Physics-Based Intelligence for Decarbonization of the Built Environment

Reinventing System Integration in the Age of Data

Lieve Helsen and The SySi Team @ KU Leuven

4th International Sustainable Energy Conference - ISEC 2026

April 16, 2026, Graz, Austria

Challenges

DECARBONIZATION of the built environment

Creation of a comfortable and healthy indoor climate
in a carbon-neutral society at an affordable cost

But also

RESILIENCE
INDEPENDENCE
SECURITY OF SUPPLY

energy efficiency

R^2ES

Department of Mechanical Engineering, Thermal Systems Simulation (The SySi) Team
KU LEUVEN

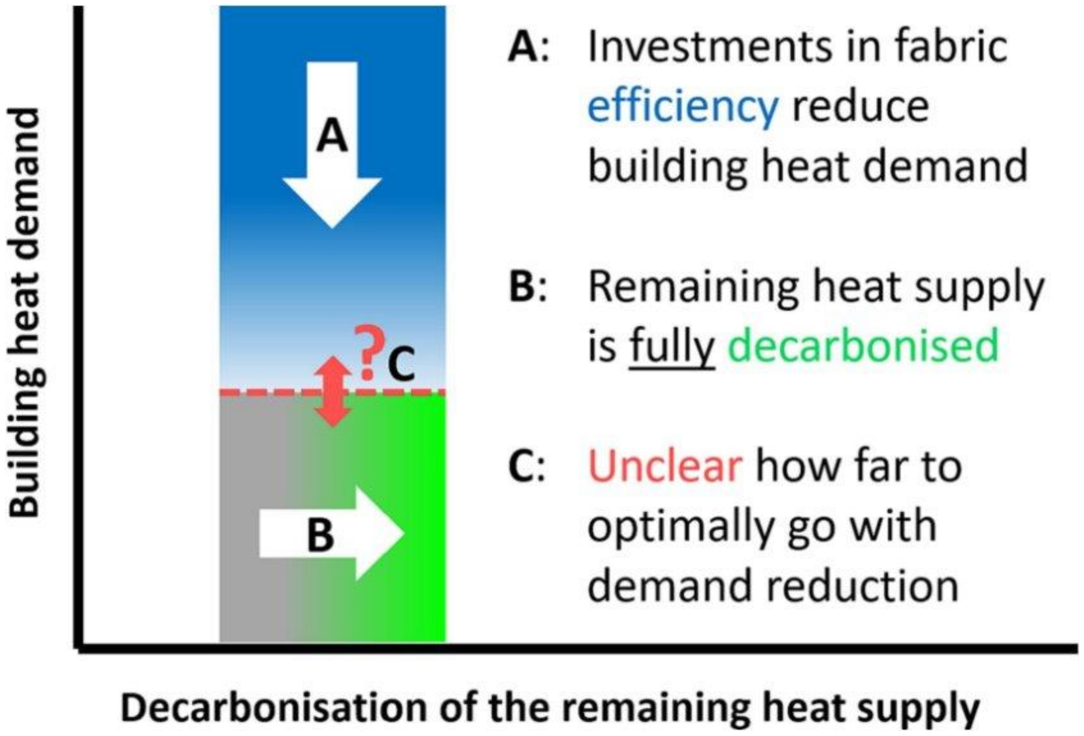
Energy efficiency and R^2ES

- Demand reduction for heating/cooling
- Decarbonization of heat/cold supply

BALANCED APPROACH

Optimal balance?

Do not go *too far* with any specific measure
to keep it cost-effective and sustainable



Source: Rosenow, J., & Hamels, S. (2023). Where to meet on heat? A conceptual framework for optimising demand reduction and decarbonised heat supply. *Energy Research & Social Science*, 104, 103223.

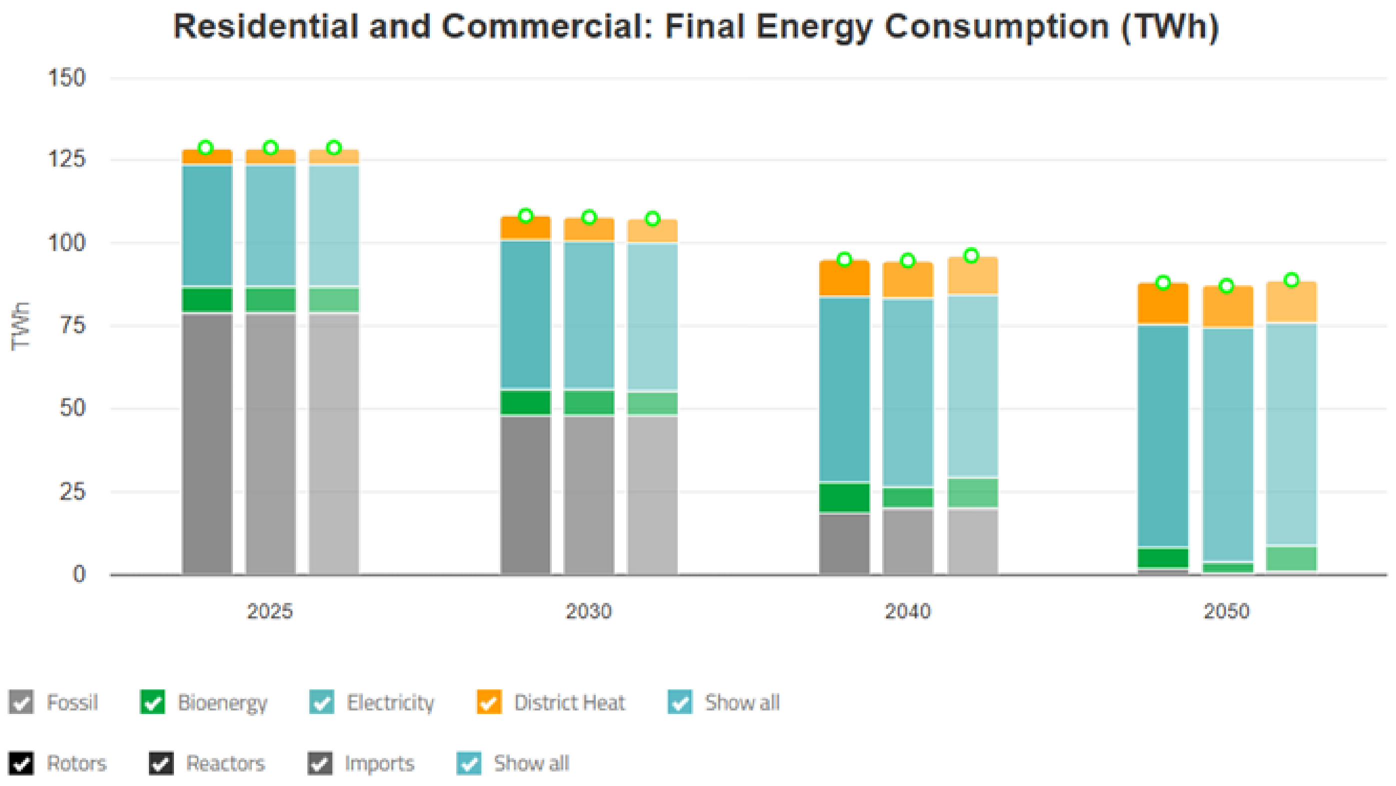
All-inclusive energy transition

Optimal balance
in interaction with other sectors

Towards a climate-neutral Belgium

Different scenarios
1. ROTORS
2. REACTORS
3. IMPORTS

Sectors
1. Cross-sectorial
2. Power
3. Industry
4. Residential and commercial
5. Transport
6. molecules



Source: EnergyVille, Paths 2050 study, https://perspective2050.energyville.be/results/main-edition-2025/residential-commercial-sector (2025)

Electrification - Heatpumpification

Growing electricity demand
Increasing share of variable RES

Grid expansion

Demand flexibility exploitation

- Building thermal capacity
- Network capacity
- Active energy storage
- Heat pump
- Hybrid (collective) supply

