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Optimal energy system design for residential buildings and districts

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Empa Materials Science and Technology

Climate change

“We must now agree on a binding review mechanism under international law, so that this century can credibly be called a century of decarbonisation.”

Angela Merkel on Climate Change
Chancellor of Germany

“Climate change is no longer some far-off problem; it is happening here, it is happening now.”

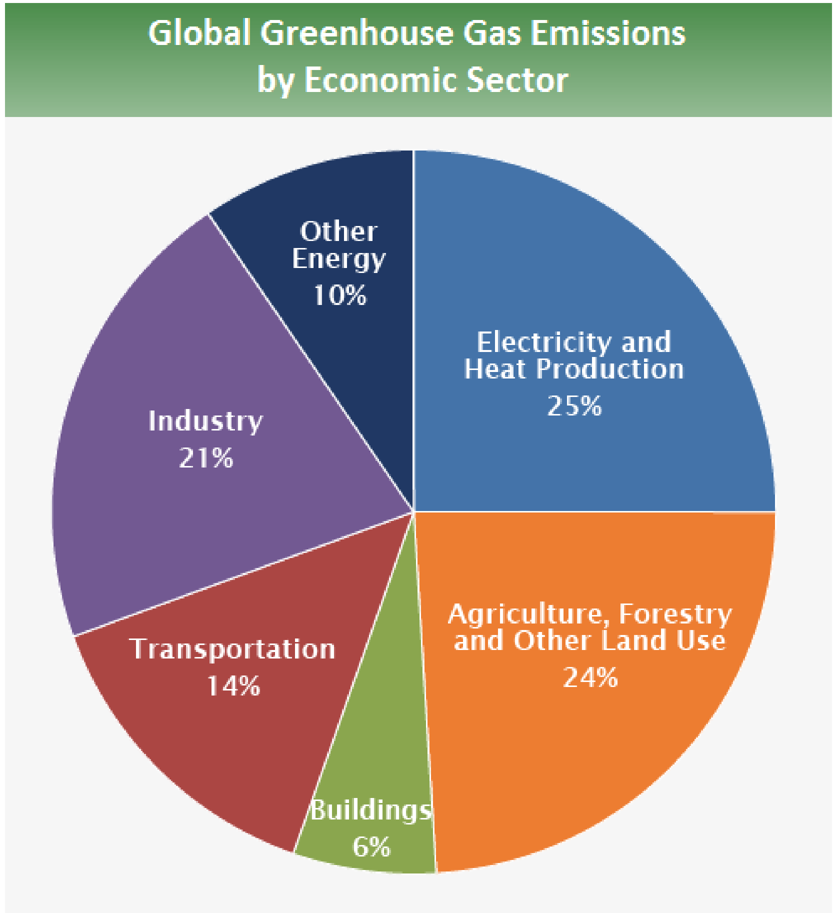
Barack Obama on Climate Change
President of the United States of America

“The time is past when humankind thought it could selfishly draw on exhaustible resources. We know now the world is not a commodity.”

François Hollande on Climate Change
President of the French Republic

Global green house gas emission by sector

- Electricity and heat production: 25%
- Buildings: 6%



Source: IPCC 2014

Energy transition and favorable policy

- Energy transition – Long-term structural change in energy systems
- Energywende, Germany
  - 85-95% reduction in greenhouse gas emissions
  - 60% renewable energy consumption
  - 50% reduction in primary energy consumption
- Energy strategy 2050, Switzerland

Question – Which path shall we take?

A historical perspective on energy transition in buildings (1500-1800)

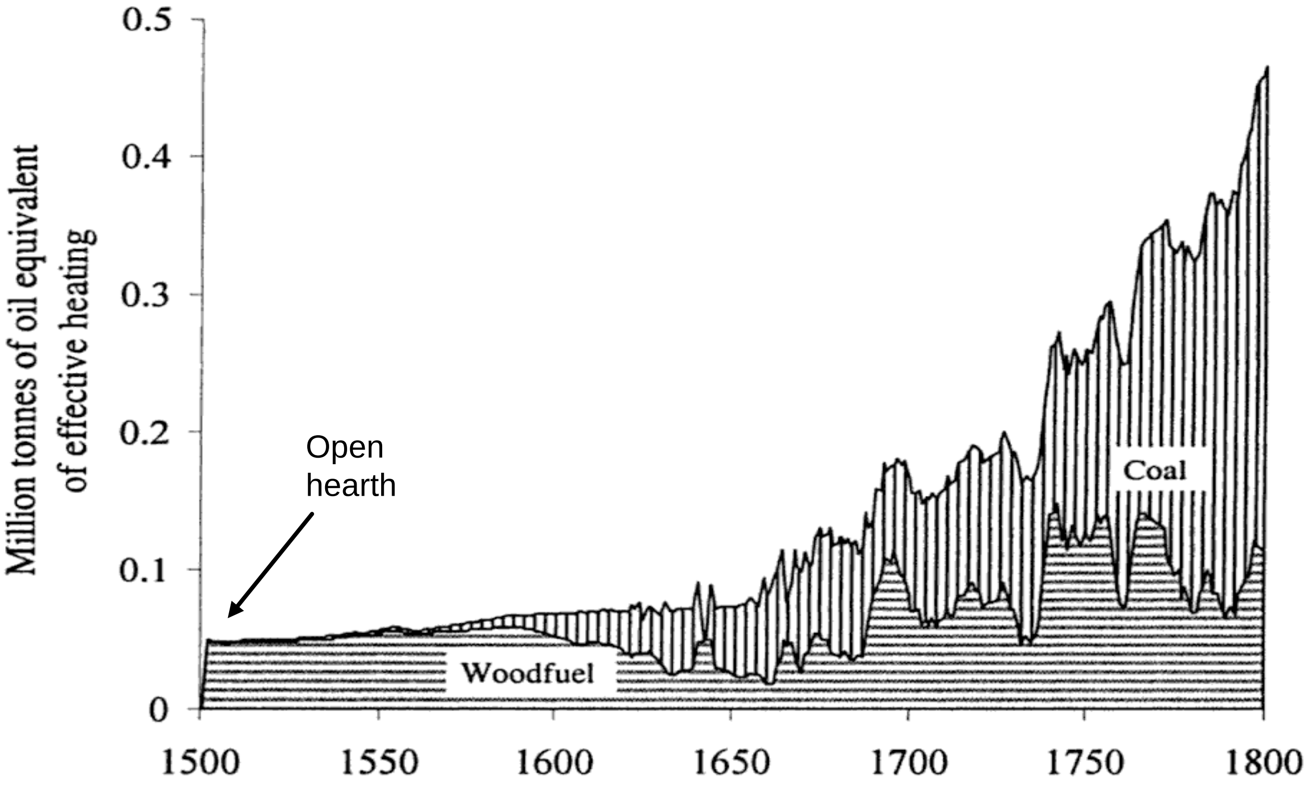


Fig: Heating services in buildings by energy source (UK)

Fig: Open hearth fireplace. Source. Pinterest

A historical perspective on energy transition in buildings (1500-1800)

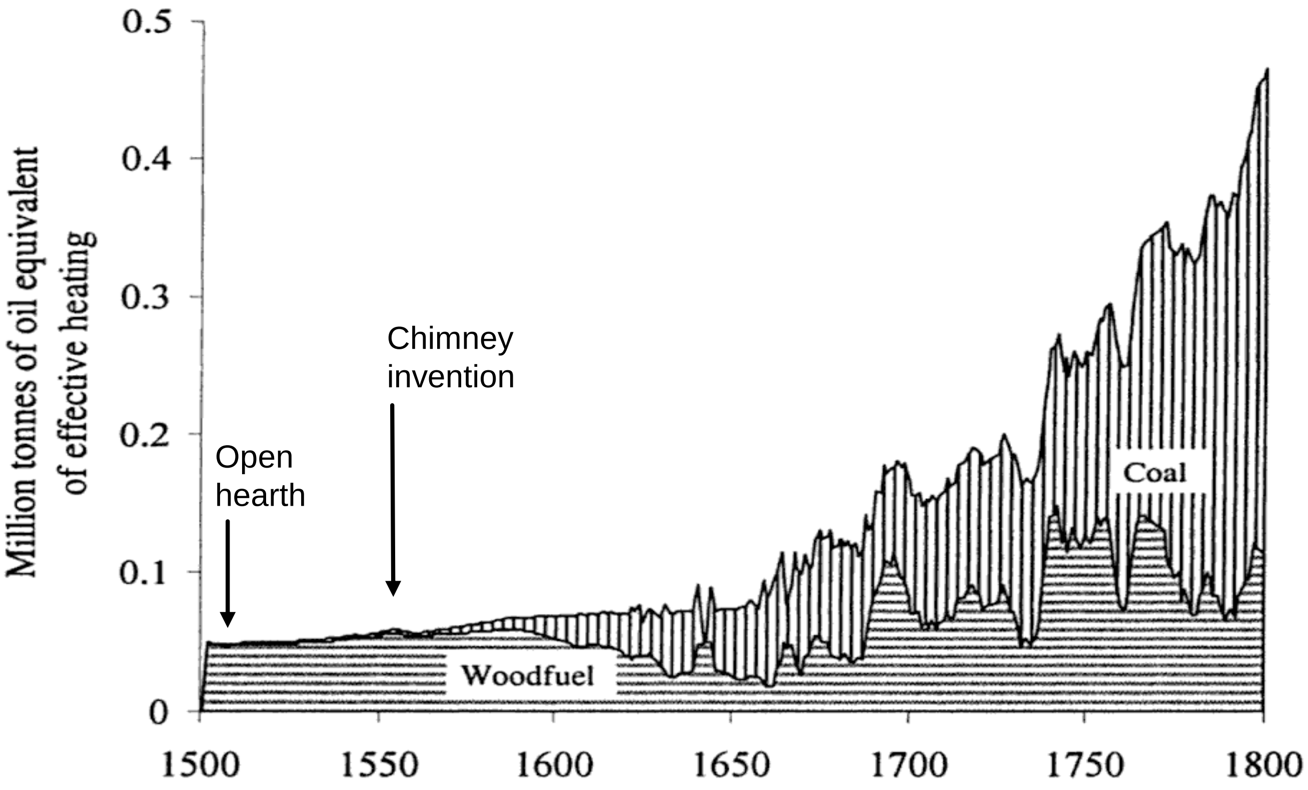


Fig: Heating services in buildings by energy source (UK)

Fig: Chimney example. Source. Pinterest

A historical perspective on energy transition in buildings (1800-1900)

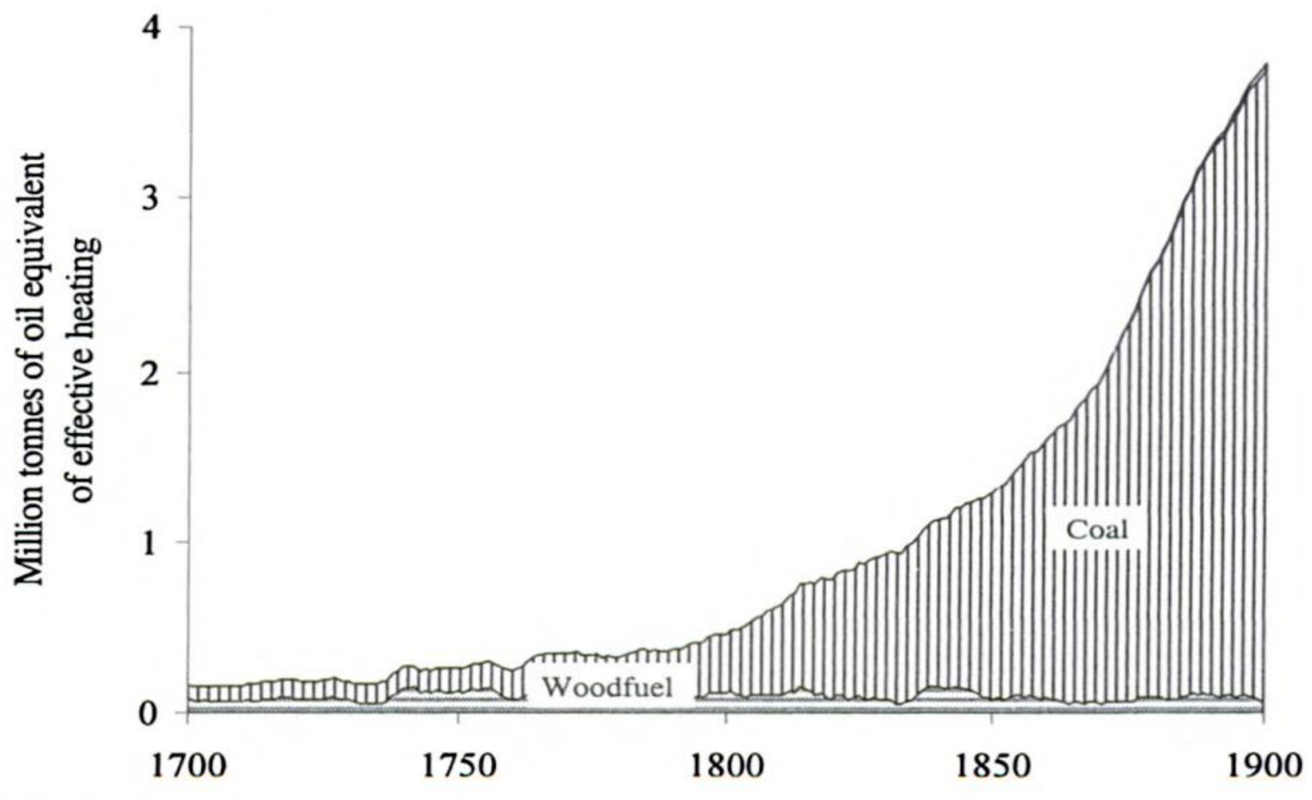


Fig: Heating services in buildings by energy source (UK)

A historical perspective on energy transition in buildings (1900-2000)

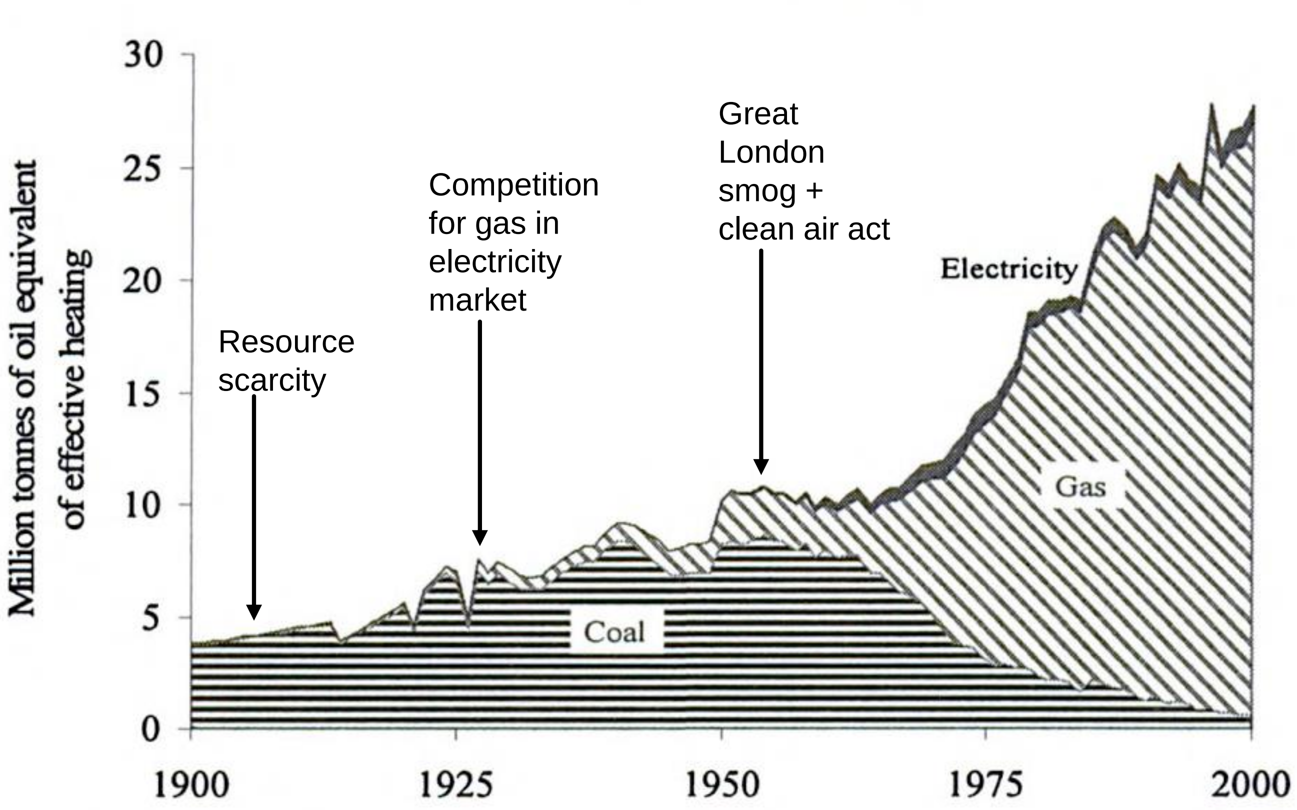


Fig: Heating services in buildings by energy source (UK)

