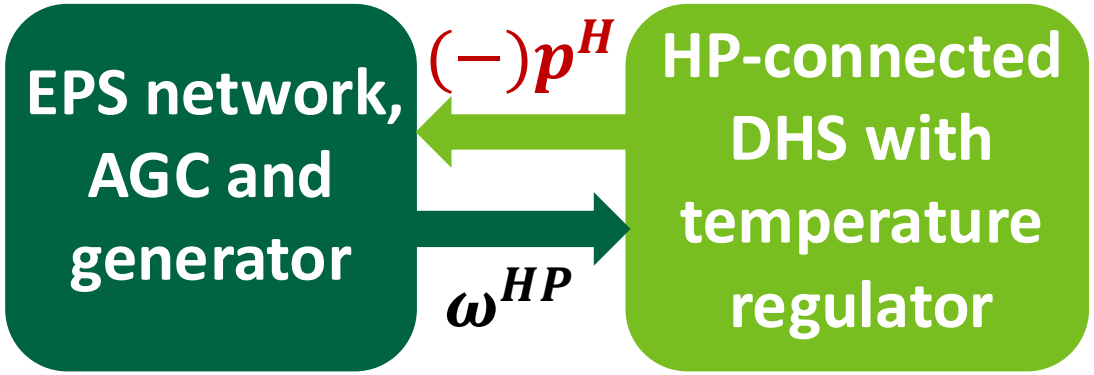
Heat accounted for almost half of total final energy consumption and 37% of energy-related CO2 emissions in 2024



IEA (2025), Annual global heat use

Annual heat consumption expanded by **6%** globally.

From One-Way HP Response to a Bidirectional DHS Port



- EPS objective: restore nominal frequency

$$\lim_{t\to\infty} \omega = 0\,.$$

- DHS objective: achieve optimal heat sharing and temperature operation.

$$\lim_{t\to\infty} e = 0\,.$$

- **One-way HP response:**

$$\omega^{HP} \to p^H$$

The EPS receives support, while the DHS passively absorbs the thermal impact.

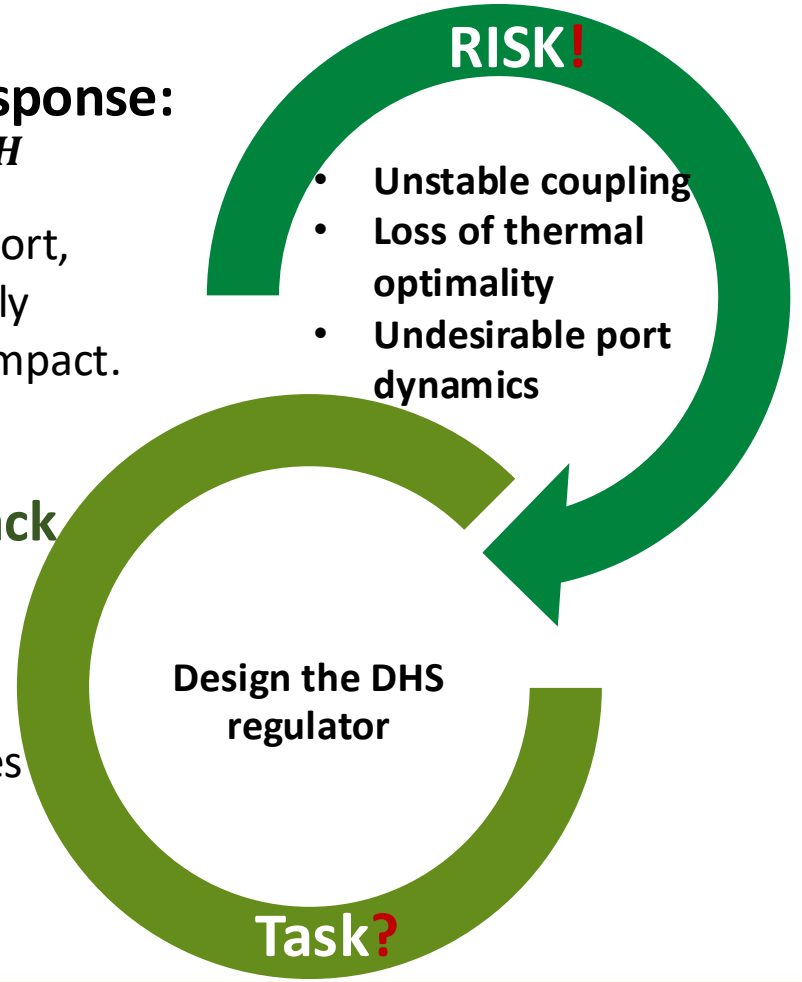
- **This work:**

ω^{HP} **+DHS feedback**

↓

p^H

The DHS regulator uses its internal states to coordinate and shape the HP response.



