Modelling and design of smart resilient net-zero solar buildings and communities

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Chair, Canadian Academy of Engineering (CAE) Roadmap to Resilient Ultra-low Energy Built Environment with Deep Integration of Renewables

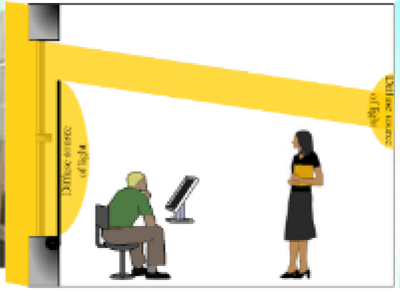
Université Concordia University

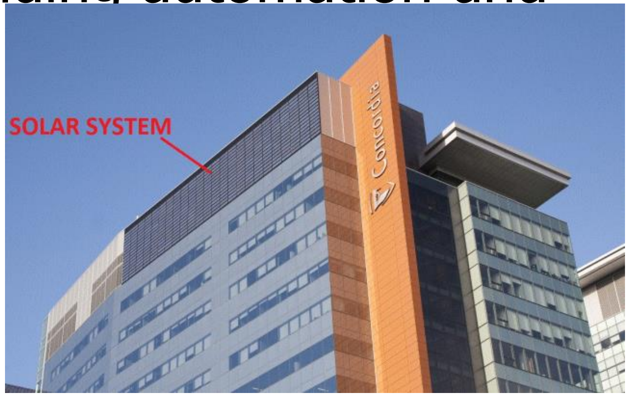
Centre for Zero Energy Building Studies
Centre d'études sur le bâtiment à consommation nulle d'énergie

Major international trends in high performance buildings

- Adoption of net-zero energy (ASHRAE) as a long term goal; nearly zero or net-zero ready in some cases until 2030. **Carbon-neutrality by 2050 is another common goal**.
- Measures to reduce/shift peak electricity demand from buildings, thus reducing the need to build new power plants; optimize interaction with smart grids; resilience to climate change**; integration of EVs; energy flexibility** in buildings;
- Steps to efficiently integrate new energy technologies such as building-integrated photovoltaics, thermal and electrical storage;
- Increased use of IoT technologies; massive amounts of data – use of artificial intelligence (AI) techniques to integrate and efficiently use building automation and information systems.