Fig: The great smog of London (1952). Source. The Verge

Key diverging factors from past energy transitions

- Deeper understanding of the engineering challenges
- Better research and development infrastructure
- Favorable energy policy
- Wide landscape of solutions, technologies

- External costs are not explicit
- Lack of clear incentives to adopt new renewable technologies
- Existing energy and social infrastructure, lock-in
- Optimal design solutions unknown

The Swiss context

Switzerland and its buildings (Energy source)

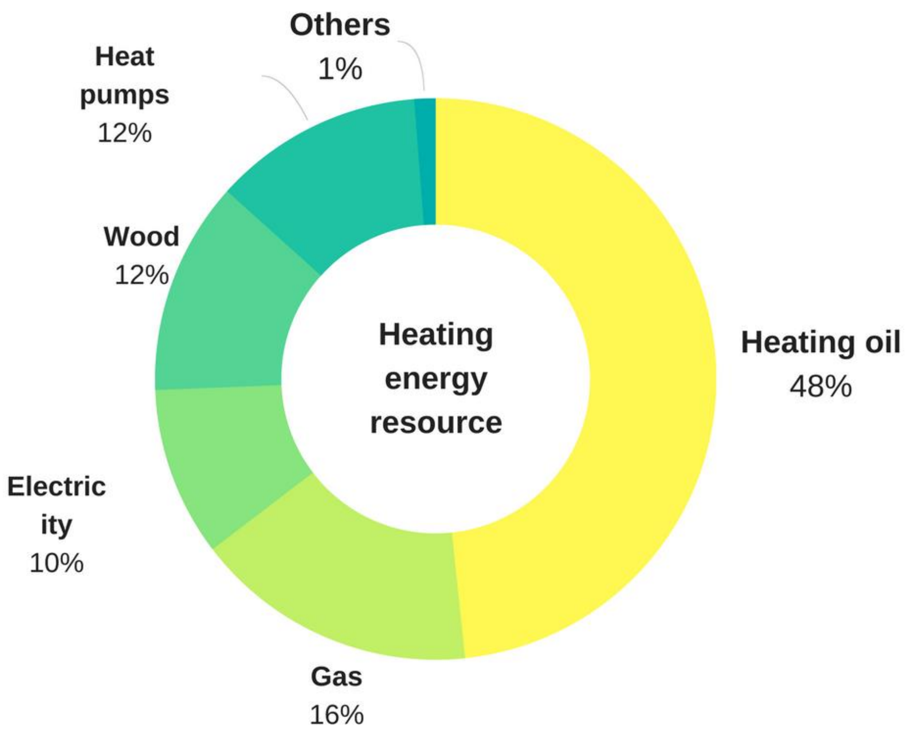


Fig: Heating services in buildings by energy source (2013)

Switzerland and its buildings (Construction)

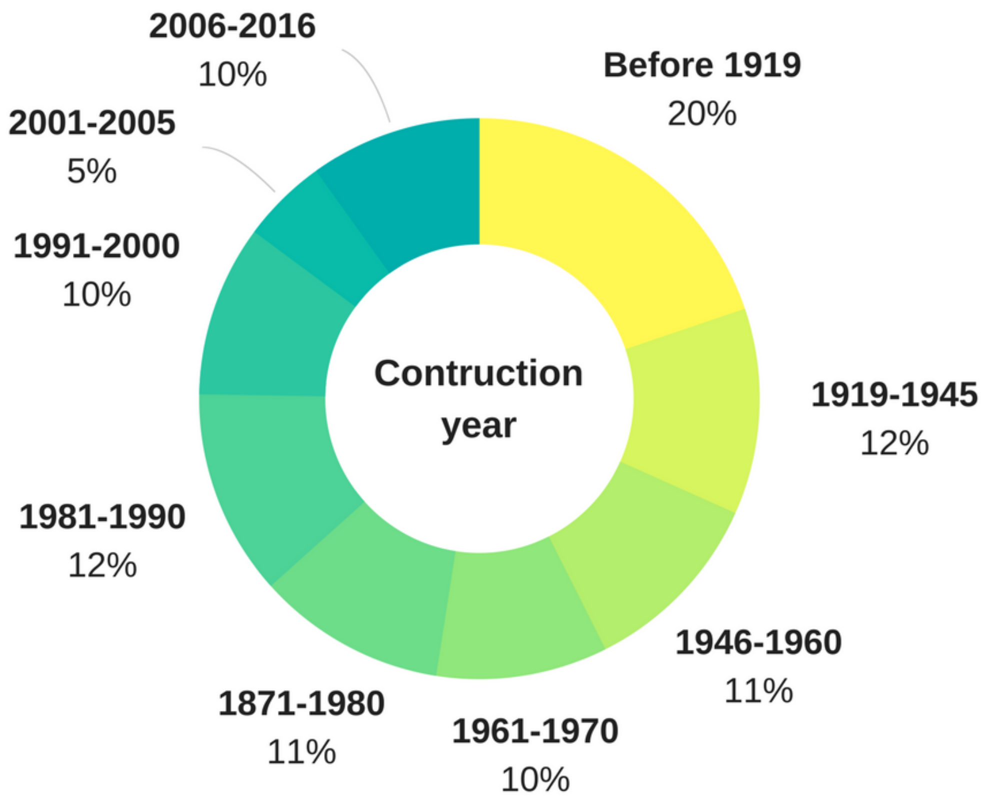


Fig: Distribution of construction year for Swiss buildings (2013)

Swiss energy strategy (SES) 2050

- Political reform for Switzerland's energy transition

- Voted as a energy law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Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Energie BFE

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Die Energieperspektiven für die Schweiz bis 2050

Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 – 2050

Ergebnisse der Modellrechnungen für das Energiesystem

Auftraggeber
Bundesamt für Energie

Ansprechpartner
Dr. Almut Kirchner

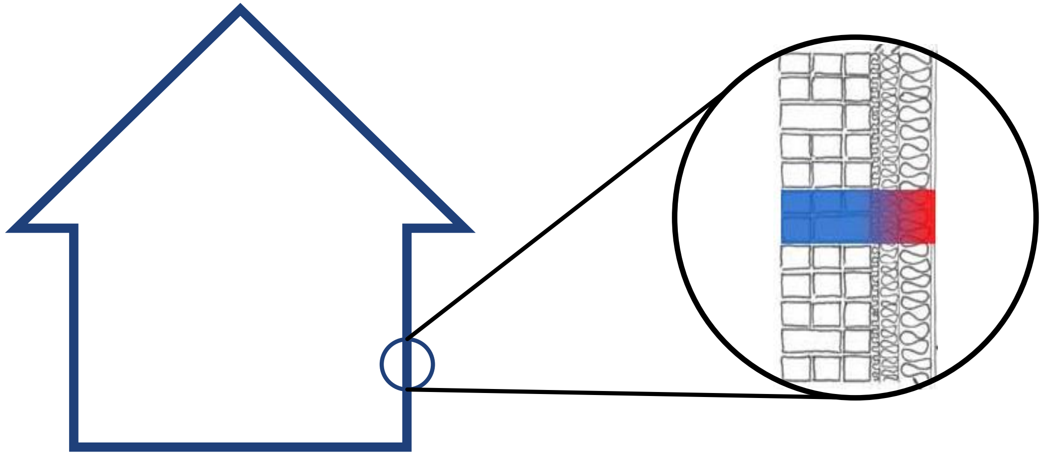
Basel, 12.09.2012
31-7255 - 7303 - 00 - 7486

SES2050 – Recommended energy interventions I

- Utilization of renewable energy resources at building/district level
  - **Solar energy**: Solar photovoltaic (PV), solar thermal collectors
  - **Geothermal**: ground source heat pumps (GSHP)
  - **Biomass**: biomass boilers
  - **Others**: air source heat pumps (ASHP), micro combined heat and power (μ-CHP)

SES2050 – Recommended energy interventions II

- Improved thermal insulation for higher energy efficiency
  - **Old technology**: Bricks, concrete, quarry stones, gypsum, air gaps, etc.
  - **New technology**: Polystyrene, polyurethane, glass wool, etc.
  - Walls, roofs, floors, windows, etc.
  - Substantial improvements in thermal properties



Swiss energy strategy 2050 – emissions targets

- CO_2 emissions targets for 2020, 2030, 2040 and 2050
- Projections for energy demand and floor area for residential buildings

$$CO_2 = \overbrace{\frac{CO_2}{EC}}^{x} \cdot \overbrace{\frac{EC}{A}}^{y} \cdot A$$

x = carbon intensity (gCO_2-eq/kWh)

y = energy consumption (kWh/m^2)

A = Floor area (m^2)

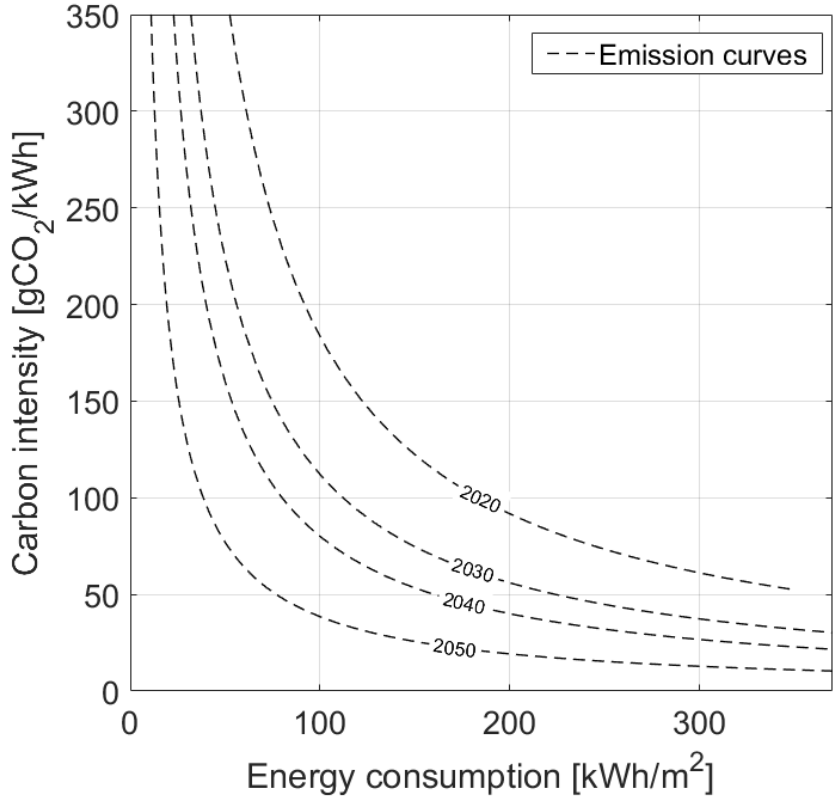


Fig: CO_2 emission targets for residential buildings in Switzerland for 2020 through 2050

Performance of energy interventions

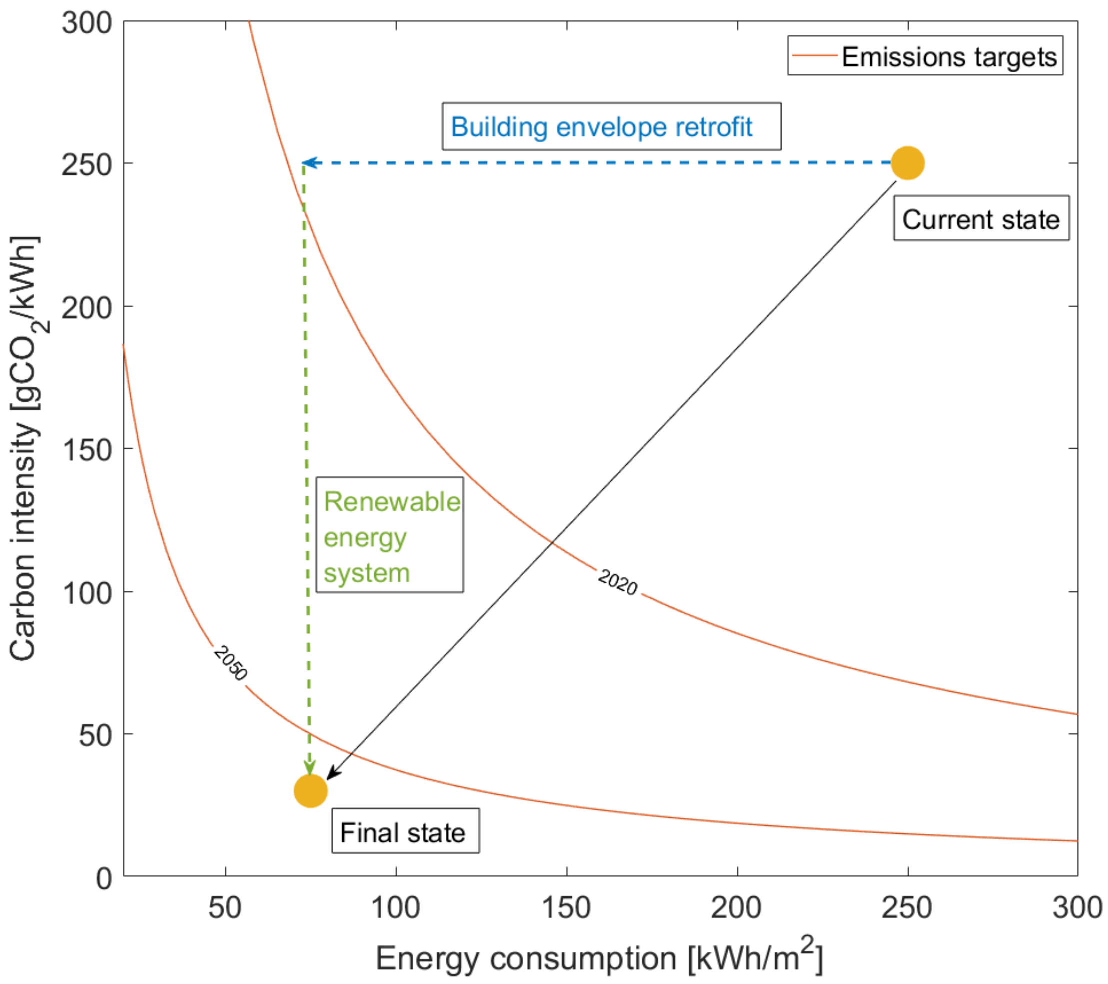


Fig: Impact of energy interventions on carbon intensity and energy consumption

Question – What are the least cost energy interventions which meet the CO_2 targets?