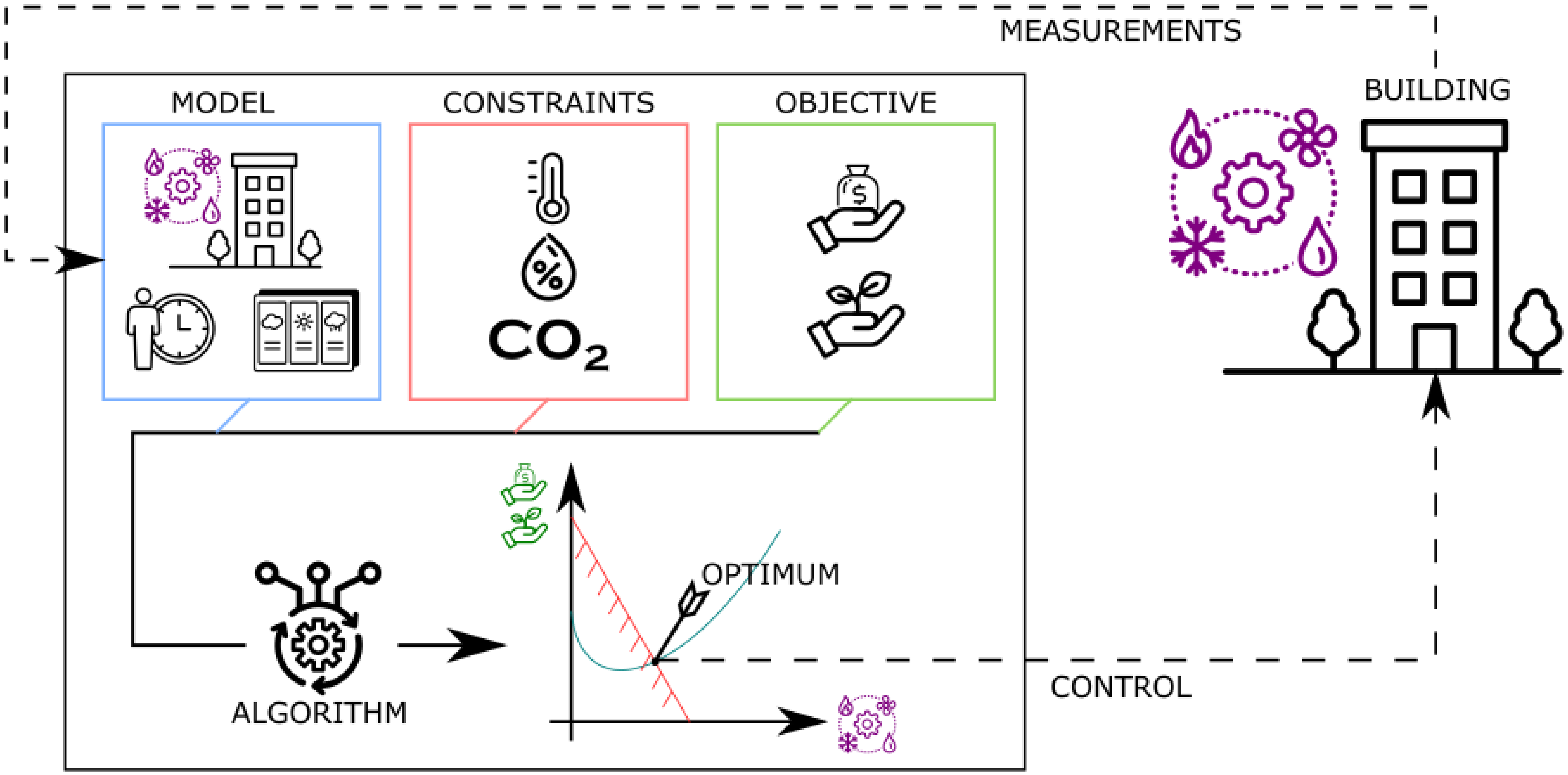
Anticipating system integrator

FLEX ENABLERS

Source: EHPA

Model Predictive Control (MPC)

White-box
Grey-box
Black-box



Source: Damien Picard and Filip Jorissen (2021)

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Physics-Based Intelligence

White-box MPC use cases

Reinventing System Integration in the Age of Data

Department of Mechanical Engineering, Thermal Systems Simulation (The SySi) Team

Use case 1 - *De Schipjes*

mintus zorg met een plus
boydens engineering
MICROTHERM THERMAL INSULATION SOLUTIONS
UNIVERSITEIT GENT
VIESSMANN
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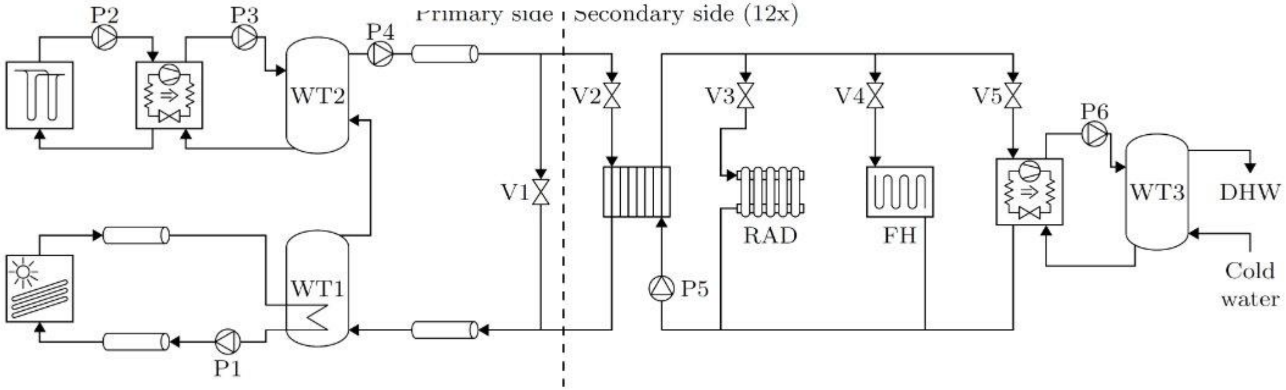

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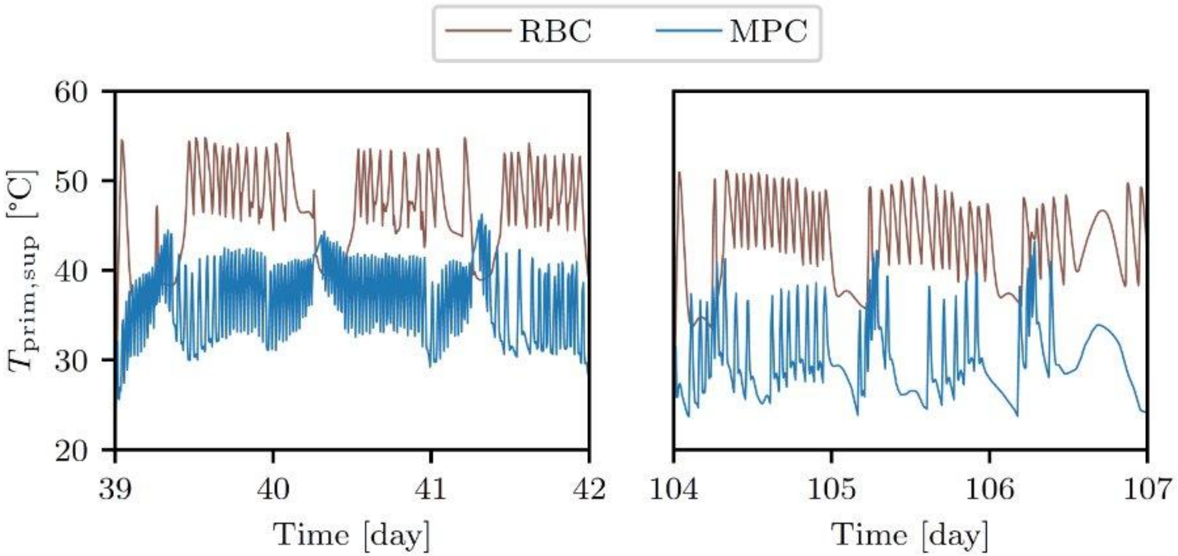
Fluves

Optimal operation *De Schipjes*

MPC automatically optimizes and lowers network temperature

- to increase COP and reduce network losses → OPEX ↓
- thereby preheating (at lower power) to fulfil demand.

	E_{el} [kWh]		Thermal discomfort [Kh]		COP_{GSHP} [-]	
Winter						
RBC	541	-6%	3.2	-3.2 Kh	3.7	+19%
MPC_{NLP}	507		0.0		4.3	
Spring						
RBC	228	-29%	0.1	+0.1 Kh	3.8	+30%
MPC_{NLP}	163		0.2		5.0	



Source: Jelger Jansen, Integrated non-linear model predictive control of a small-scale fourth generation district heating system, PhD Thesis, KU Leuven, Supervisors: Lieve Helsen and Filip Jorissen (2024).