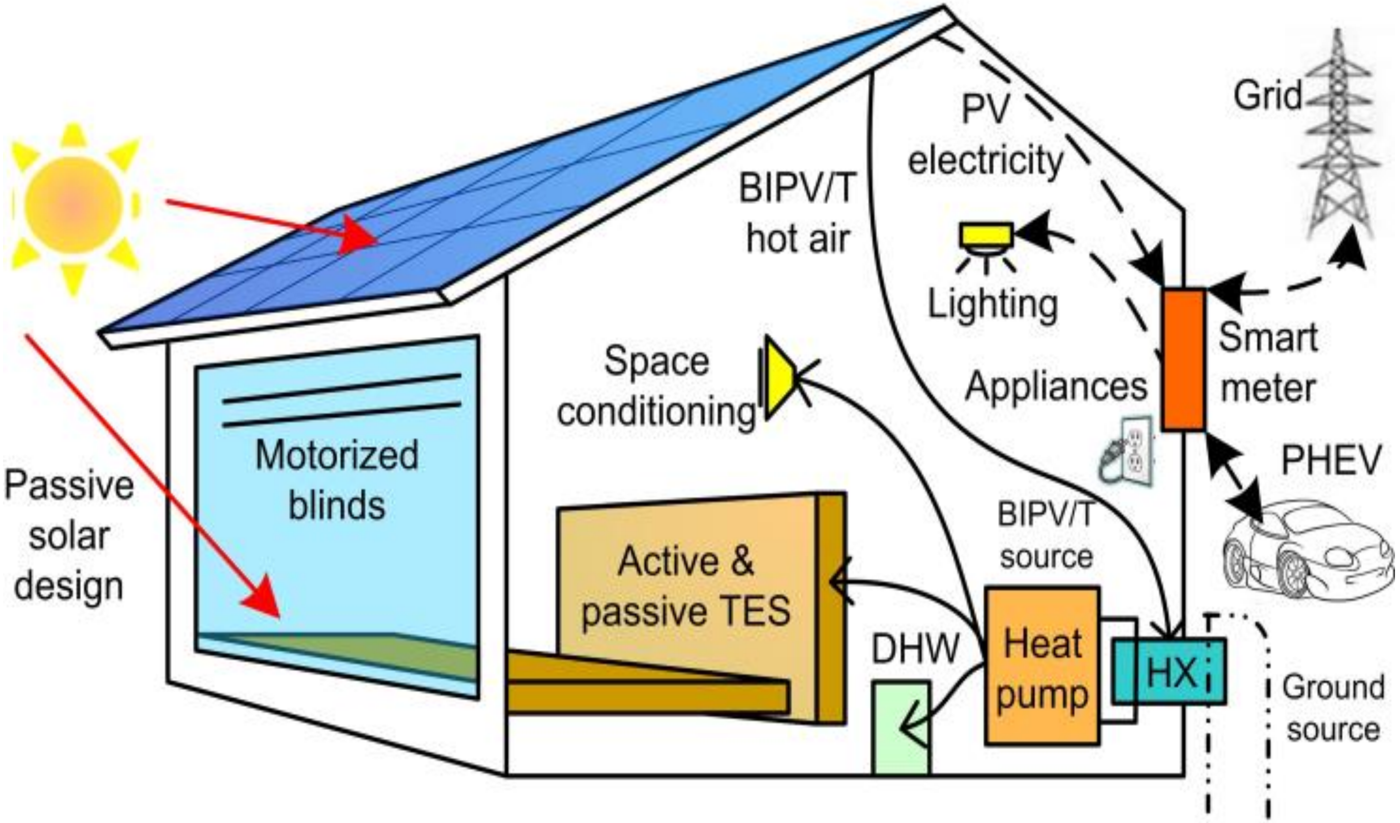



NREL RSF Bottom-up shades **STPV** EcoTerra **BIPV/T** **Concordia JMSB**

Smart Solar Building concept – towards resilience/net zero

Optimal combination of solar and energy efficiency technologies and techniques provides **different pathways to high performance and an annual net-zero energy balance**

Solar energy: electricity + daylight + heat



Integrated approach to **energy efficiency and passive design**

Integrated design & operation

Solar optimization: requires **optimal design of building form**

Key design variables: **geometry – solar potential, thermal insulation, windows, BIPV, energy storage**

Prominent projects – solar and net-zero buildings

Near net-zero house

Ecoterra house (Chen et al., 2010)

- 2-story residential building
- Roof BIPV/T:
  - *DHW heating*
  - *Space heating*
  - *Clothes dryer*
  - *2007 - 2011*

University building

JMSB (Athienitis et al., 2010)

- High-rise institutional building
- UTC – PV/T hybrid
- Façade BIPV/T
  - *Fresh air pre-heating heating*
  - *2009*

Municipal Library

BIPV/T roof on Varennes library

- 2-story institutional building
- Roof BIPV/T
  - *Fresh air pre-heating heating*
  - *2011, 2016, ongoing*

Team Montreal

DPD (Rounis et al., 2018)

- 2-story residential building
- *Row house typology*
- Roof BIPV/T
  - *Air/water Heat Pump*
  - *Storage tank*
  - ***Solar Decathlon China 2018***