Mathematical optimization – Linear programming

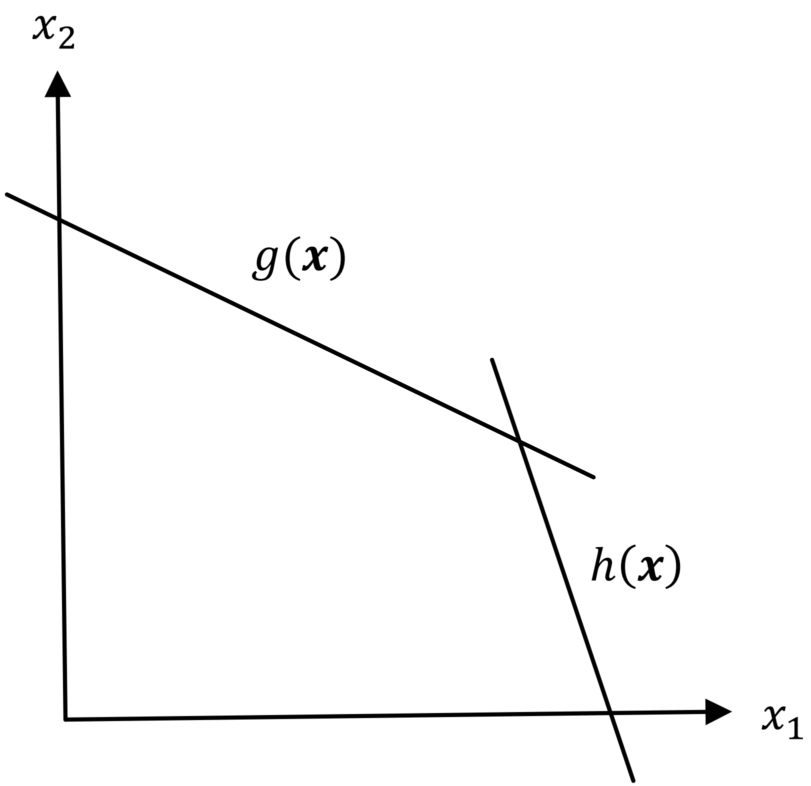
Minimize: $f(\boldsymbol{x})$

Subject to: $g(\boldsymbol{x}) \leq 0$

$h(\boldsymbol{x}) = 0$

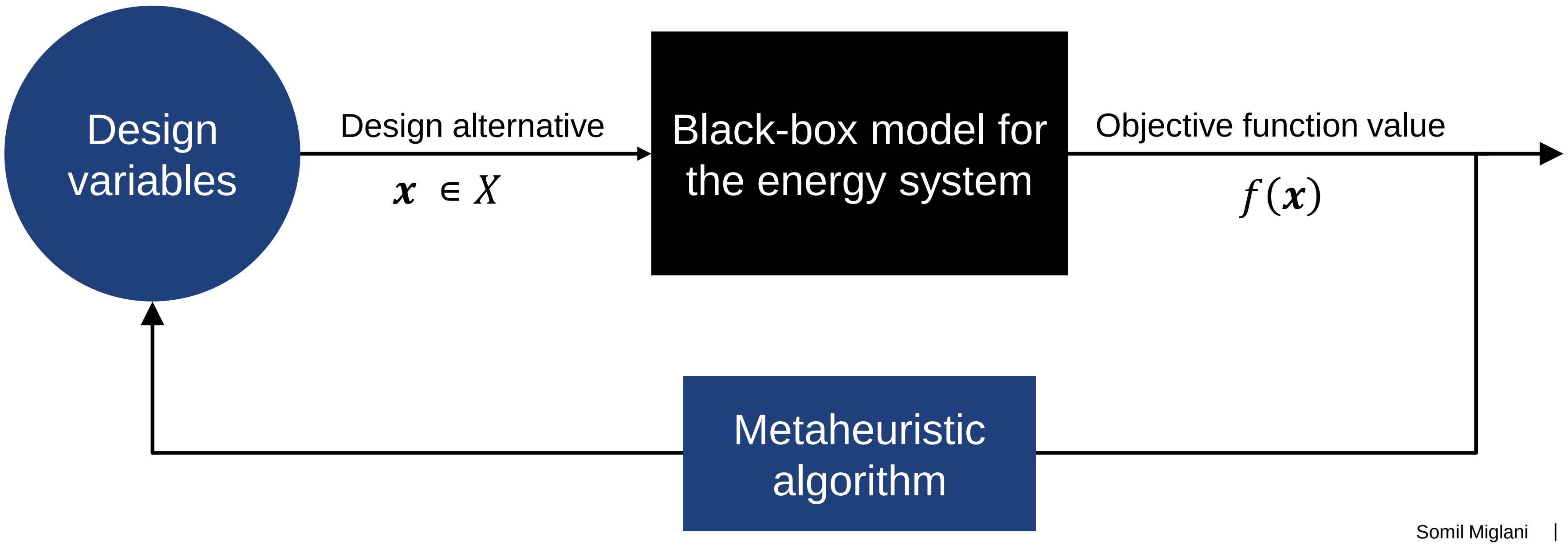
$x_{min} \leq \boldsymbol{x} \leq x_{max}$

$\boldsymbol{x} \in X$



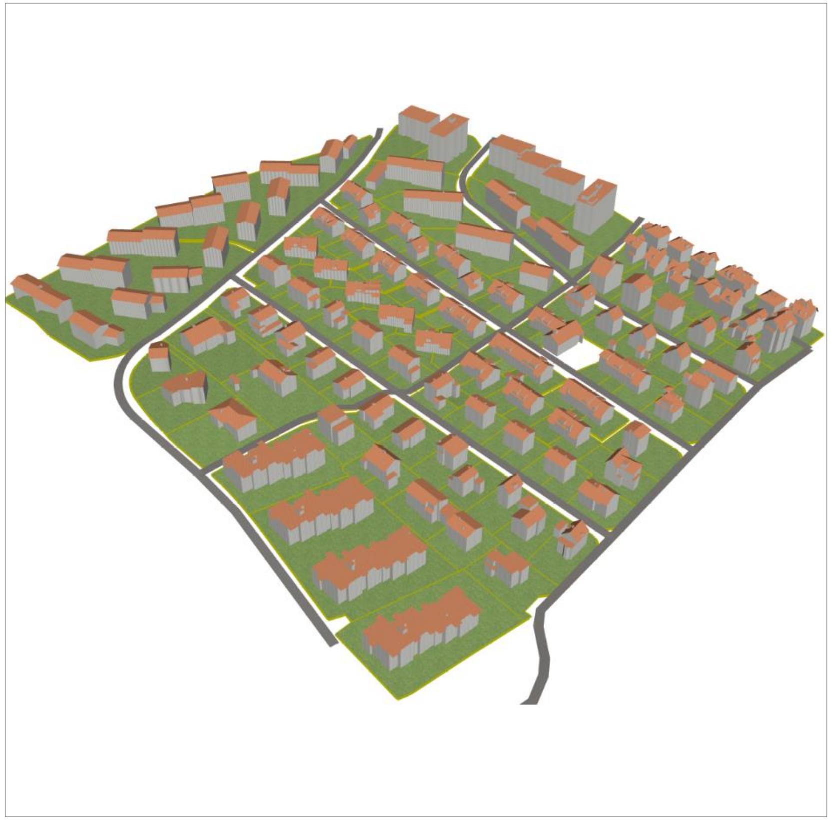
Mathematical optimization – Metaheuristic algorithms

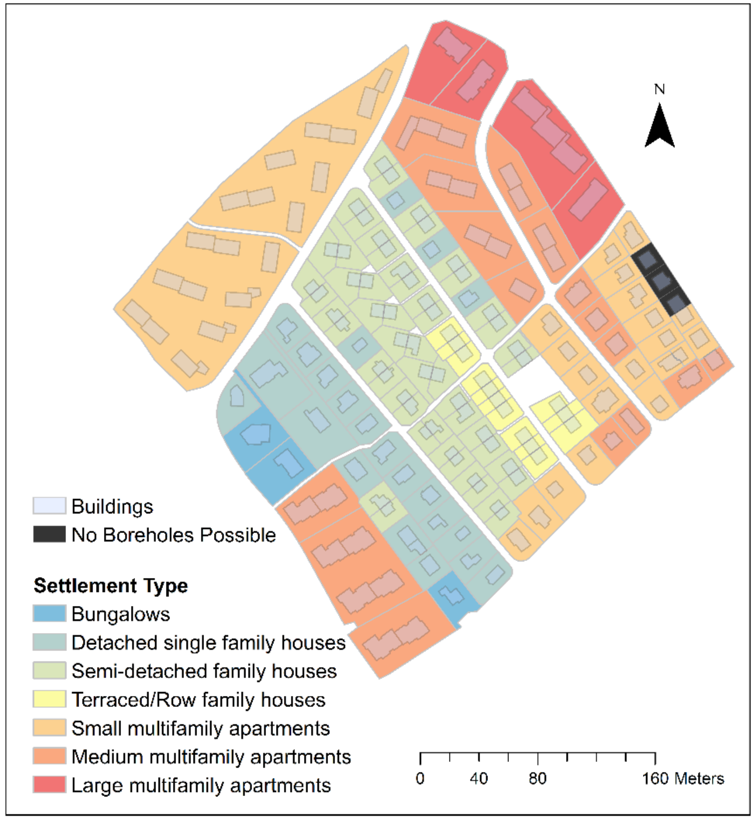
- High level search based optimization
- Ideal for complex non-linear energy system models



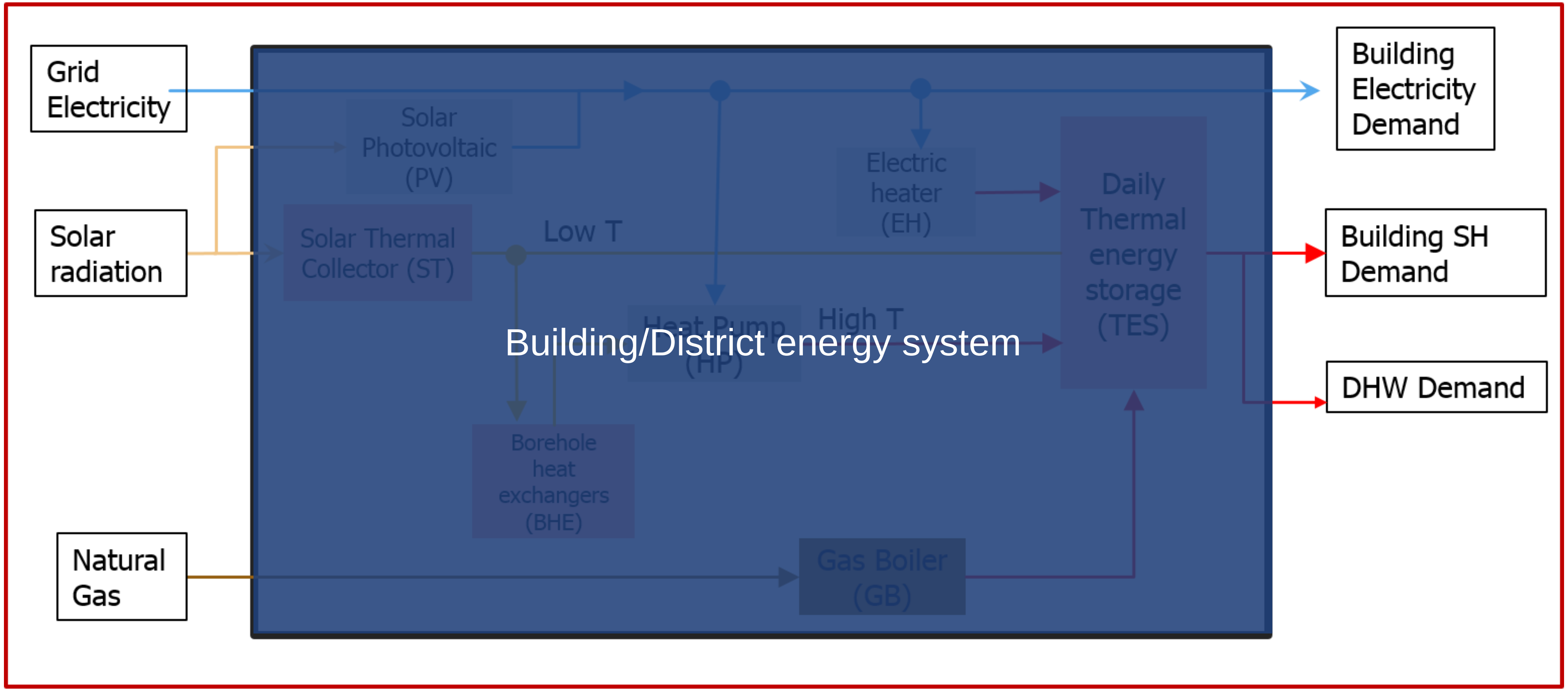
Case study

- Residential neighborhood in Zurich
- 170 buildings
- High solar, geothermal potential

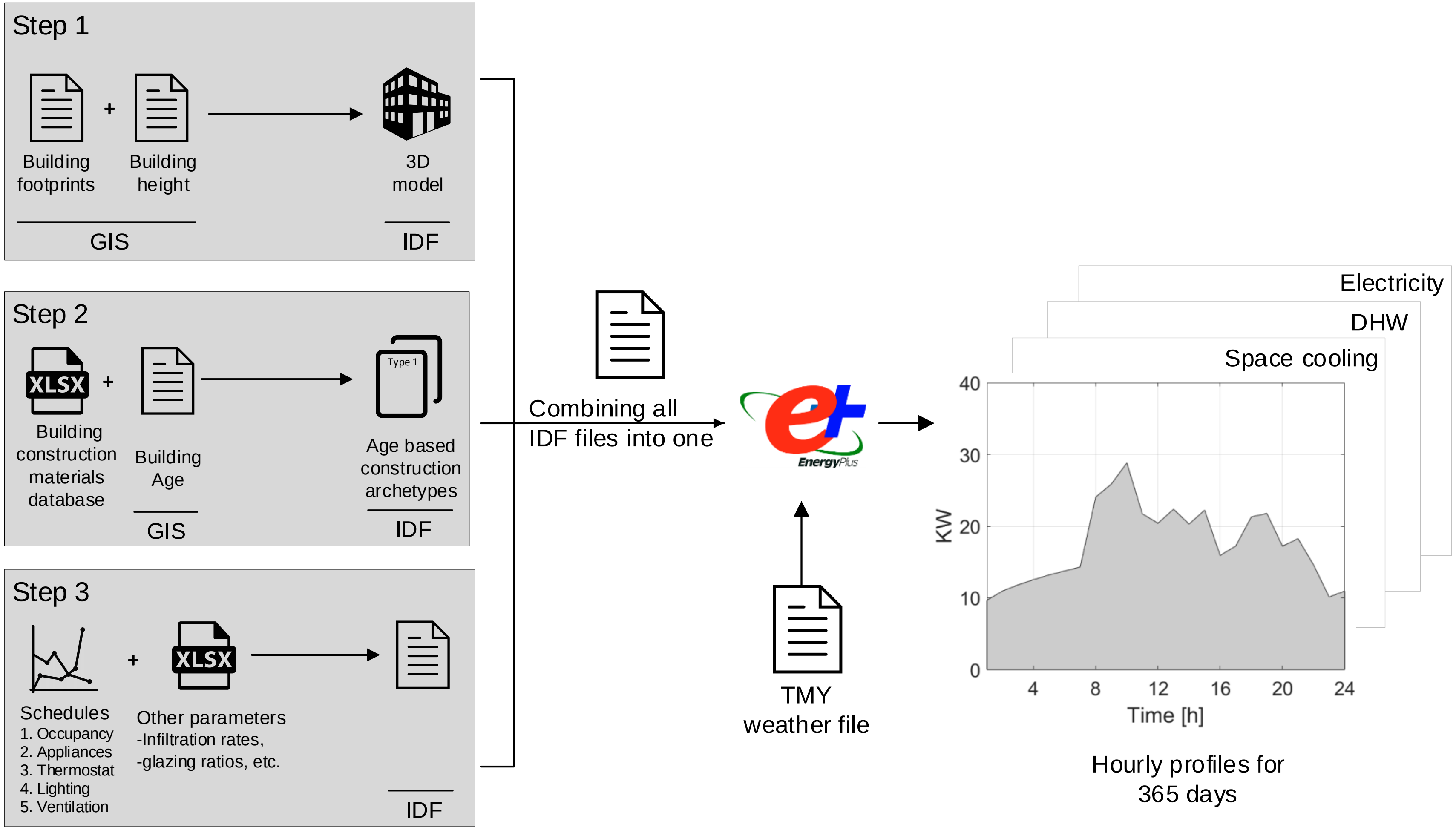




Building energy system – inputs and outputs



Building energy demand simulation – overview



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Building energy demand simulation – results