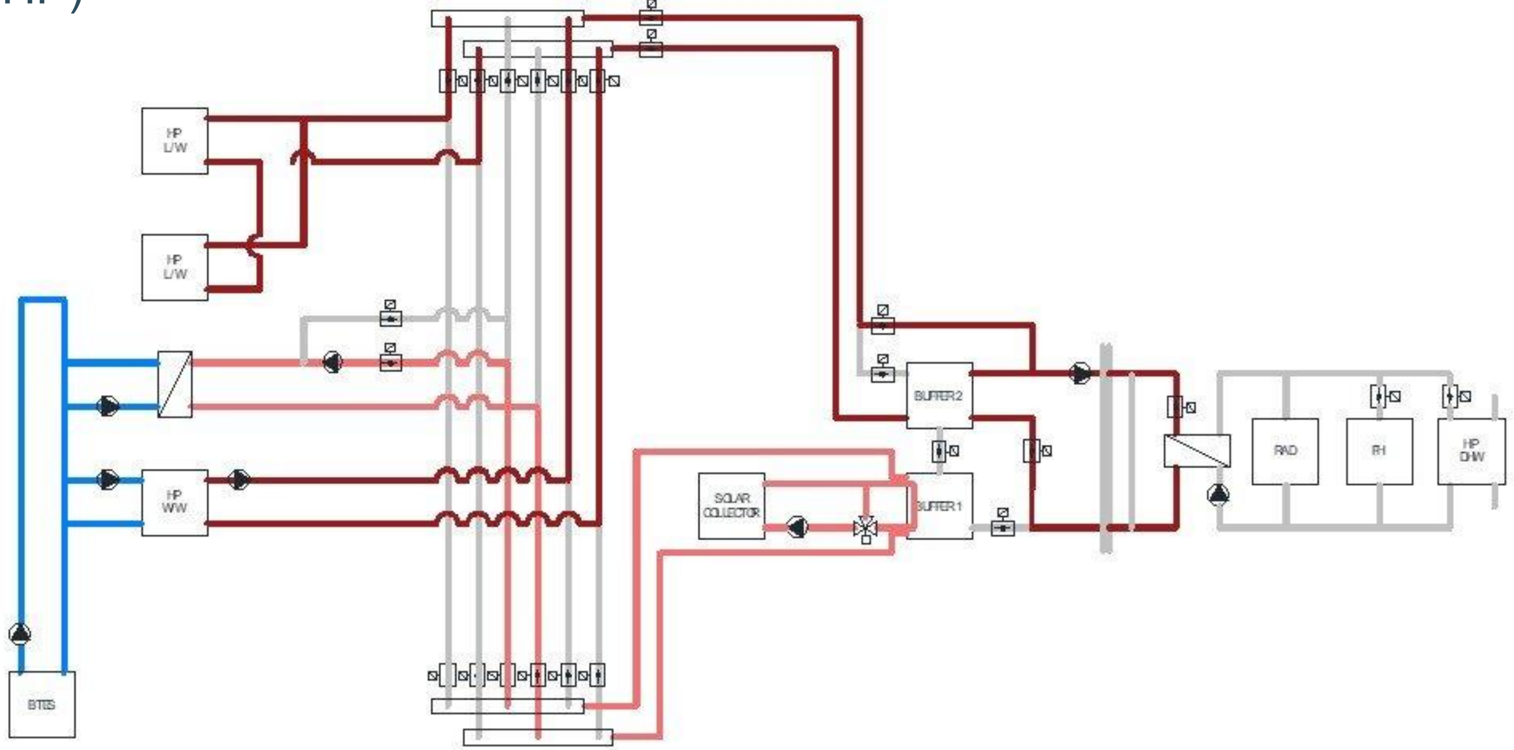
FLEX in Design *De Schipjes*

Funded by the European Union

SEEDS

Increase and exploit FLEX in design

- Further hybridisation (GSHP + ASHP)
- Two extra boreholes (glass fibre)
- Hydraulic switch
- MPC implementation



Source: Sweco

FLEX in Design *De Schipjes*

Funded by the European Union

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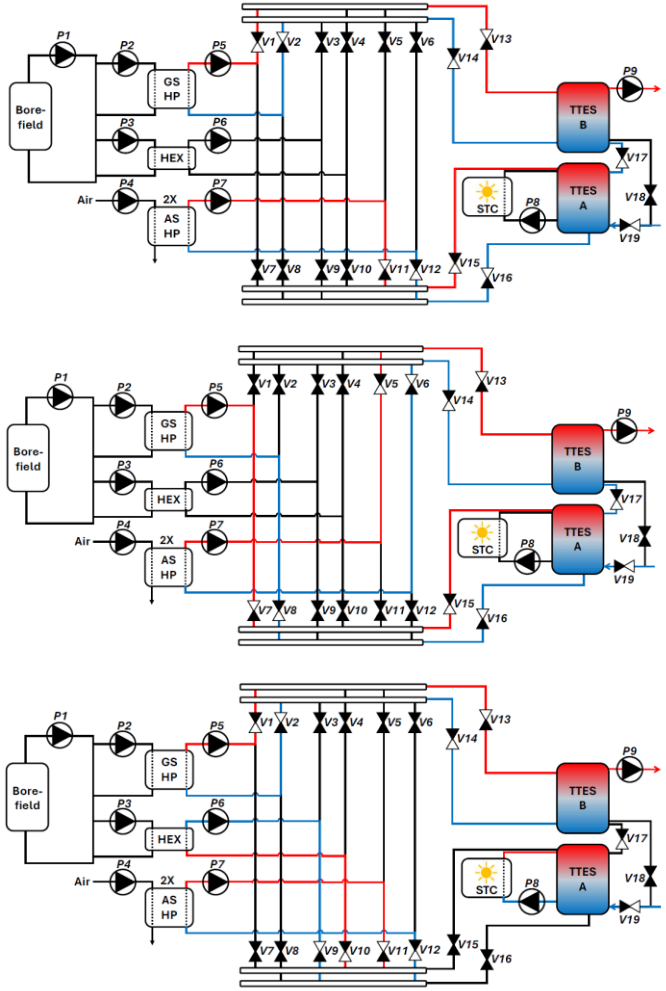
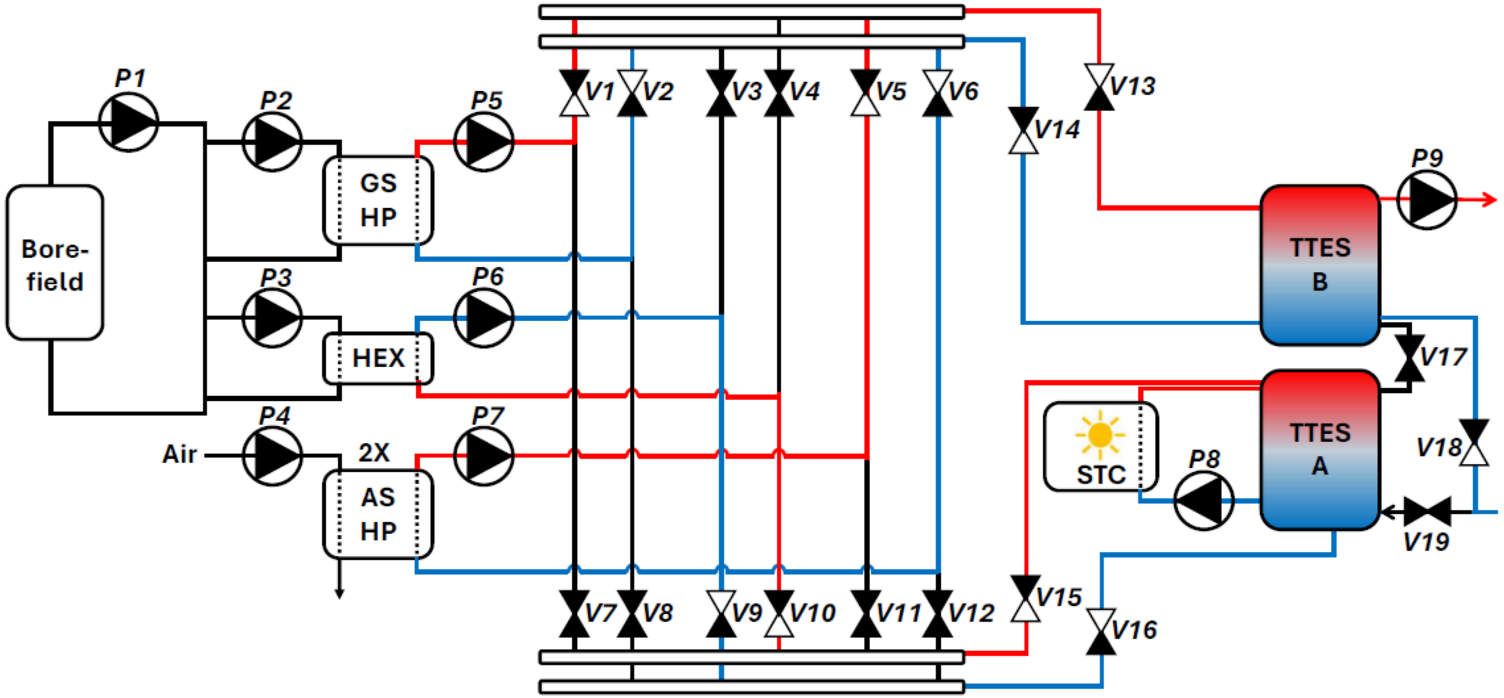
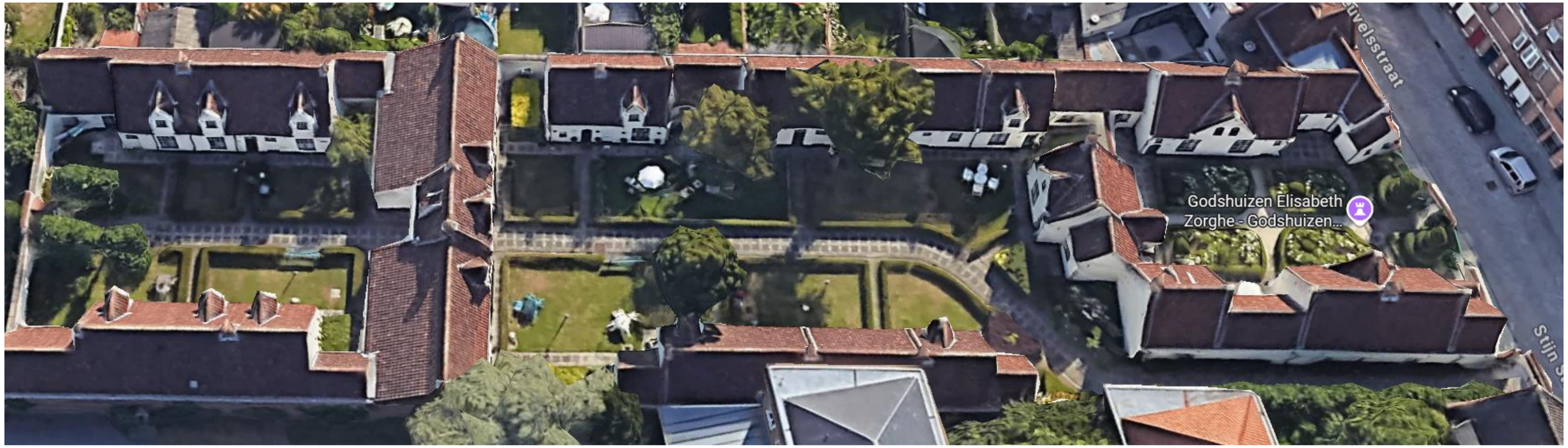




Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).