Varennes Library – Canada’s first institutional solar NZEB

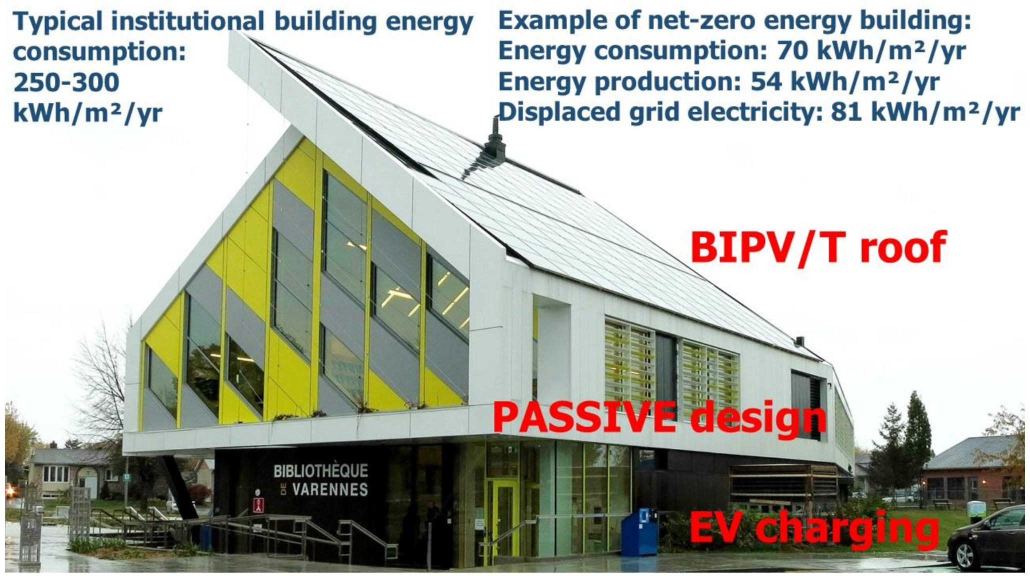
Officially opened May 2016

- 110 kW BIPV system (part BIPV/T)
- Geothermal system (30 ton)
- Radiant floor slab heating/cooling
- EV car charging
- Building received major awards (e.g. **Canadian Consulting Engineering Award of excellence**)

Market is ready for such projects provided standardized BIPV products are developed
Now modelling and optimizing operation and grid interaction under a NSERC Hydro Quebec Chair

We guided the energy design of the building

Case Study: Varennes Library (archetype NZEB - small institutional)



- The first institutional solar net-zero energy building (NZEB) in Canada.
- Market is ready for such projects -- provided standardized BIPV products are developed
- Now modelling, optimizing operation and grid interaction under a NSERC-HQ Chair

Our team provided advice: **choice and integration of technologies and early stage building form**
Design required several iterations - e.g. **final choice of BIPV system required minor changes in roof** design for full coverage.
Roof slope close to 40 degrees to reduce snow accumulation.

Design and rendering

Varennes Library Inauguration (May 2016): C. Kapsis, A. Athienitis, M. Damphousse (mayor), V. Dermardiros, R. Dumoulin

Typical institutional building energy consumption:
250-300 kWh/m²/yr

Example of net-zero energy building:
Energy consumption: 70 kWh/m²/yr
Energy production: 54 kWh/m²/yr
Displaced grid electricity: 81 kWh/m²/yr