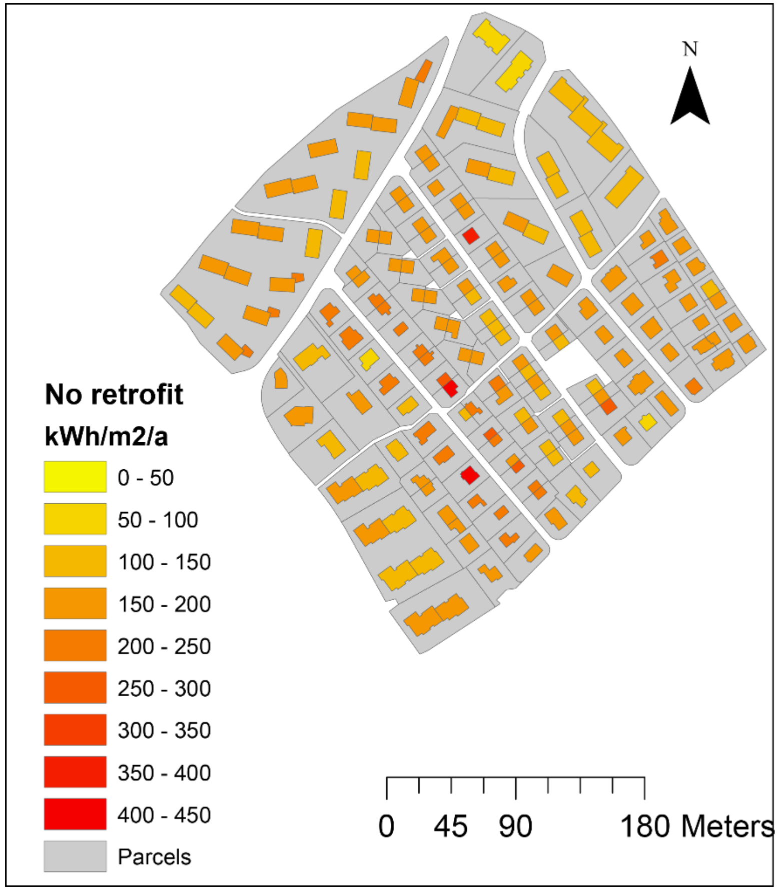


Fig: Annual energy demand – No retrofitting (kWh/m^2/a)

Building energy demand simulation – results

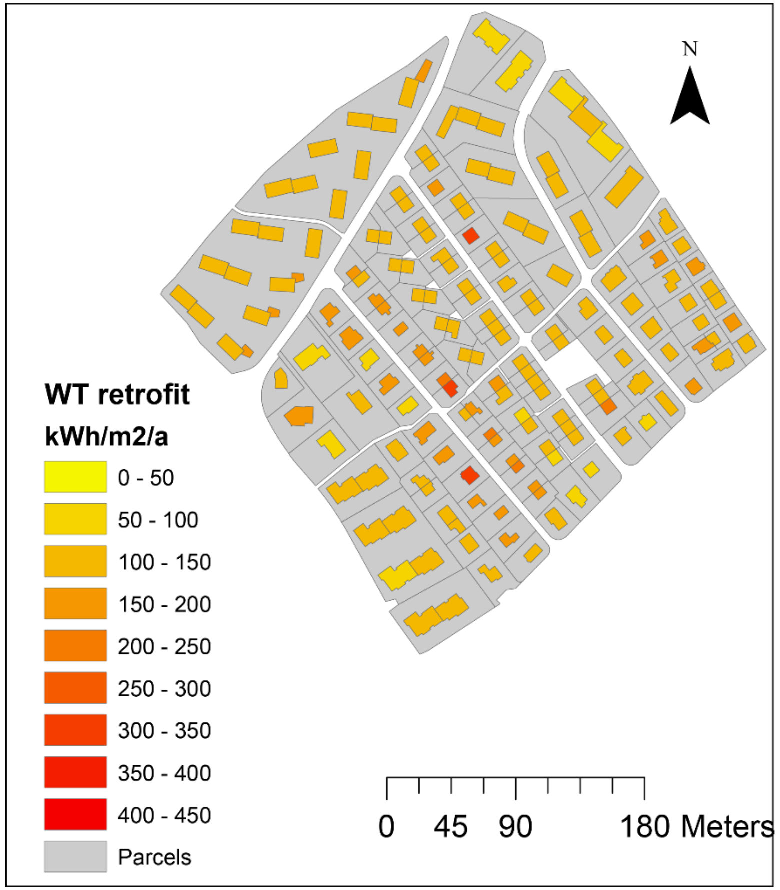


Fig: Annual energy demand – Window retrofitting (kWh/m²/a)

Building energy demand simulation – results

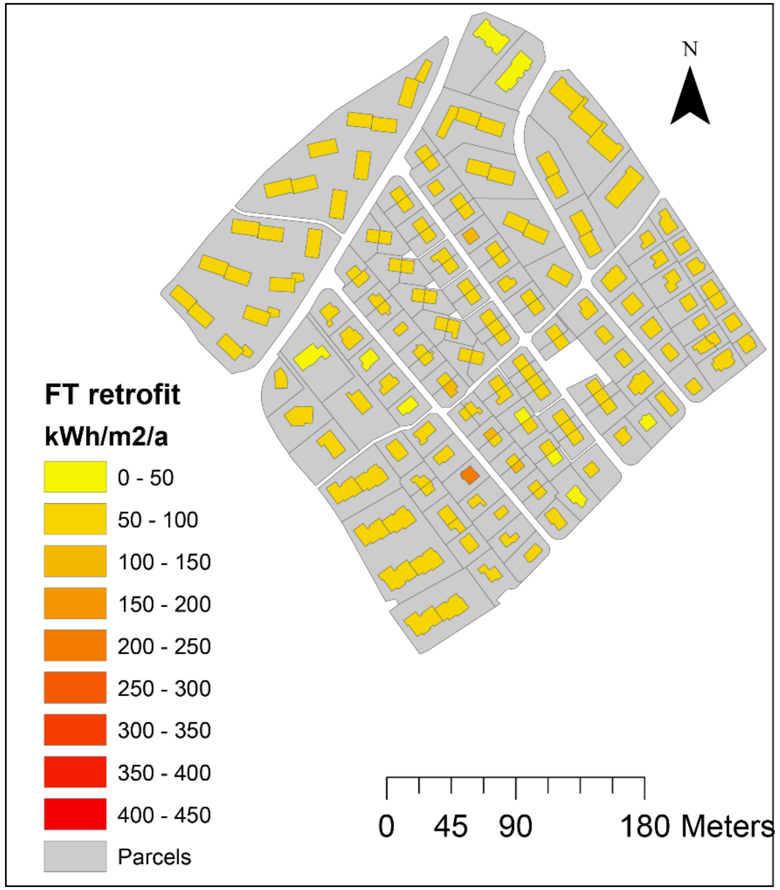


Fig: Annual energy demand – facade retrofitting (kWh/m^2/a)

Building energy demand simulation – results

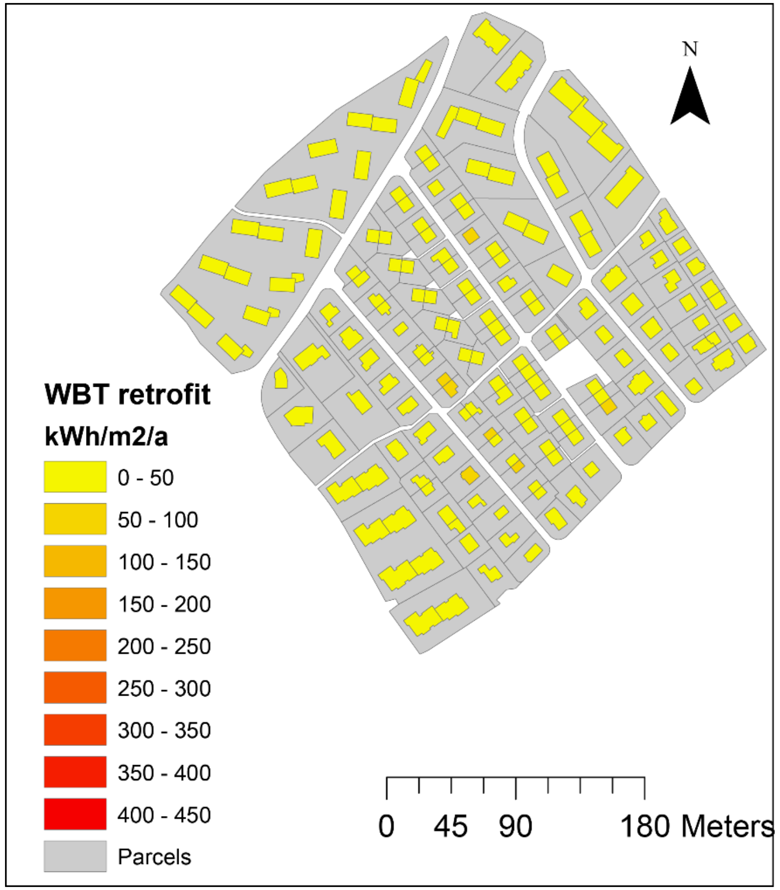
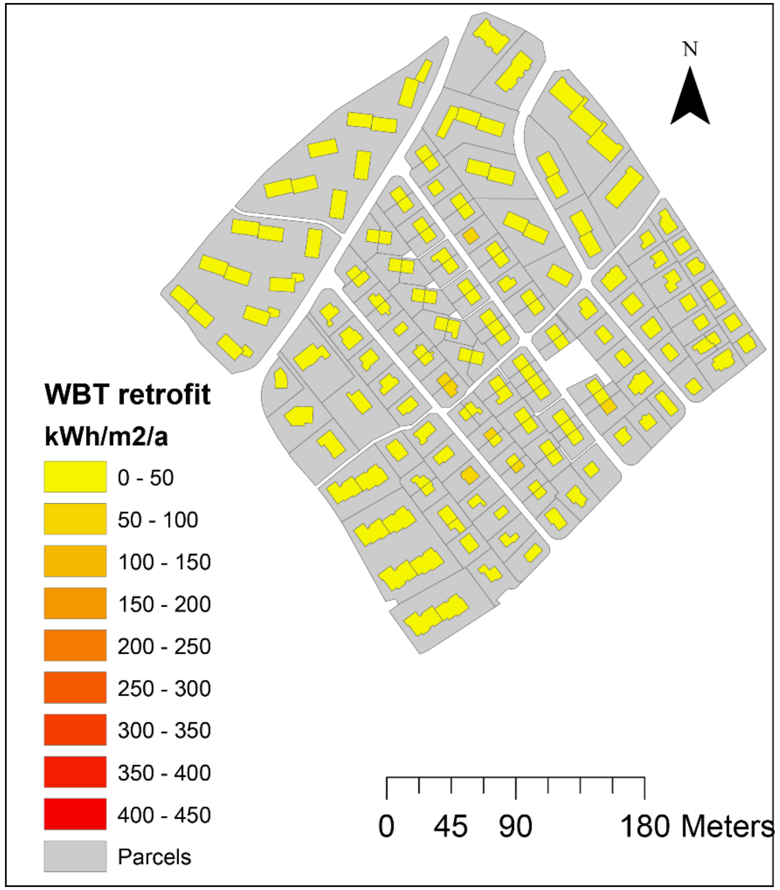


Fig: Annual energy demand – Whole building retrofitting (kWh/m^2/a)

Building energy demand simulation – results



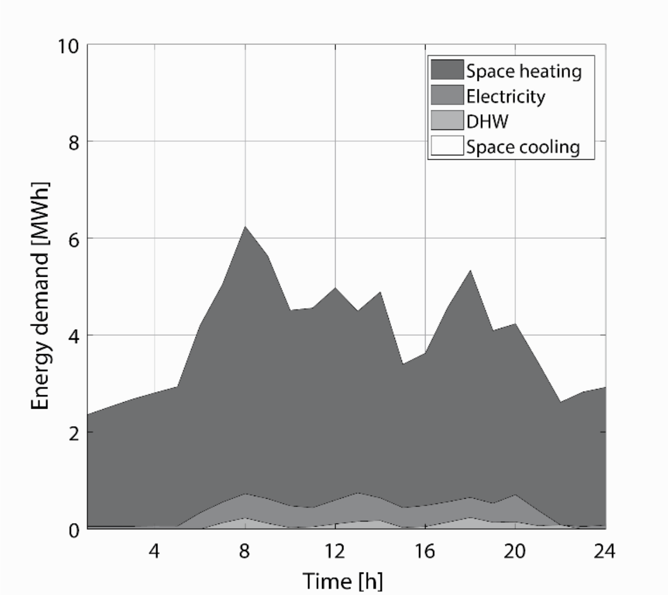


Fig: Hourly energy demand for a winter day

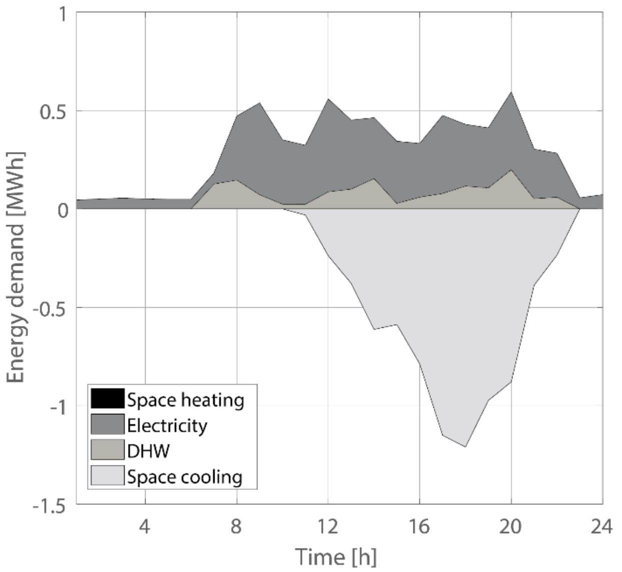
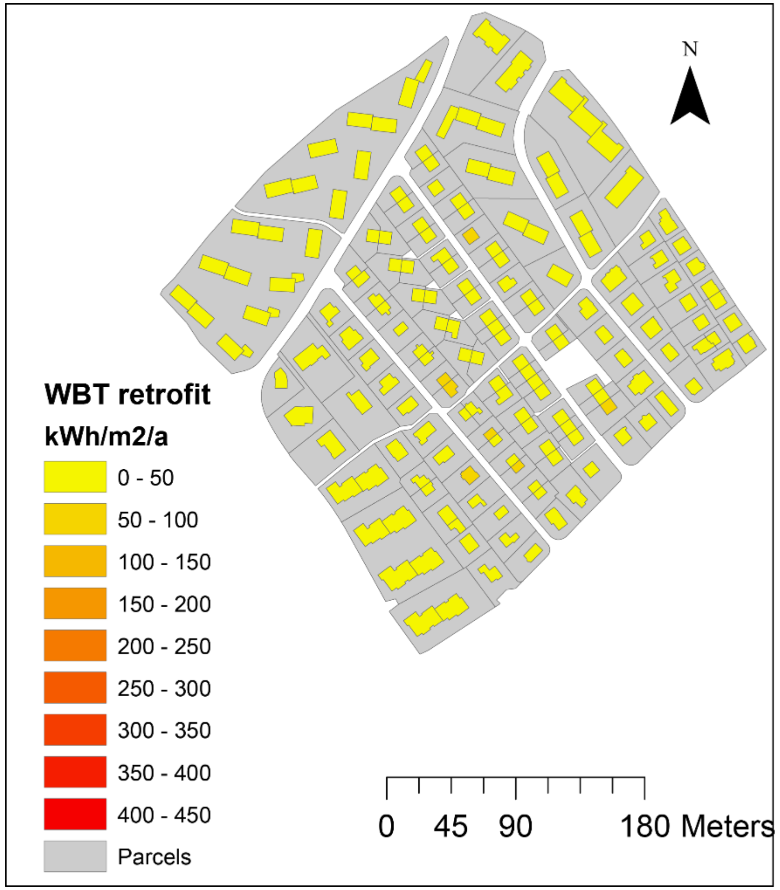


Fig: Hourly energy demand for a summer day

Fig: Annual energy demand – Whole building retrofitting (kWh/m²/a)