Use case 2 – *Stijn Streuvelsstraat*



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Co-design *Stijn Streuvelsstraat*

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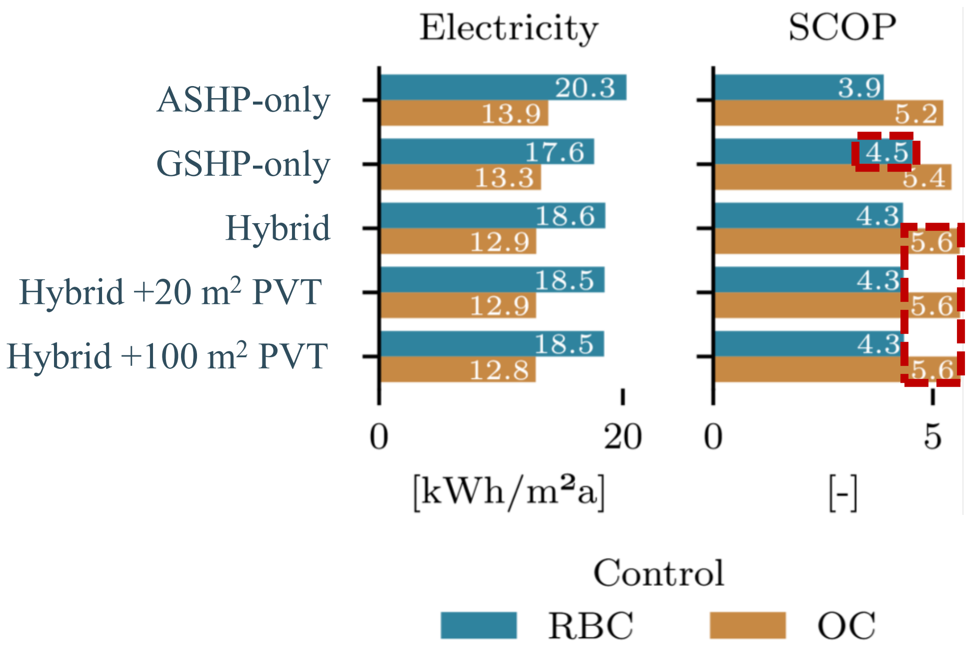
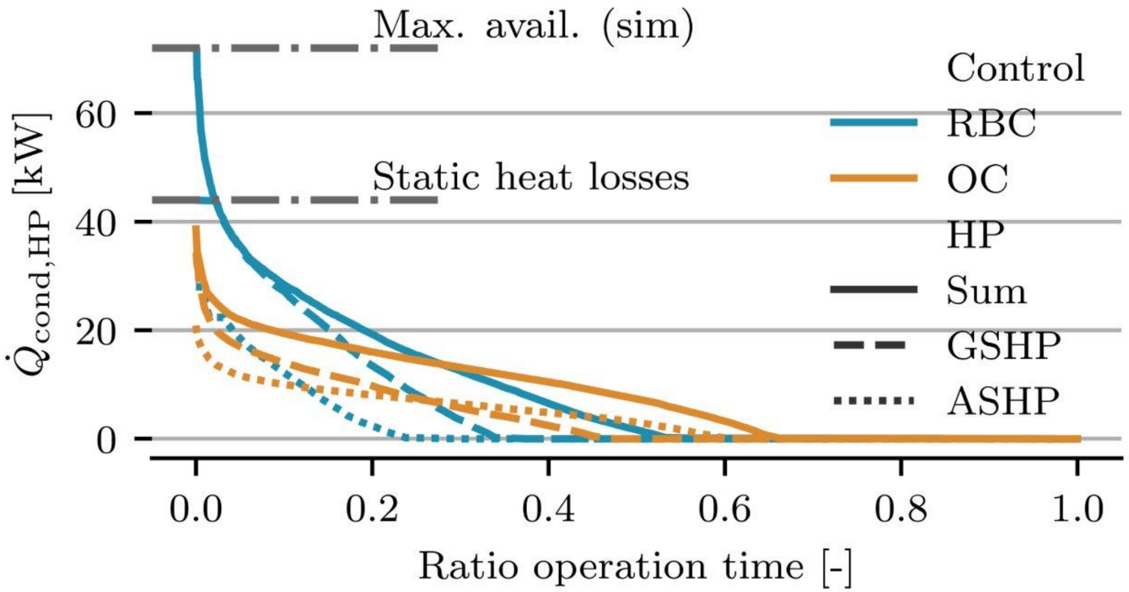
SEEDS

Model-based co-design using optimal control



Sizing of HPs – Load-duration curves



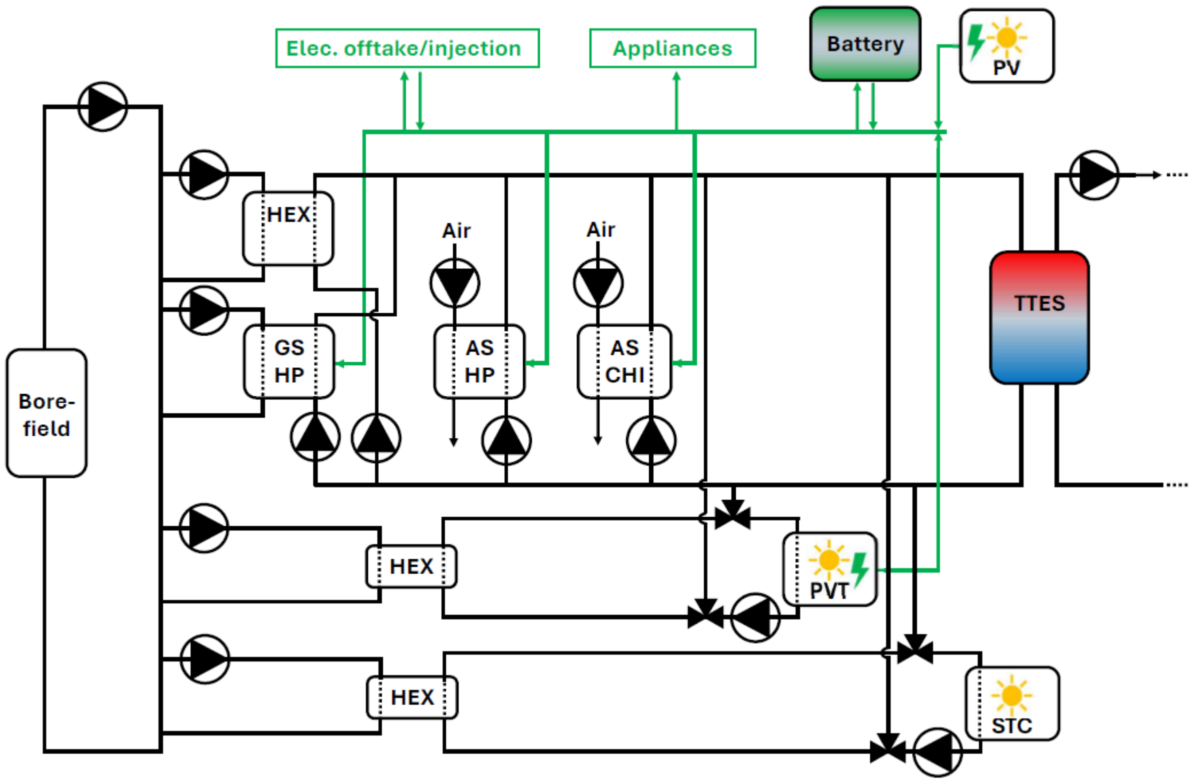
Source: Karl Walther, Louis Hermans, Lone Meertens, Lieve Helsen, Simplifying decision-making in model-based co-design of building energy systems through automatically generated optimal controls, presented at the *BS2025 Conference*, Brisbane (2025).

Use case 3
Integrated Optimal Control and Design (IOCD)

Simultaneous Optimisation

Centralised Energy Hub

- Optimal sizing
- Optimal control
- Minimal TCO
  OPEX and CAPEX
- Stress tests
  - Typical weather
  - Extreme weather

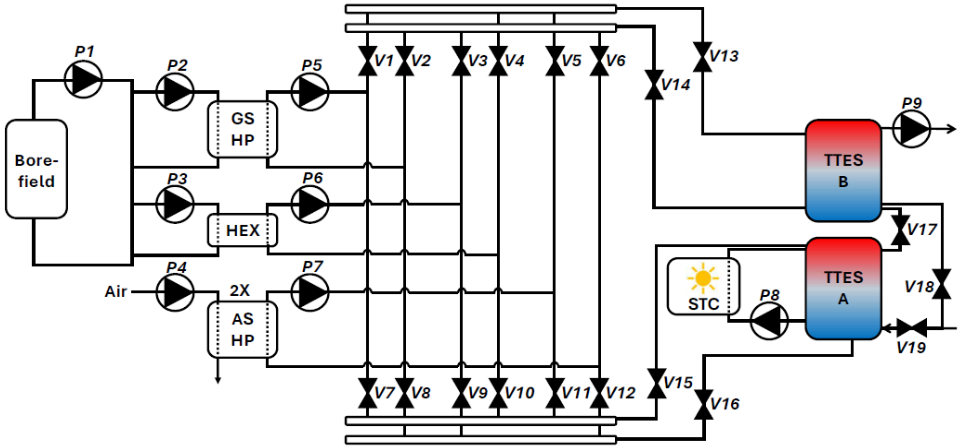


Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).