District heating system port formulation

ω^{HP} → Regulated HP-connected DHS → p^H

Takeaway: The augmented DHS regulator achieves optimal heat sharing and the desired temperature operation while shaping the grid-facing heat-pump response.

- Temperature dynamics:
  $\dot{T} = -AT + B_1 h^G + B_2 h^P + w^h$
- DHS regulation error:
  $e = \begin{bmatrix} 0 \\ 1^T F^D \end{bmatrix} T + \begin{bmatrix} F^M \\ 0 \end{bmatrix} h^G$

$$\dot{x} = A_{Aug} x + B_{cl}^{(\omega)} \omega^{HP} + B_{Aug} h^G + B_{cl}^{(h)} w^h$$

$$x = [T^{\mathrm{T}} \quad \xi^{\mathrm{T}}]^{\mathrm{T}}$$

$$\dot{\xi} = e$$

$$h^G = -\boldsymbol{K}x$$

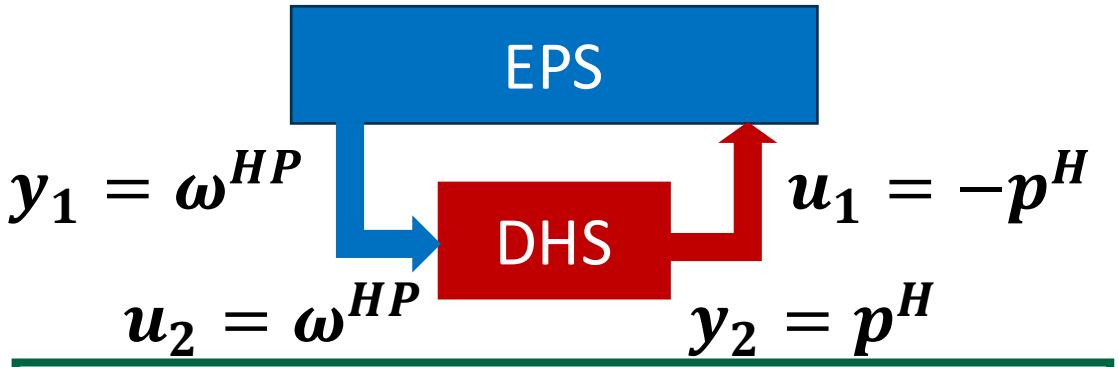
$$\dot{x} = A_{cl} x + B_{cl}^{(\omega)} \omega^{HP} + B_{cl}^{(h)} w^h$$

$$h^P = CoP(\gamma^E \omega^{HP} + \gamma^H Sig^H) = CoP\, p^H$$

DHS feedback: $Sig^H = 1^T F^D T$

Lemma 3. Steady-state DHS regulation
At equilibrium, $e = 0$ implies that optimal heat sharing and the desired temperature operation are achieved.

Regulated district heating system port design framework



Theorem 1. If the closed-loop augmented DHS is strictly passive from u_2 to y_2, and A_{cl} is Hurwitz, then the coupled optimal equilibrium is asymptotically stable.

- **DHS regulation requirement:** Ensures the desired thermal equilibrium

A_{cl} **Hurwitz** $\Longrightarrow$ **e** $\rightarrow$ **0** $\Longrightarrow$optimal heat sharing and desired temperature operation

Takeaway: Passivity guarantees stable coupling; loop shaping determines how the DHS dynamics interact with the EPS.

- **Passivity constraint:** Guarantees stable EPS–DHS interconnection

EPS passive + DHS passive = stable coupling

Guaranteed by EPS passivity result (Lemma 2)

★ H_∞ **loop-shaping constraint:** Retain the desired direct HP frequency response while limiting undesirable oscillatory interactions between the DHS and EPS.

$$\min \|W_{HP}(s)G(s)\|$$

Mixed H_∞- passivity framework shapes the DHS port

Results

Takeaway: The joint design suppresses undesirable DHS-induced oscillatory interactions while preserving DHS thermal objectives.