Building energy demand simulation – results



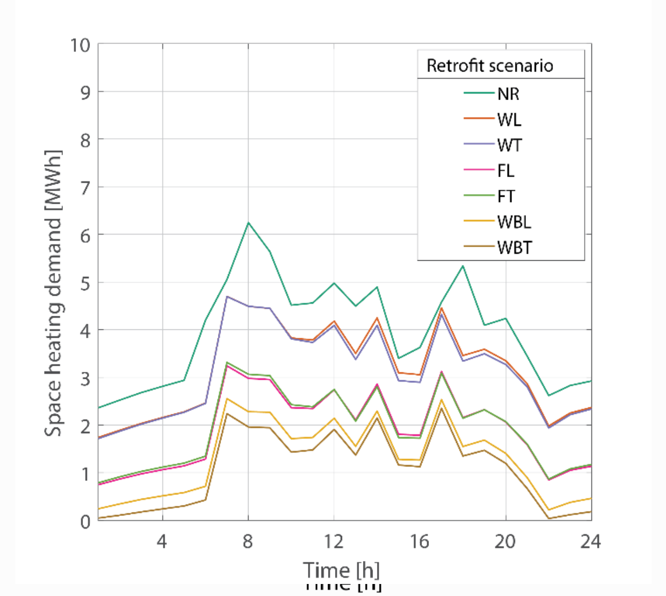


Fig: Hourly energy demand for winter day for different retrofit scenarios

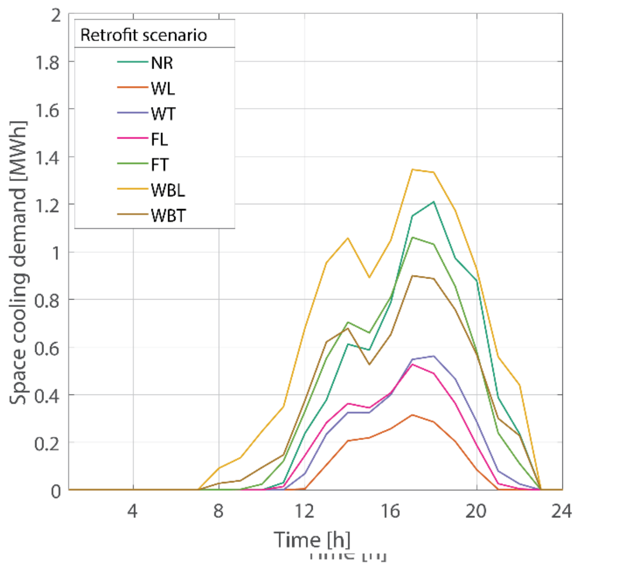


Fig: Hourly energy demand for summer day for different retrofit scenarios

Fig: Annual energy demand – Whole building retrofitting ($kWh/m^2/a$)

Incident solar irradiation modeling for building rooftops

- GIS based workflow
- Digital elevation model (DEM)
- 3D building models
- Atmospheric attenuation

- **Result**: Hourly solar irradiation on each rooftop

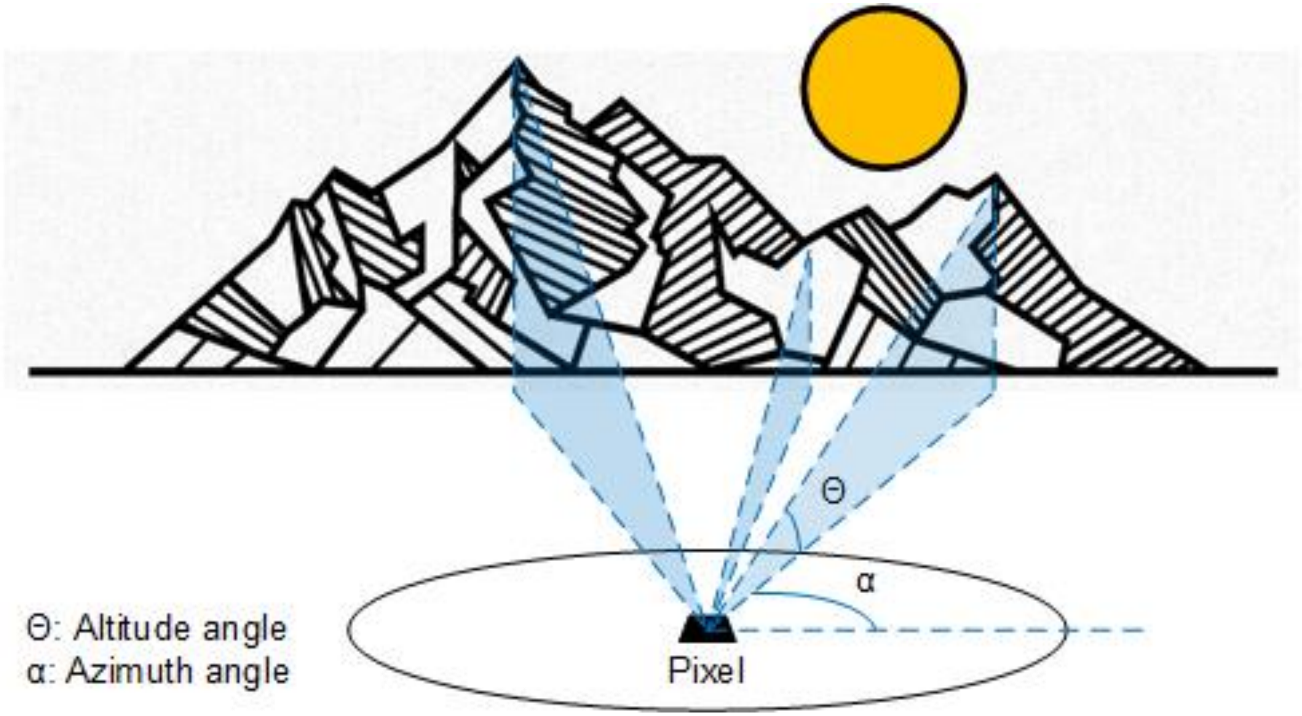


Fig: Incident solar irradiation modelling using DEMs and GIS tools

Incident solar irradiation modeling – results

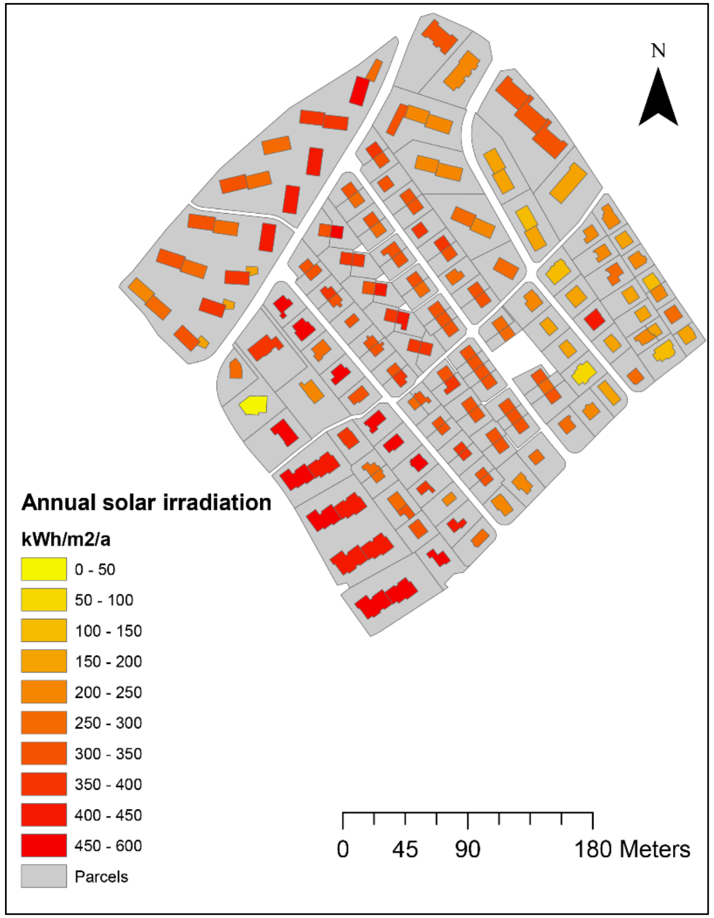
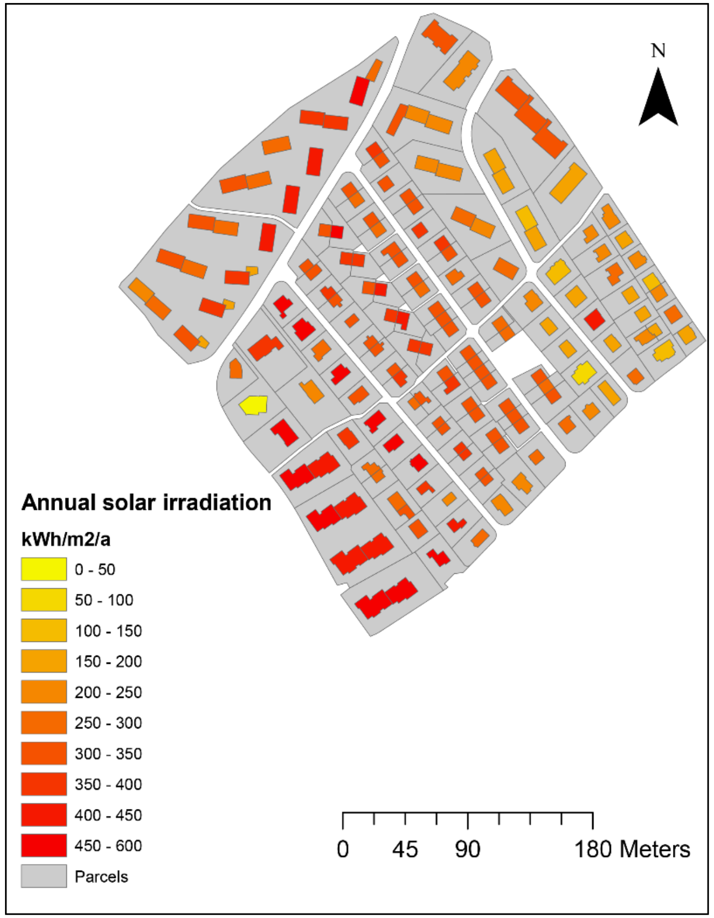


Fig: Annual solar irradiation per unit floor area (kWh/m^2/a)

Incident solar irradiation modeling – results



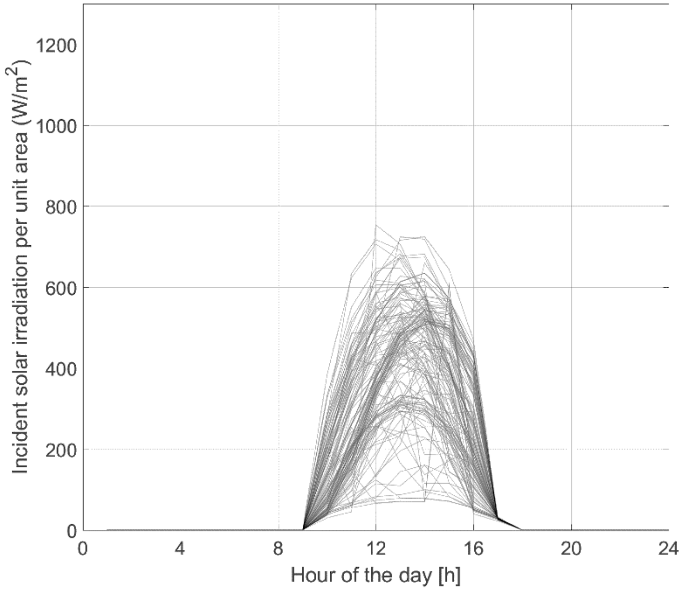


Fig: Hourly solar irradiation for a winter day

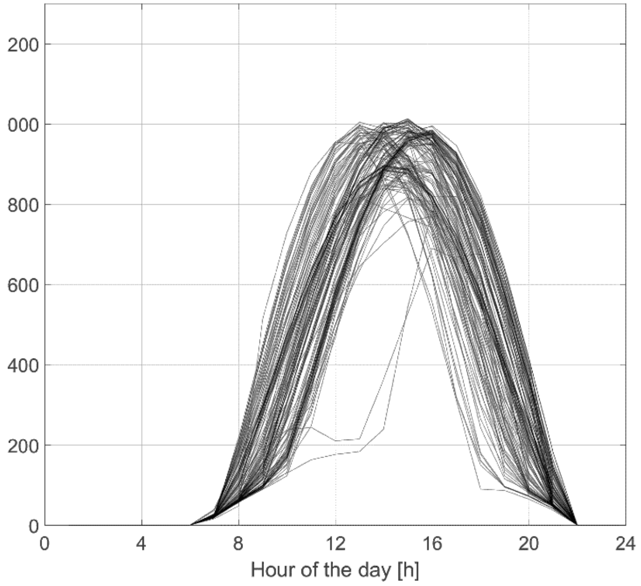


Fig: Hourly solar irradiation for a summer day

Fig: Annual solar irradiation per unit floor area (kWh/m^2/a)

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Seasonal mismatch between supply and demand

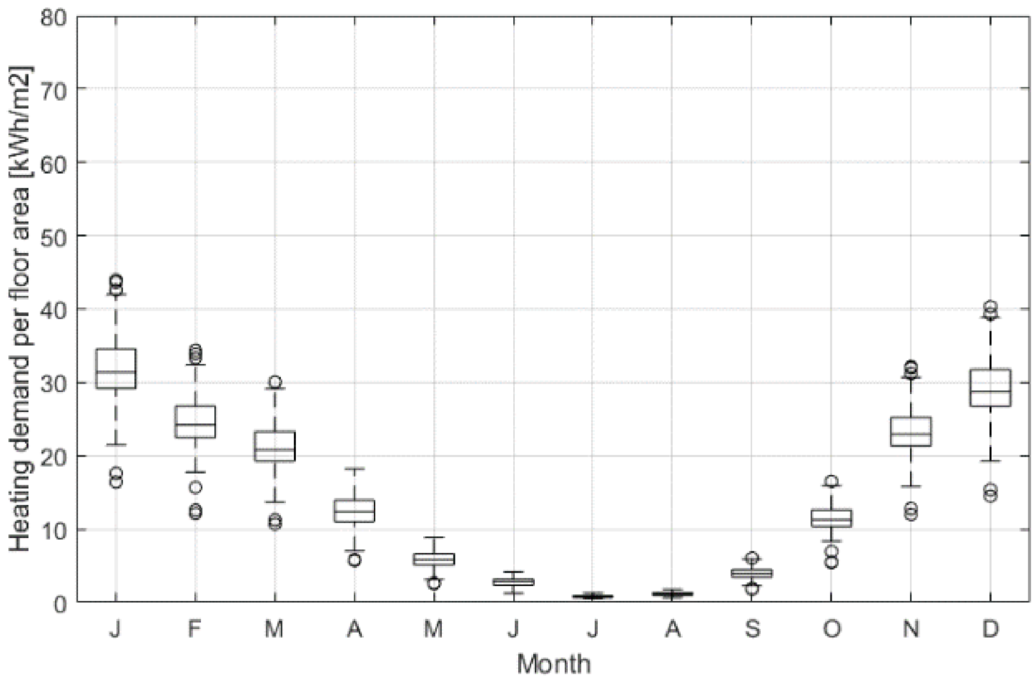

Fig: Monthly energy demand per unit floor area for all buildings (kWh/m^2)

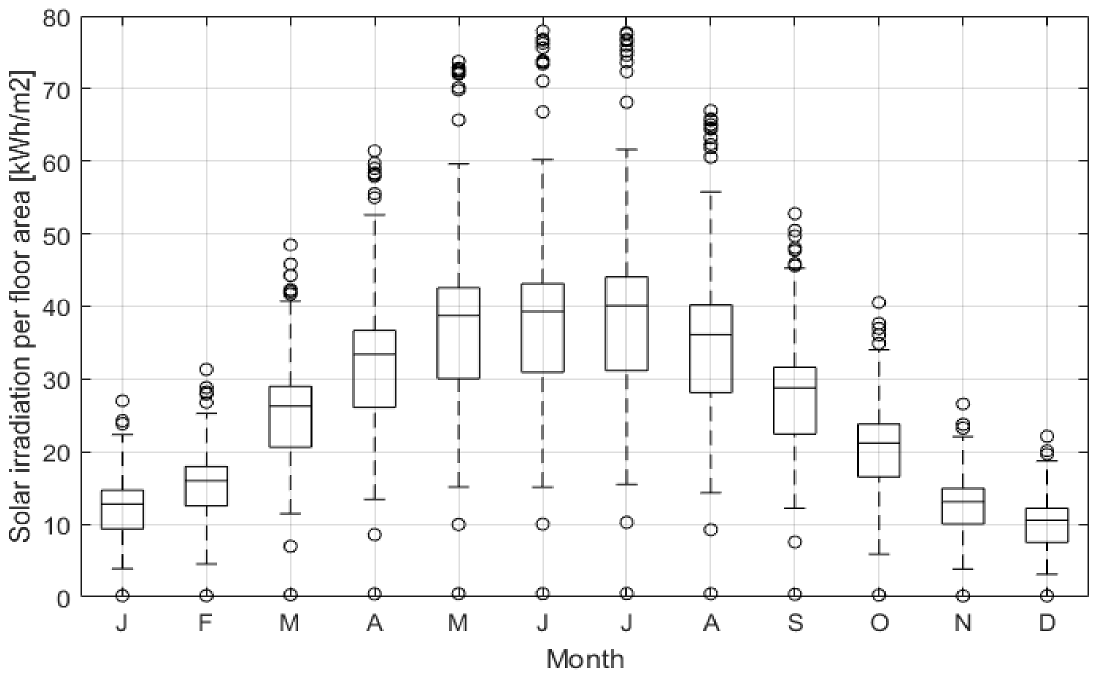

Fig: Monthly solar irradiation per unit floor area for all buildings (kWh/m^2)

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Question – How can the seasonal mismatch in demand and supply be managed?