De Schipjes - IOCD

Funded by the European Union

SEEDS



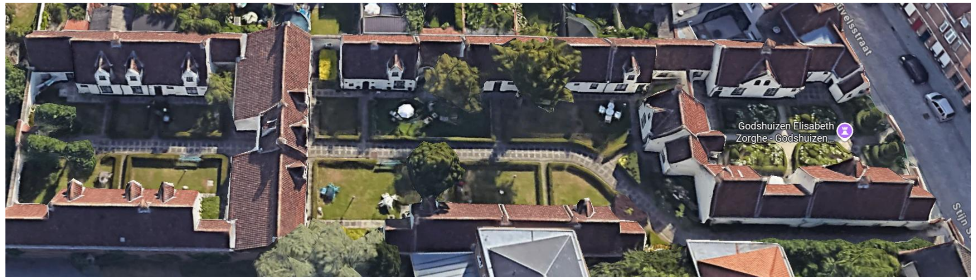
Technology	Unit	TMY REF RBC	TMY REF OC	TMY OPT	XMY REF RBC	XMY REF OC	XMY OPT
ASHP	kW	28	28	13.8	28	28	9.1
GSHP	kW	44	44	11.0	44	44	32.8
Borefield length	m	1250	1250	315	1250	1250	770
Borefield depth	m	125	125	105	125	125	55
Borefield config.	m	5×2	5×2	3×1	5×2	5×2	7×2
ASCHI	kW	0	0	0.0	0	0	0.0
TTES	m^3	1.9	1.9	0.8	1.9	1.9	1.2
PV	m^2	0	0	20.0	0	0	20.0
STC	m^2	17.6	17.6	0.0	17.6	17.6	0.0
PV-T	m^2	0	0	15.8	0	0	15.7
Battery	kWh	0	0	0.0	0	0	0.0
Discomfort	$\frac{Kh}{zone}$	34	31	44	158	59	84
CAPEX	k€	112.2	112.2	51.0	112.2	112.2	71.3
OPEX	k€	212.2	182.0	163.9	232.8	208.4	192.5
Maint. cost	k€	30.0	30.0	14.2	30.0	30.0	18.0
TCO	k€	354.3	324.1	229.1	375.0	350.6	281.9
	ΔTCO		–9%	-35%		-7%	-25%

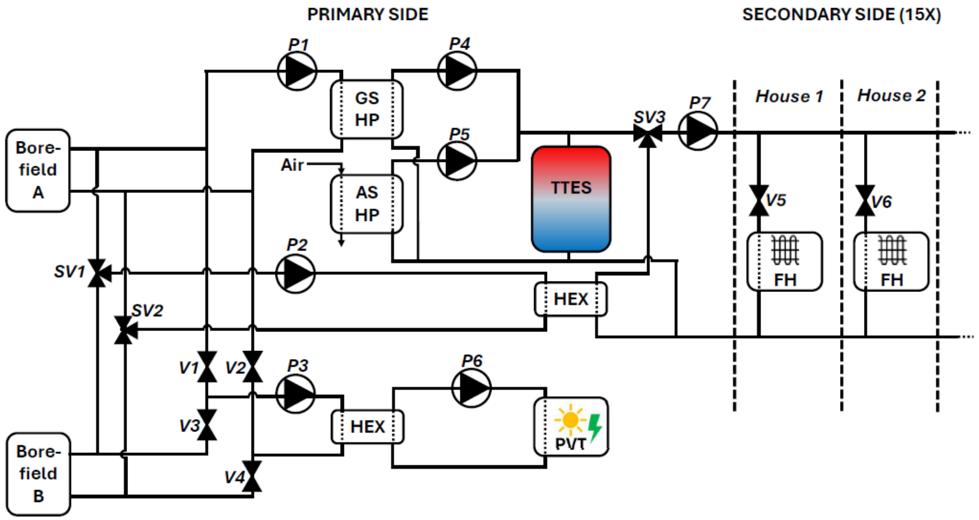
Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).

Stijn Streuvelsstraat - IOCD

Funded by the European Union

SEEDS



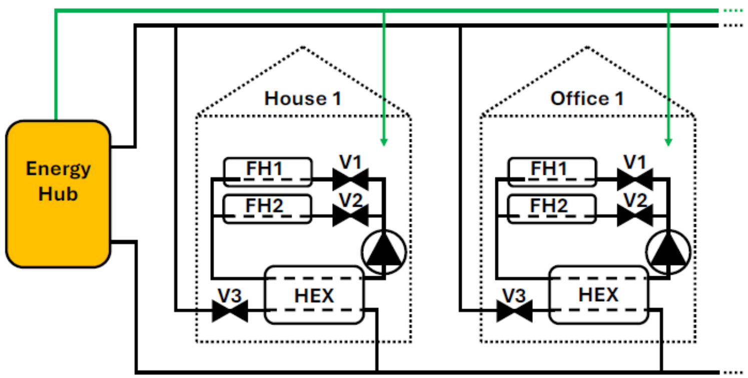


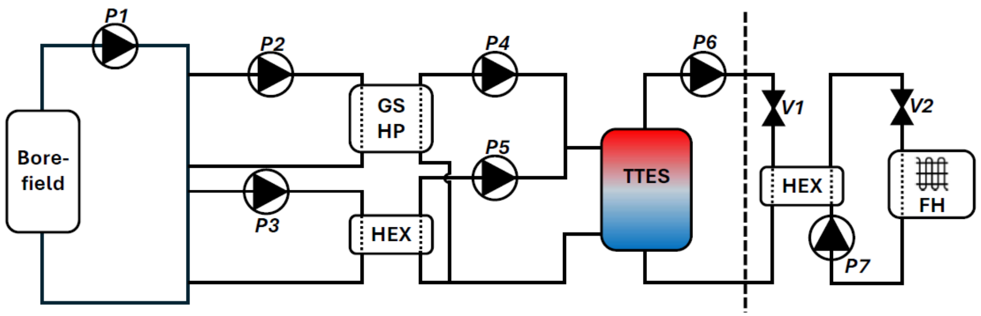
Technology	Unit	TMY REF RBC	TMY REF OC	TMY OPT	XMY REF RBC	XMY REF OC	XMY OPT
ASHP	kW	28	28	17.6	28	28	17.6
GSHP	kW	40	40	7.1	40	40	19.0
Borefield length	m	1000	1000	220	1000	1000	525
Borefield depth	m	125	125	110	125	125	105
Borefield config.	m	4 × 2	4 × 2	2 × 1	4 × 2	4 × 2	5 × 1
ASCHI	kW	0	0	0.0	0	0	0.0
TTES	m^3	0.5	0.5	1.9	0.5	0.5	1.1
PV	m^2	100	100	100.0	100	100	100.0
STC	m^2	0	0	2.4	0	0	0.0
PV-T	m^2	20	20	0.0	20	20	0.0
Battery	kWh	0	0	0.6	0	0	1.0
Discomfort	$\frac{Kh}{zone}$	7	19	30	50	24	40
CAPEX	k€	130.5	130.5	65.2	130.4	130.4	79.5
OPEX	k€	188.6	119.4	146.0	216.9	143.1	172.8
Maint. cost	k€	35.4	35.4	18.1	35.4	35.4	21.3
TCO	k€	354.4	285.2	229.3	382.7	308.9	273.7
	ΔTCO		–20%	-35%		-19%	-28%

Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).