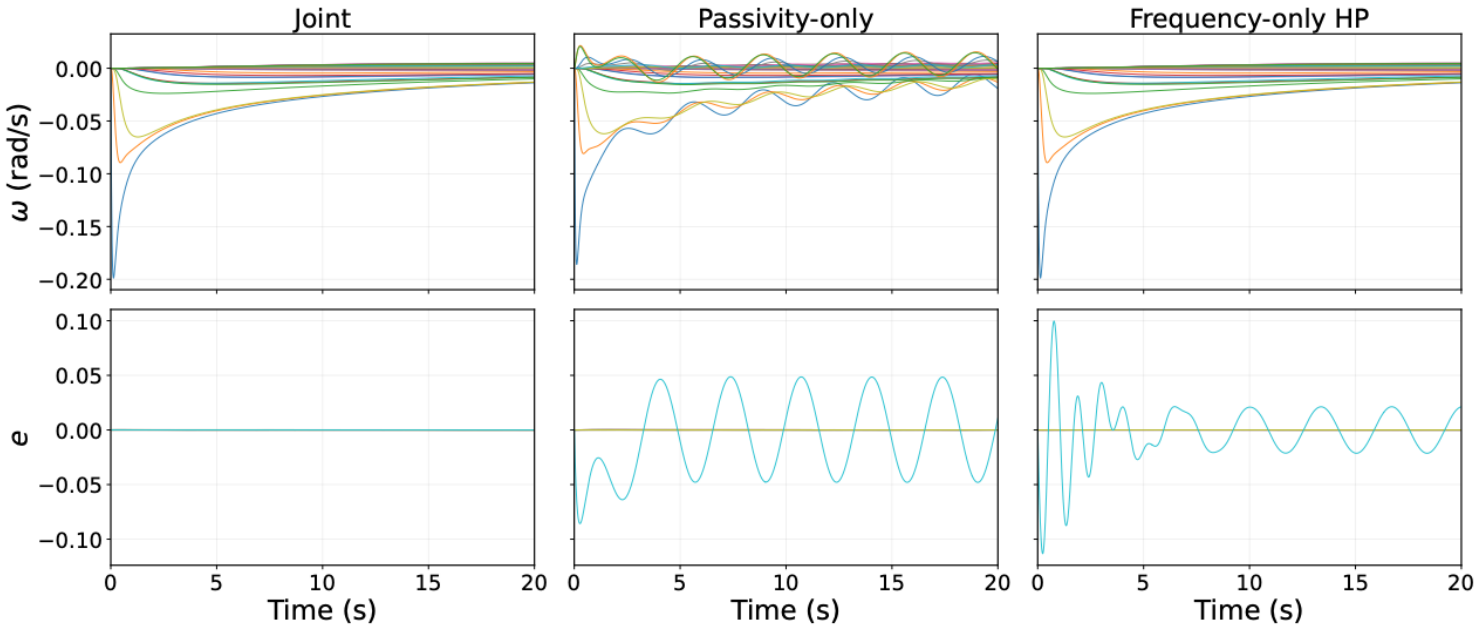


Fig 1. Optimality error in heating system and frequency transient in power system (frequency-only HP v.s passivity-only augmented heating v.s. joint augmented heating support modes)

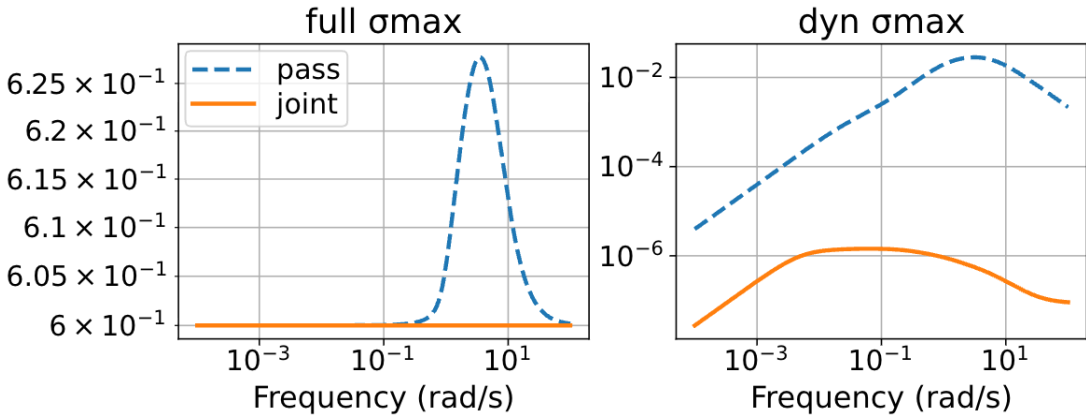


Fig. 2. Frequency response $\omega^{HP} \rightarrow p^H$

Frequency	J_{freq,L_1}	J_{u,L_2}
0.0016 Hz	0.24	0.11
0.016 Hz	**0.006**	**0.021**
50 Hz	0.008	0.019

Table 1. Joint / passivity-only ratio

Bidirectional DHS-port shaping enables stable, thermally coordinated, and tunable frequency support.

Conclusions

- Formulate the HP-connected DHS as a bidirectional electro--thermal port.
- Develop a mixed H_∞-passivity synthesis that ensures stable EPS--DHS interconnection and DHS optimality.
- Demonstrate improved frequency-support dynamics while preserving thermal regulation.

Broader insight
The DHS port is not restricted to reproducing a direct HP response. Its dynamic contribution can be shaped for different grid-service objectives, while maintaining DHS regulation and stable coupling.

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