Ground source heat pumps (GSHPs)

- Borehole heat exchanger (BHE) + heat pump
- Deep underground (~10-500m) at constant temperature all through the year
- Heat extraction + rejection
- Ground acts as heat source and long-term storage

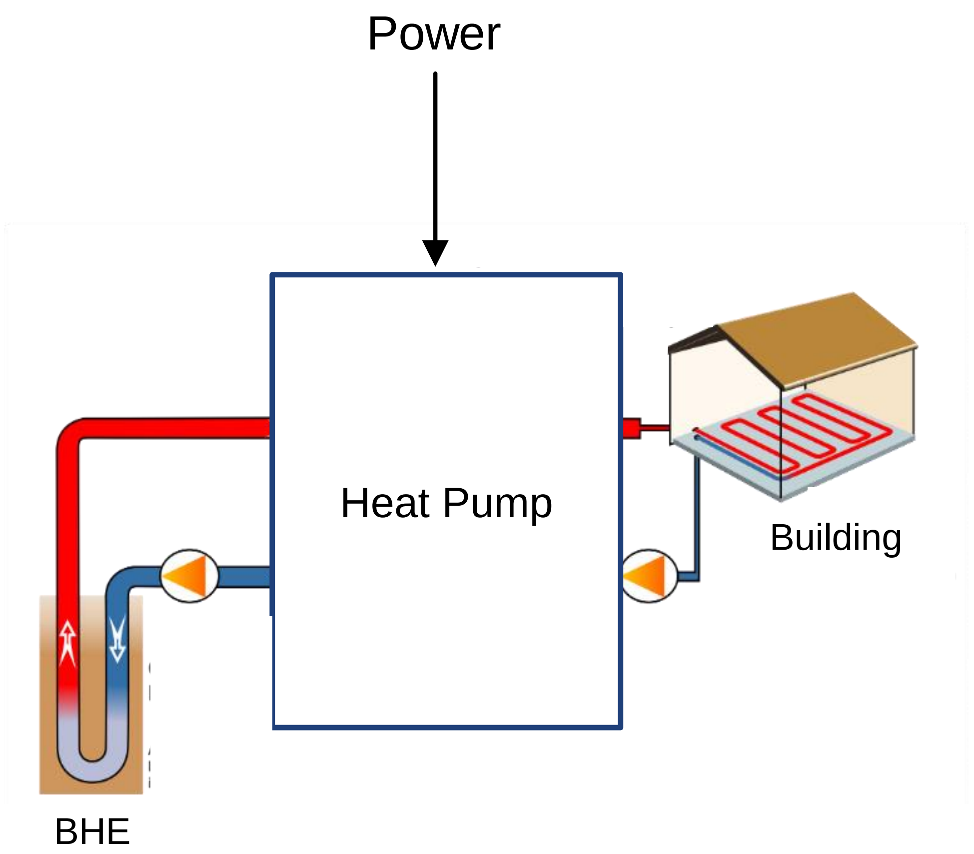


Fig: Schematic of a ground source heat pump
Figure adapted from: http://nzgeothermal.org.nz/ghanz/geothermal-heat-pumps/

Limitation to geothermal energy extraction

- Long-term heat extraction can cool down the local ground
- Heat pump efficiency drops due to lower source temperature
- Can be solved by
  - Storing excess solar energy in summer
  - Constraining heat pump operation

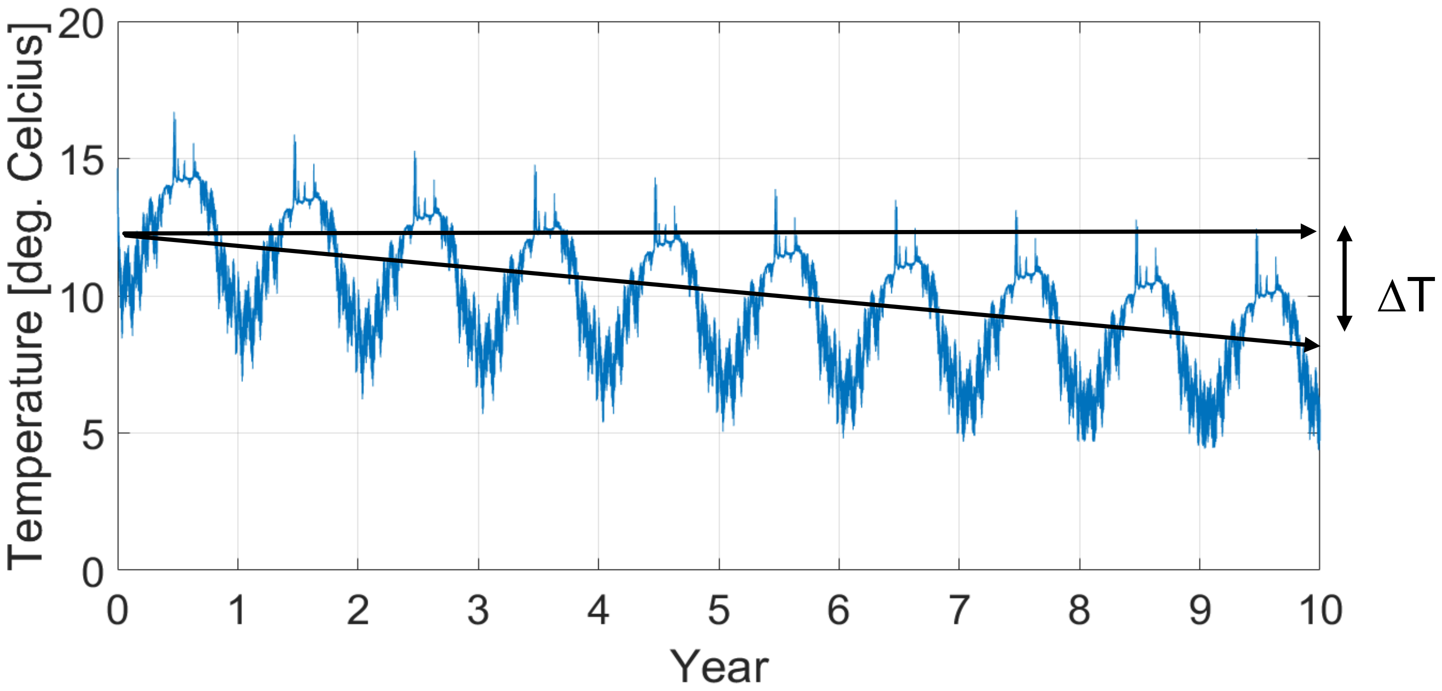
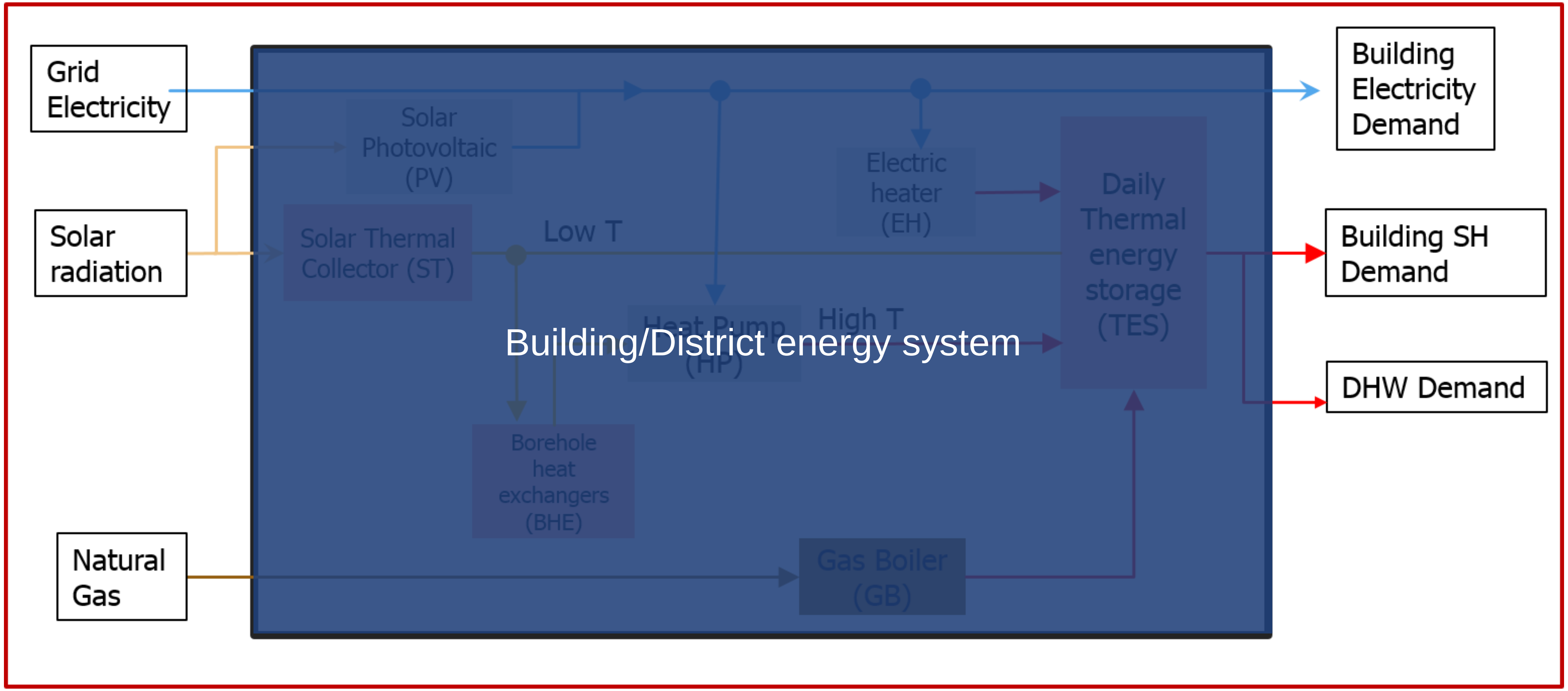
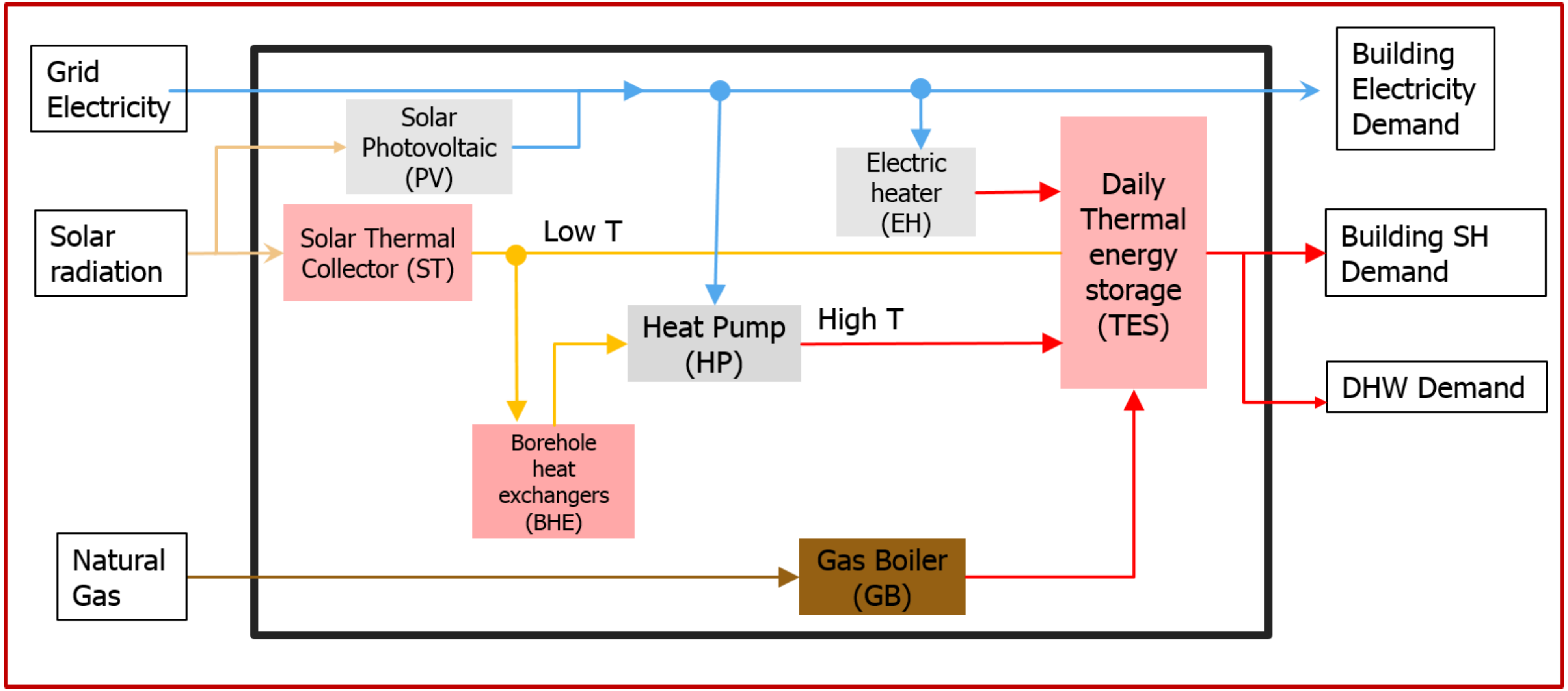