Cooling-Dominated Virtual Case - IOCD

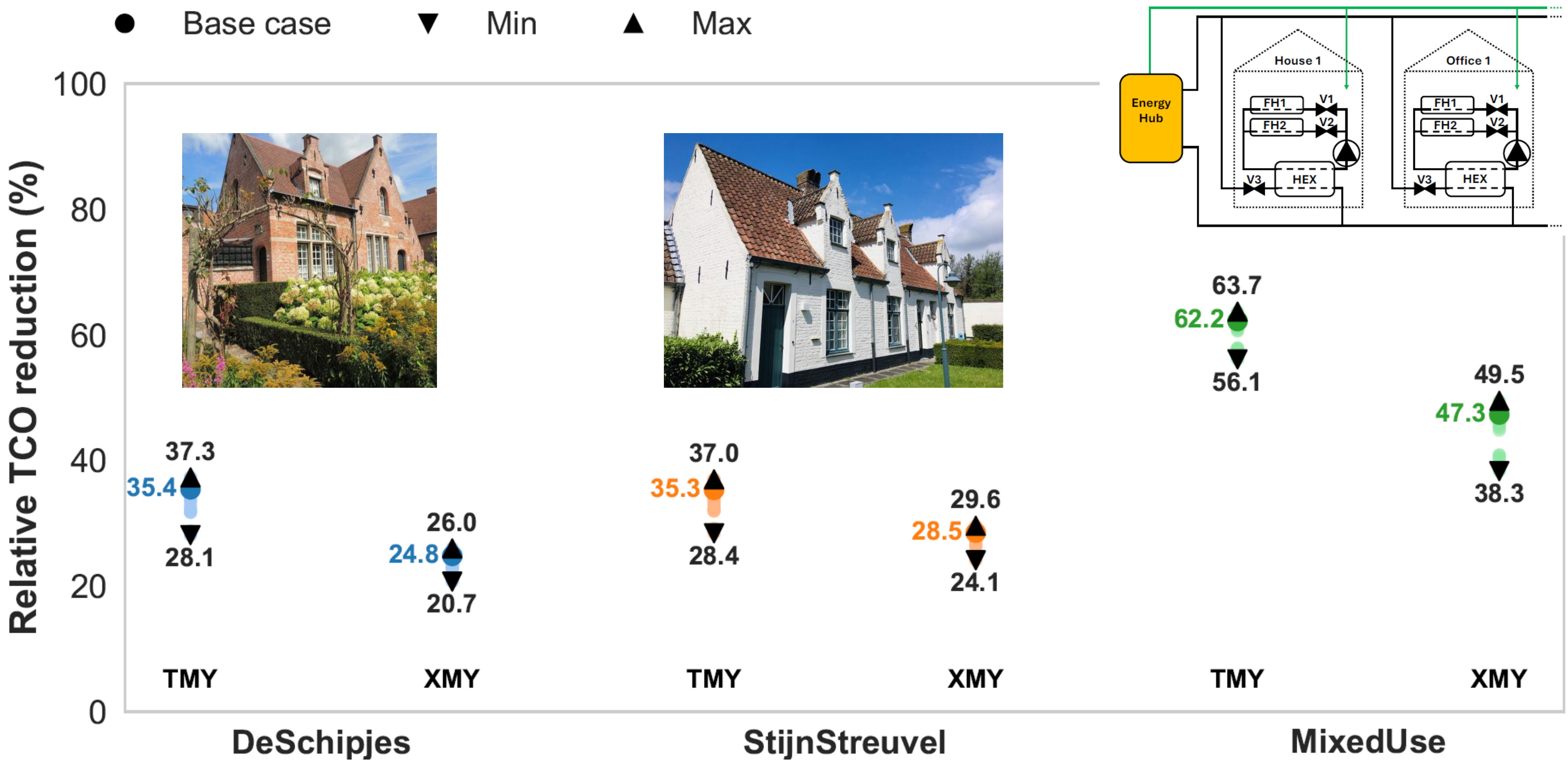
Funded by the European Union





Technology	Unit	TMY REF RBC	TMY REF OC	TMY OPT	XMY REF RBC	XMY REF OC	XMY OPT
ASHP	kW	0	0	0.0	0	0	0.0
GSHP	kW	30	30	15.3	30	30	21.8
Borefield length	m	3060	3060	520	3060	3060	660
Borefield depth	m	170	170	130	170	170	110
Borefield config.	m	6×3	6×3	2×2	6×3	6×3	3×2
ASCHI	kW	0	0	7.6	0	0	13.6
TTES	m^3	0.5	0.5	1.6	0.5	0.5	1.2
PV	m^2	0	0	31.8	0	0	40.4
STC	m^2	0	0	0.0	0	0	0.0
PV-T	m^2	0	0	0.0	0	0	0.0
Battery	kWh	0	0	0.0	0	0	0.0
Discomfort	$\frac{Kh}{zone}$	44	23	28	171	27	36
CAPEX	k€	133.4	133.4	46.4	133.4	133.4	63.5
OPEX	k€	45.9	27.7	19.3	50.4	34.6	29.9
Maint. cost	k€	24.9	24.9	11.5	24.9	24.9	16.6
TCO	k€	204.2	186.0	77.2	208.7	192.9	110.0
	ΔTCO		–9%	-62%		-8%	-47%

Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).



Source: Louis Hermans, Integrated Optimal Control and Sizing of Low-Carbon Multi-Energy Vector Districts, PhD Thesis, KU Leuven, Supervisor: Lieve Helsen (2026).

Use case 4
Neutral-Temperature Thermal Network

Funded by the European Union

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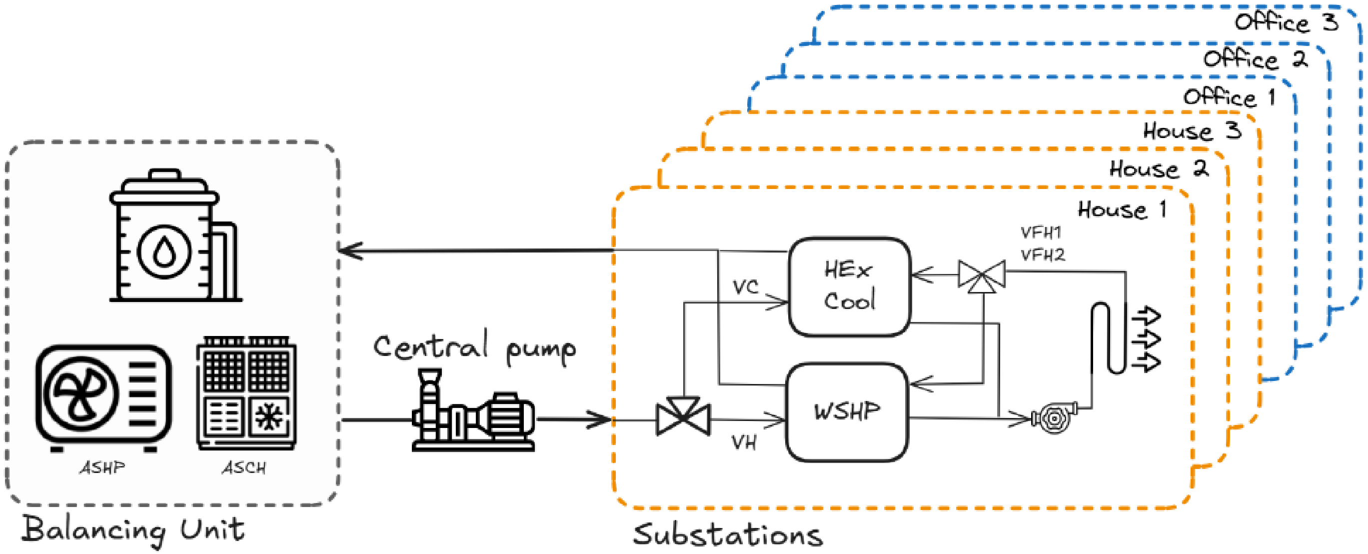
Cooling-Dominated Virtual Case – Energy Circularity

BiD

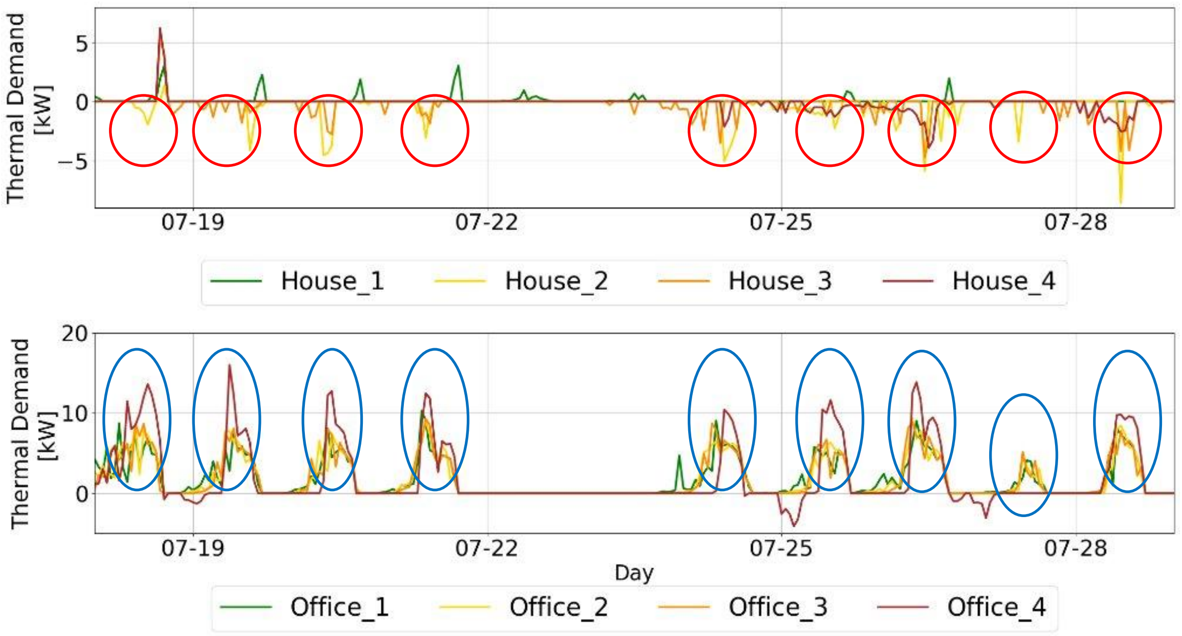
- Different building functions
- Synergy
- MPC determines optimal operation

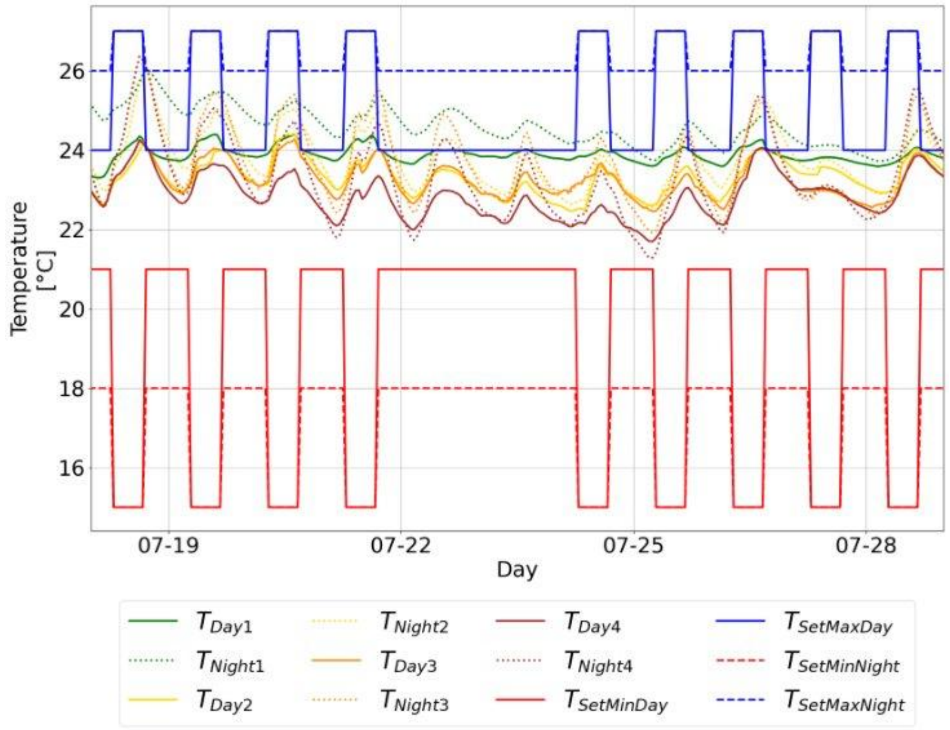


Source: Anna Dell'Isola, Karl Walther, Lieve Helsen, Building renovation level requirements for a 5th Generation District Heating and Cooling Network, presented at the *BS2025 Conference*, Brisbane (2025).

Synergy in a mixed-use neutral-temperature network

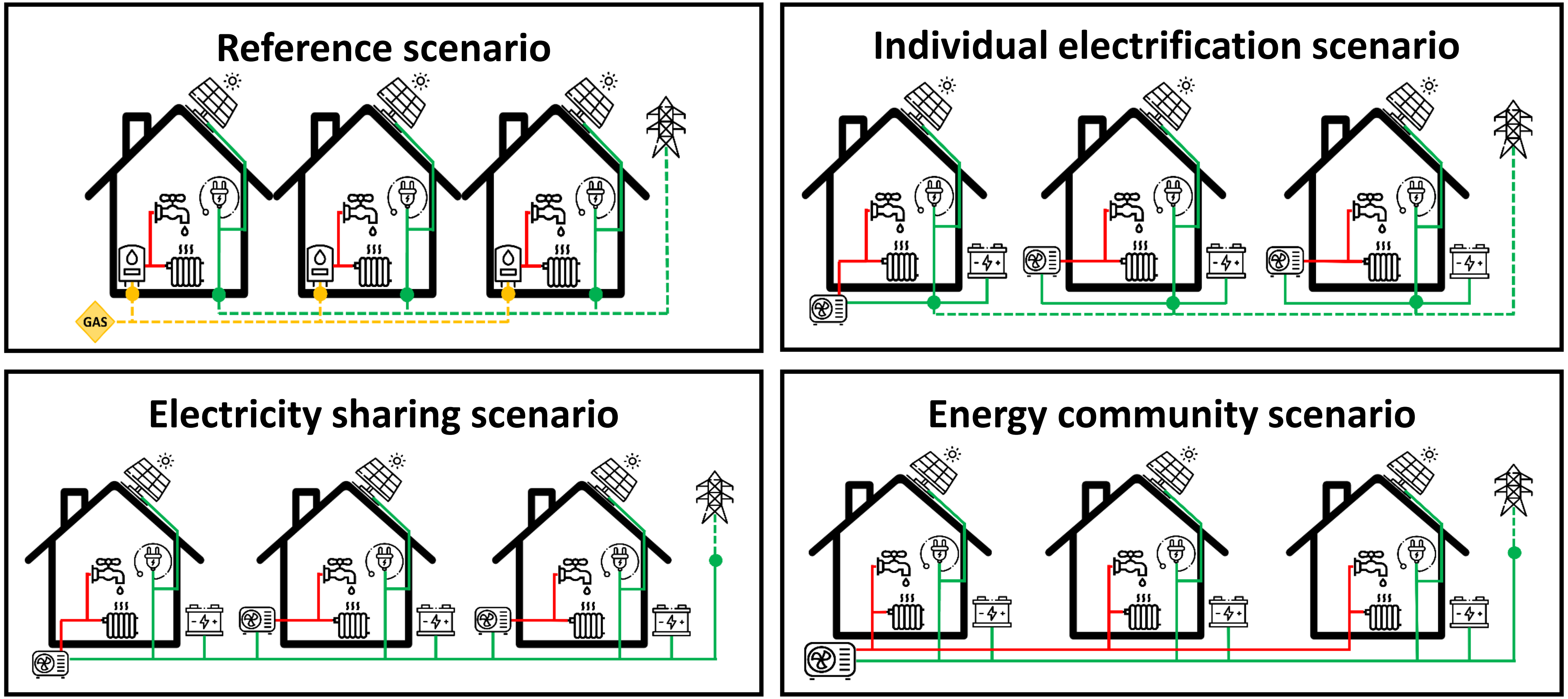
Energy circularity - MPC activates heat pump in lower-performing residential buildings, thereby reducing the network temperature to avoid overheating in well-insulated offices





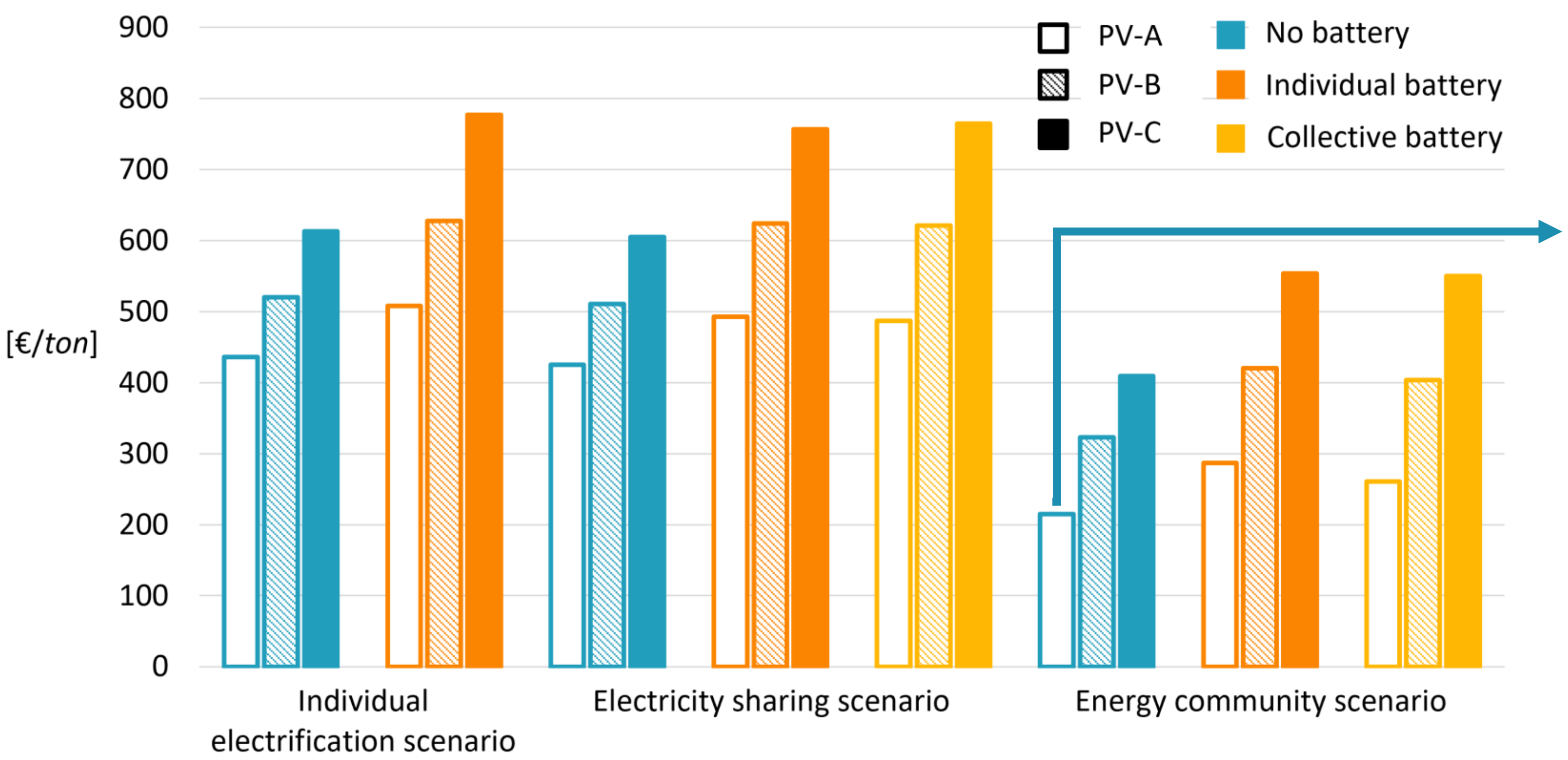
Source: Anna Dell'Isola, Karl Walther, Lieve Helsen, Building renovation level requirements for a 5th Generation District Heating and Cooling Network, presented at the *BS2025 Conference*, Brisbane (2025).