Fig: Long-term temperature variation for BHEs

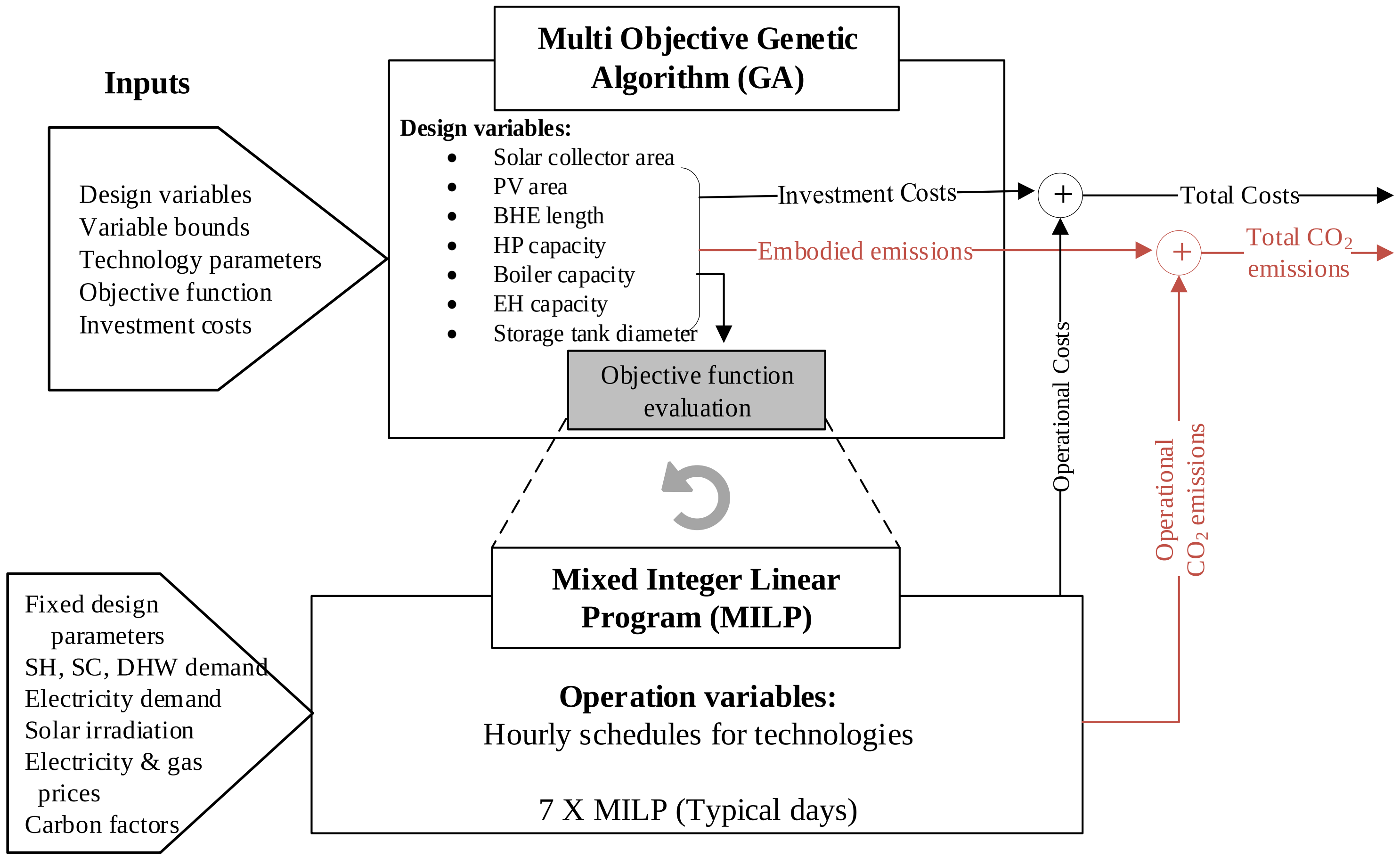
Energy system – inputs and outputs



Energy system – technologies and configuration



Building energy system optimization



Optimal energy interventions – example building

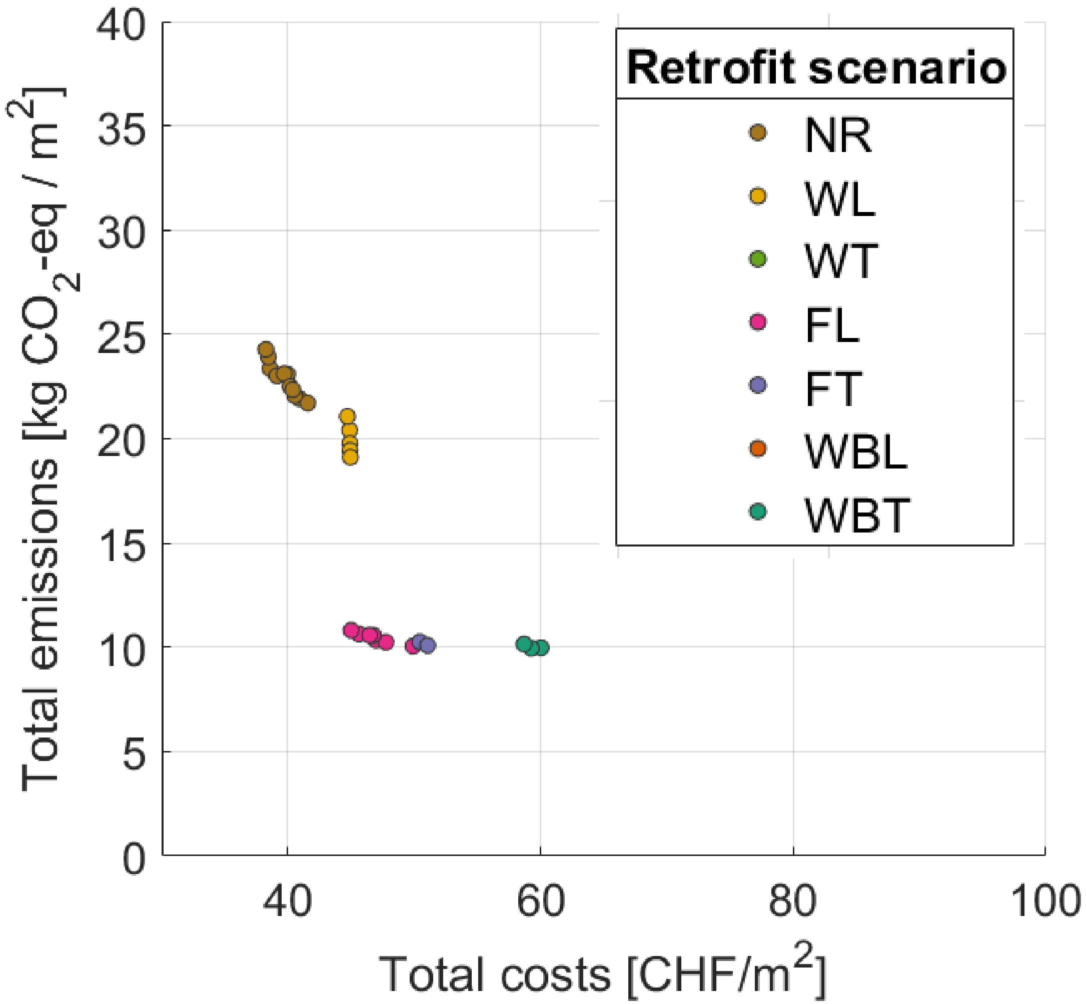


Fig: Pareto optimal energy interventions

Optimal energy interventions – details

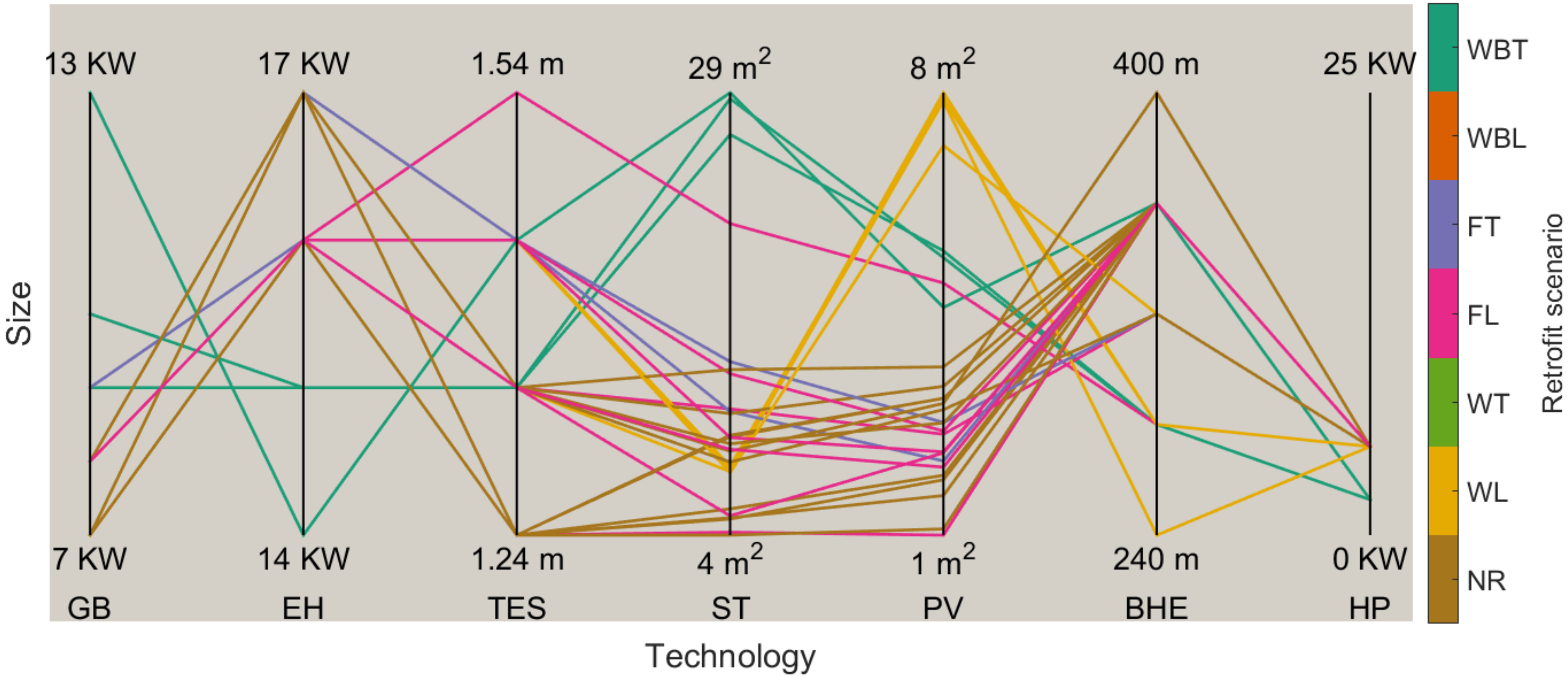
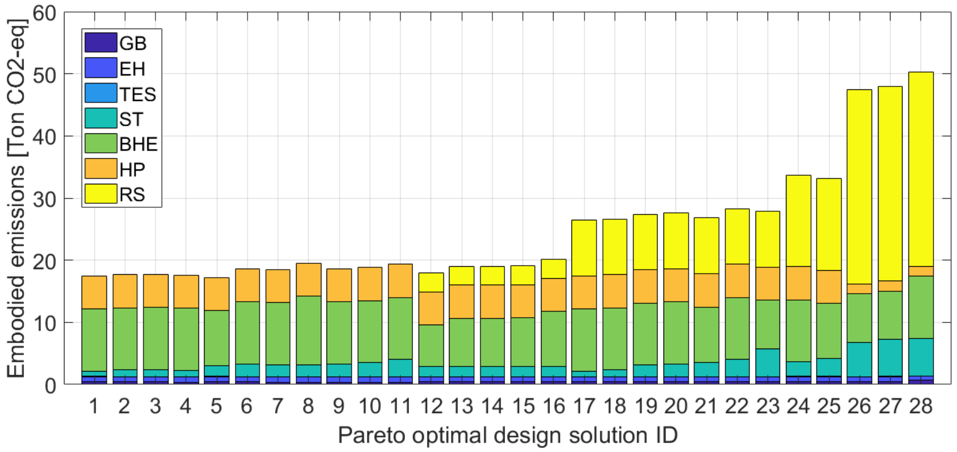


Fig: Technology sizes and building retrofitting for Pareto optimal energy interventions

Costs and CO_2 emissions

Fig: Embodied emissions



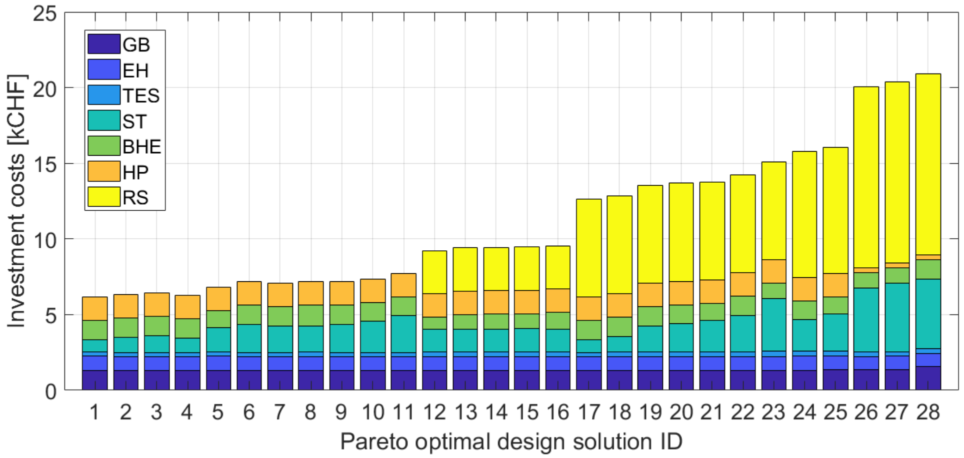
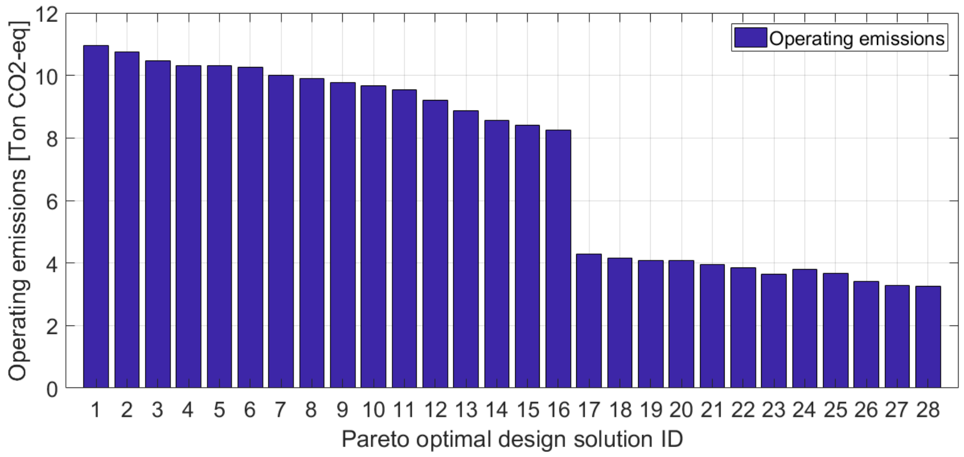


Fig: Investment costs

Fig: Operating emissions



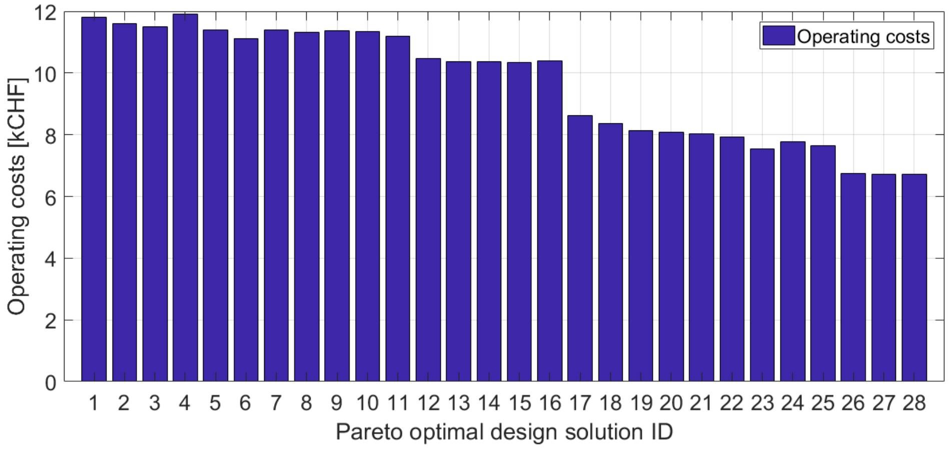
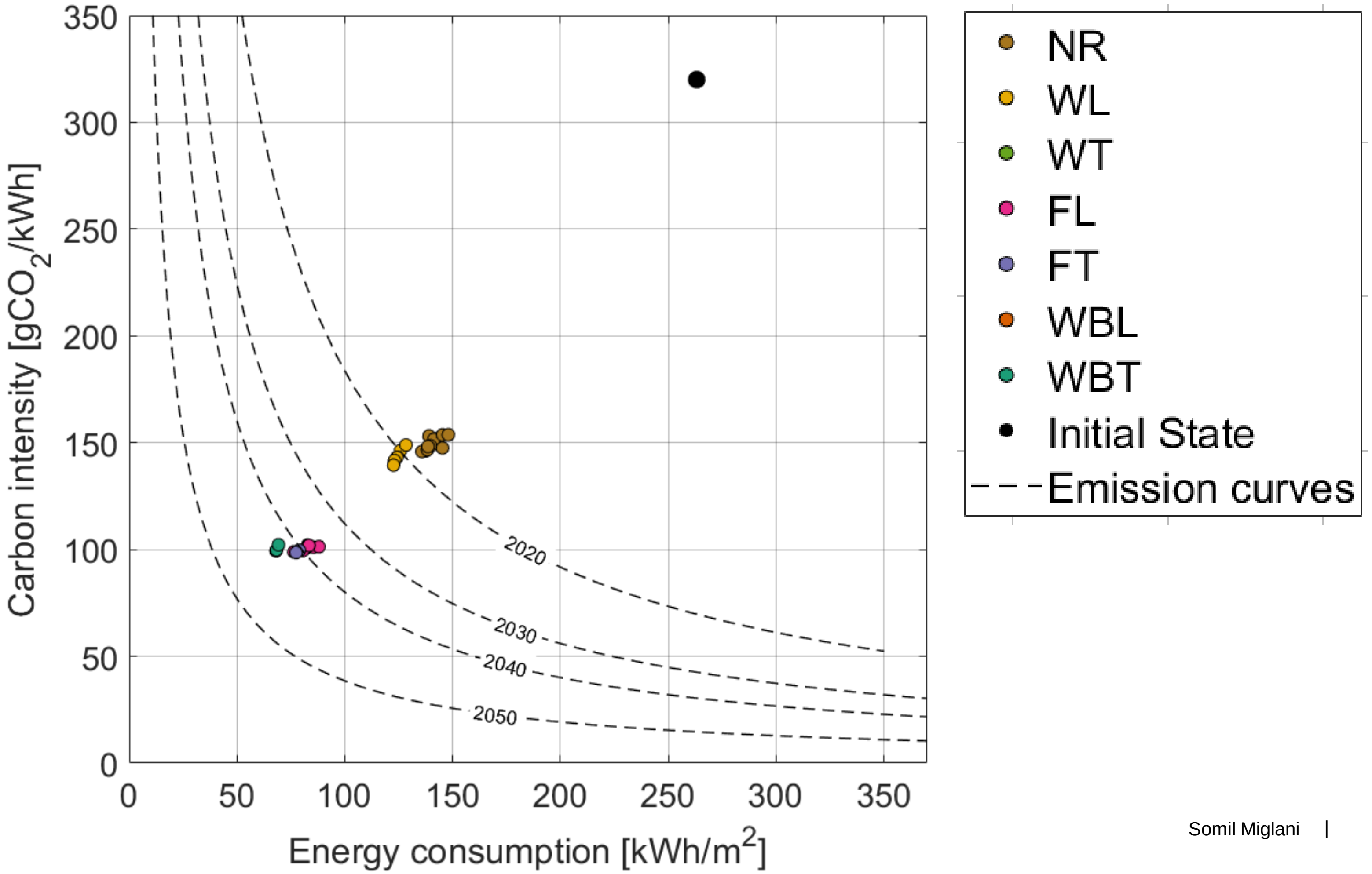