Use case 5 - Multi-energy vector tiny cluster



Source: Lucas Verleyen, Lieve Helsen, The role and CO_2 emission reduction cost of battery energy storage in fully integrated, optimally controlled micro energy communities. *Energy & Buildings* 357 (2026) 117123.

CO_2 emission reduction cost for tiny cluster



PV-A based on plug load demand
PV-B based on plug load + heat pump demand
PV-C full roof

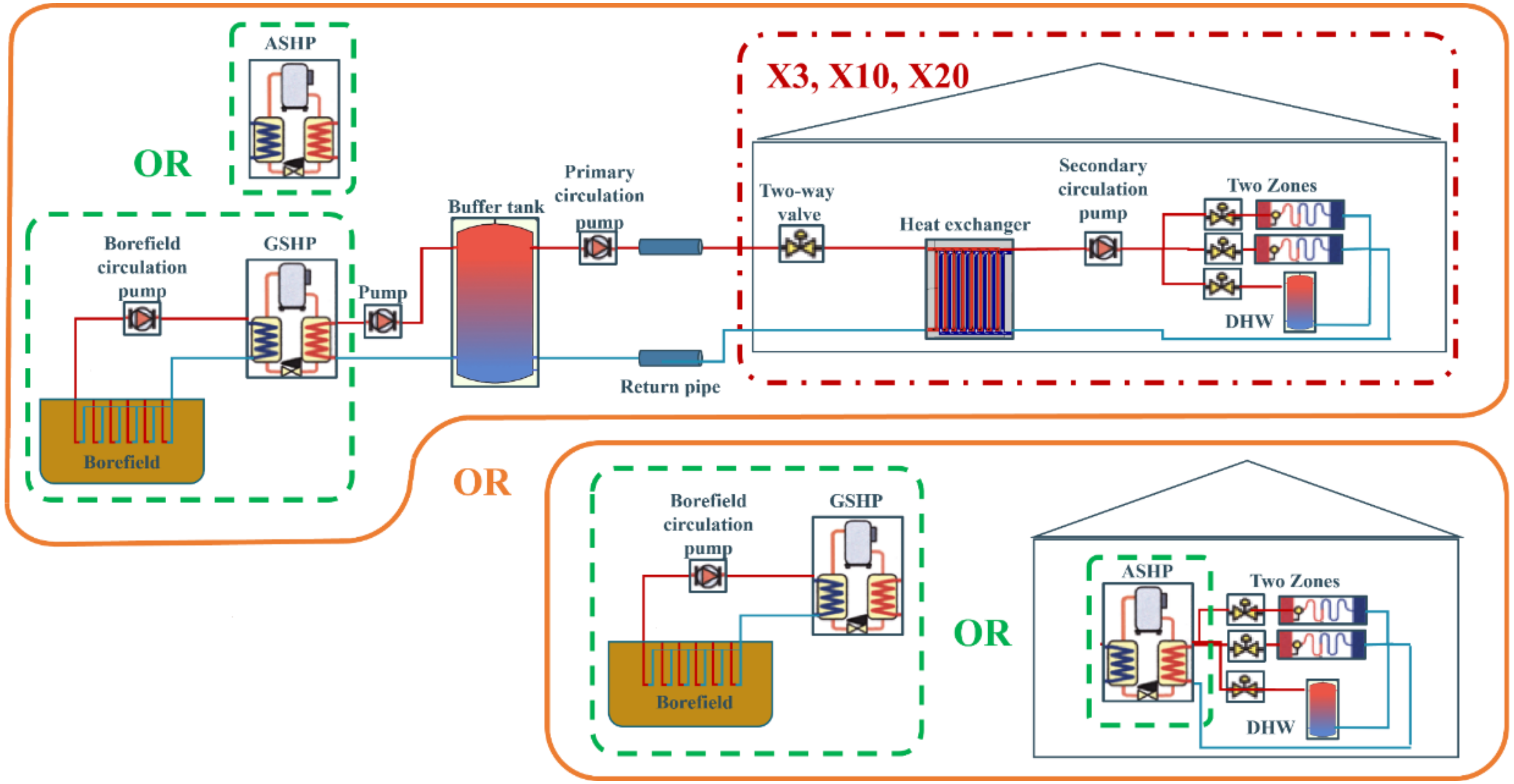
Energy community with PV–A performs best
€ 215/ton CO_2

Compare to:

- EU ETS: € 32-80/ton CO_2
- EU-ETS2 (starts in 2027): € 46/ton CO_2
- To reach CO_2 targets in 2030:
  € 261/ton CO_2 (Günther et al. 2024)
  € 130-286/ton CO_2 (Abrell et al. 2024)

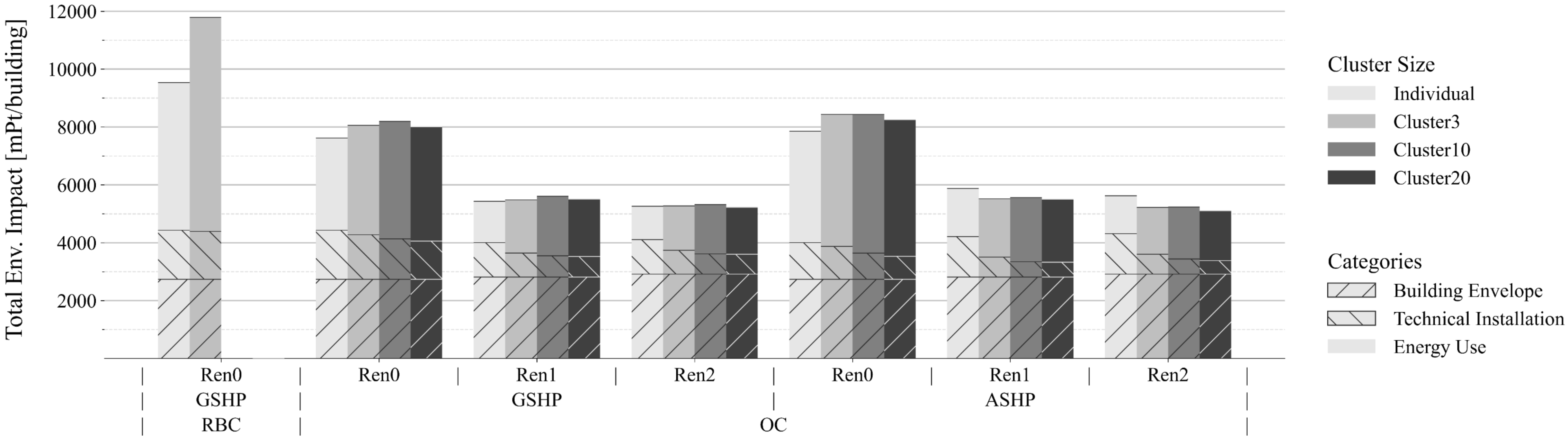
Source: Lucas Verleyen, Lieve Helsen, The role and CO_2 emission reduction cost of battery energy storage in fully integrated, optimally controlled micro energy communities. *Energy & Buildings* 357 (2026) 117123.

Use case 6 – *Social District Egelsvennen*



Source: Naomi Adam, Lieve Helsen, Environmental trade-offs in collective heating systems: A life cycle perspective on cluster size, presented at the *SES 2025 Conference*, Copenhagen (2025).

Environmental Life Cycle Impact



Source: Naomi Adam, Jelger Jansen, Els Van de moortel, Lieve Helsen, Environmental Trade-Offs in Collective Heating Systems: A Life Cycle Perspective on Cluster Size, submitted to *Renewable and Sustainable Energy Transition* (2026).

System Integration leads to System Solutions

Enabler for all-inclusive energy transition
sustainable & circular economy

System Solutions

Physics as foundation - Data as leverage

Informed decisions
Correct and robust sizing
System FLEX exploited
Minimal energy use/cost and maximal comfort
Automated Optimization, Scalable Workflow through distributed MPC
From TRL to SRL (S = system, society, social, synergy, smart …)
Innovative Integrated Solutions

More in the RHC-ETIP session "From Insights to Action: digitalisation and AI for Next-Generation Renewable Heating & Cooling Systems"

Department of Mechanical Engineering, Thermal Systems Simulation (The SySi) Team

Herman Teirlinck Building, Brussels (5600 m^2)

MPC by Builtwins

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EBC
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IBPSA Project 1

IBPSA Project 2

KU LEUVEN

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AGENTSCHAP INNOVEREN & ONDERNEMEN

TECHPED
Technically feasible positive energy districts

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zorg met een plus

boydens engineering

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