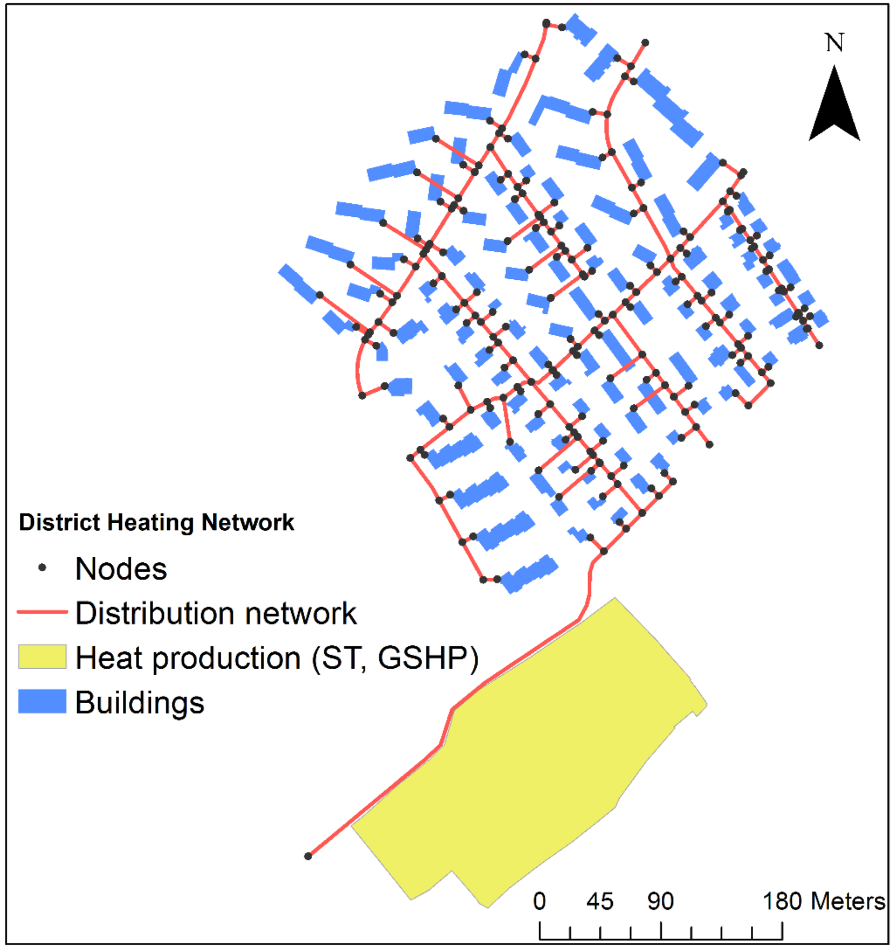
Fig: Operating costs

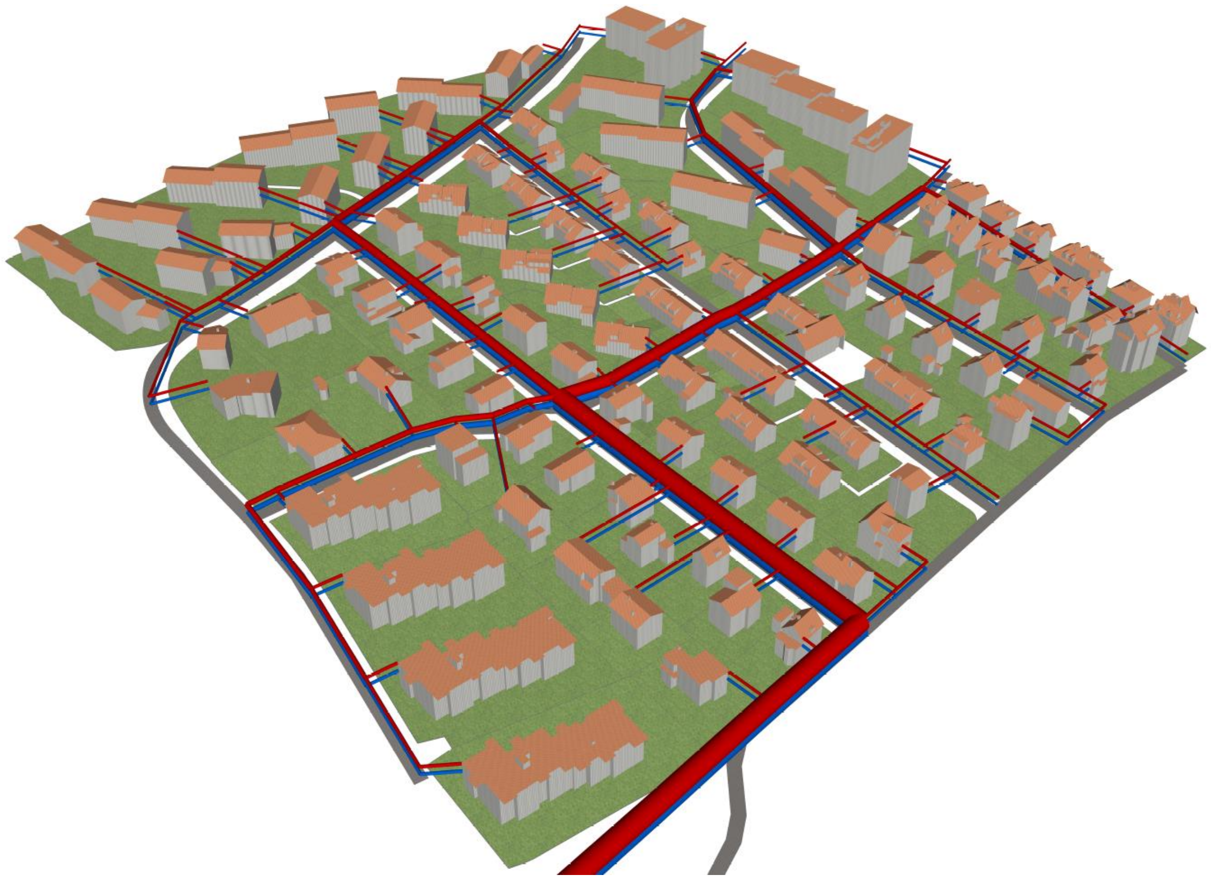
Question – Do they meet the CO_2 targets?

Performance evaluation against CO_2 targets



District energy systems – future work





Summary and conclusion

- Methods for energy system optimization for buildings using bottom-up modeling and simulation
- Seasonal storage is needed to balance mismatch in renewable energy supply and demand, GSHPs can help
- Whole building retrofitting needed in order to reach the 2040 targets
- At the current investment costs of energy interventions

Publications

- Journal publications
  - Miglani, S., Marquant, J., Orehounig, K., Carmeliet, J. (2018). Assessing the performance optimal energy interventions for buildings and districts against energy policy targets for CO2 emissions. Energy Policy. *Upcoming*.
  - Miglani, S., Orehounig, K., Carmeliet, J. (2018). Integrating a detailed thermal model of ground source heat pumps and solar regeneration within building energy system optimization. Applied energy. *In press*.
  - Miglani, S., Orehounig, K., Carmeliet, J. (2018). A methodology to calculate long-term shallow geothermal energy potential for an urban neighborhood. *Energy and Buildings*, 159, 462 –473.
  - Miglani, S., Orehounig, K., & Carmeliet, J. (2017). Design and optimization of a hybrid solar ground source heat pump with seasonal regeneration. In *Energy Procedia* (Vol. 122, pp. 1015–1020).

- Conference publications
  - Miglani, S., Orehounig, K., & Carmeliet, J. (2017). A methodology for the optimal operation of a residential building's heating system with focus on thermal modelling of GSHPs. *Proceedings of ECOS 2017 - The 30th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems, San Diego, California, USA, (July)*
  - Miglani, S. A., Orehounig, K., & Carmeliet, J. (2016). Assessment of the ground source heat potential at building level applied to an urban case study. *Status-Seminar «Forschen Für Den Bau Im Kontext von Energie Und Umwelt» Assessment*, (September), 1–13.
  - Miglani, S. A., Orehounig, K., & Carmeliet, J. (2015). A method for generating hourly solar radiation profiles on building rooftops accounting for cloud cover variability. *Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale Future Buildings and Districts Sustainability from Nano to Urban Scale*, 717–722.

Acknowledgements

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Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

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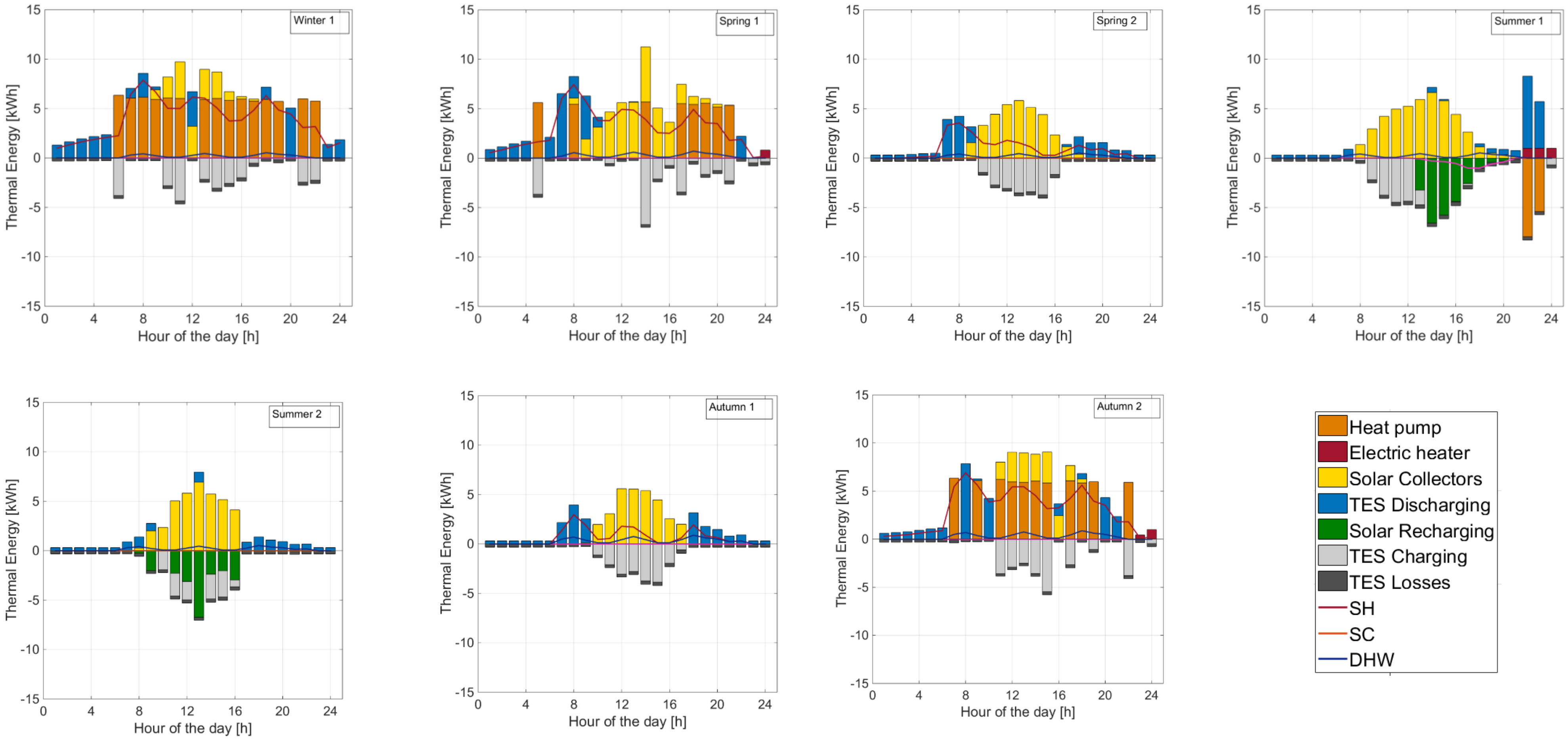
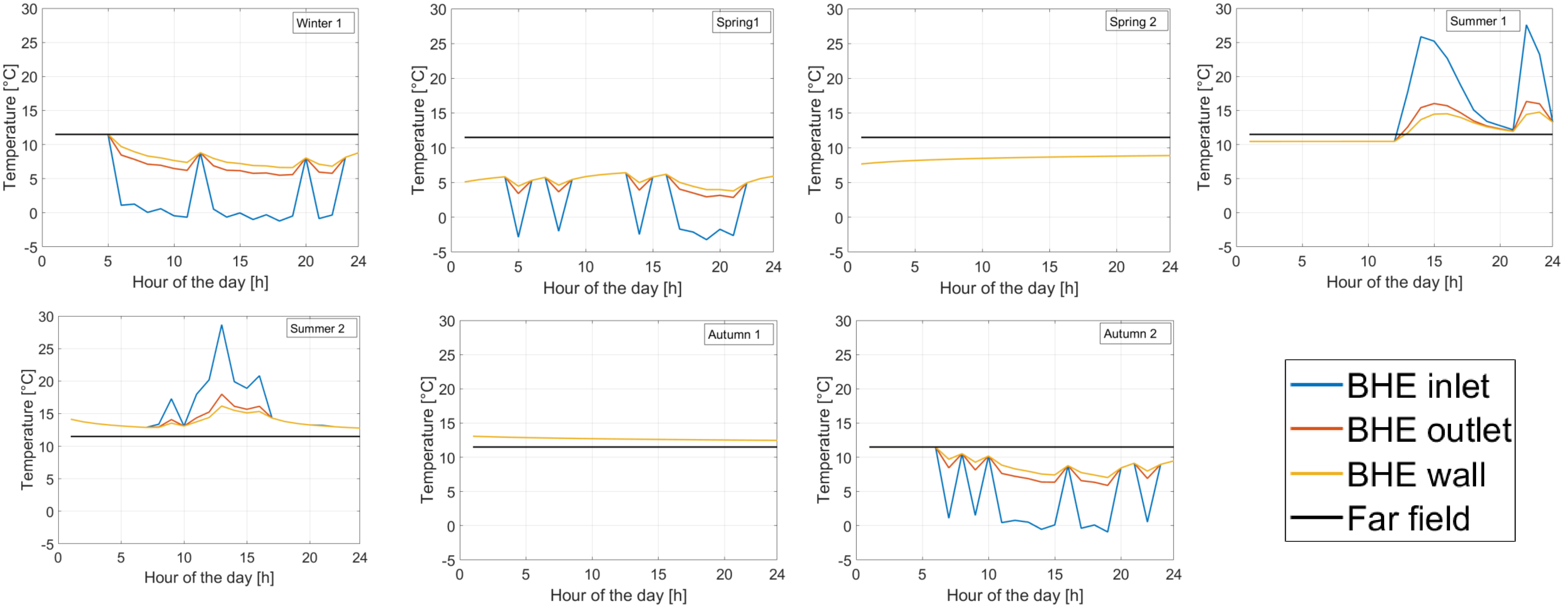
Contact: miglanis@ethz.ch

Thank you for your attention

Optimal system operation (Heating)



Borehole heat exchanger (BHE) operation



Long-term operation of the BHE