Overview of energy flows in a NZEB like Varennes Library

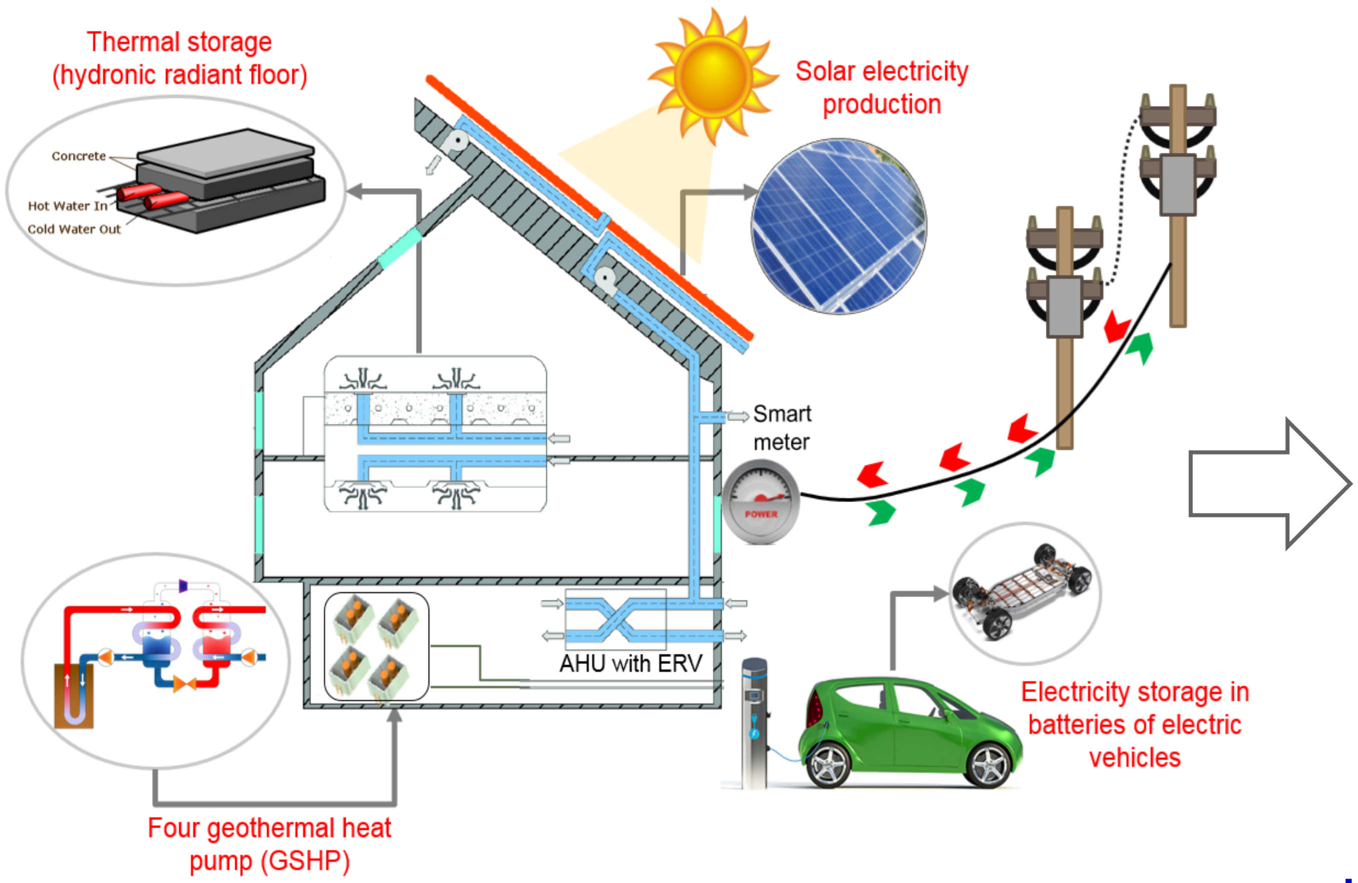
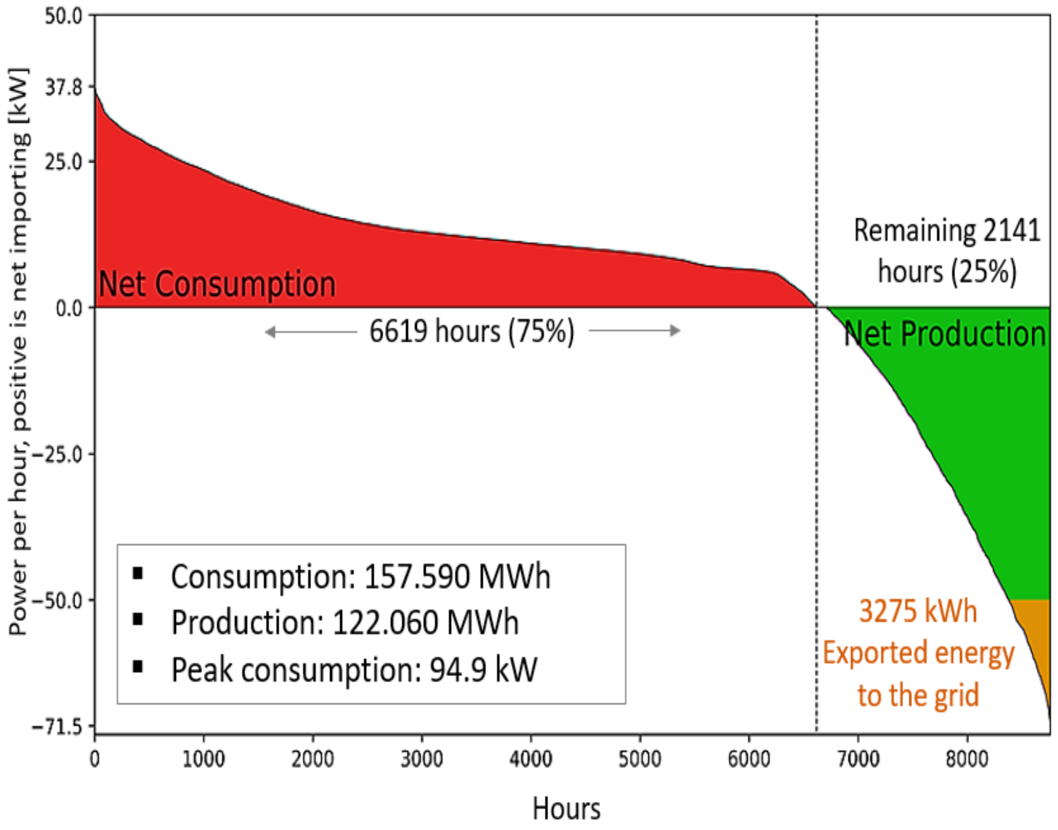


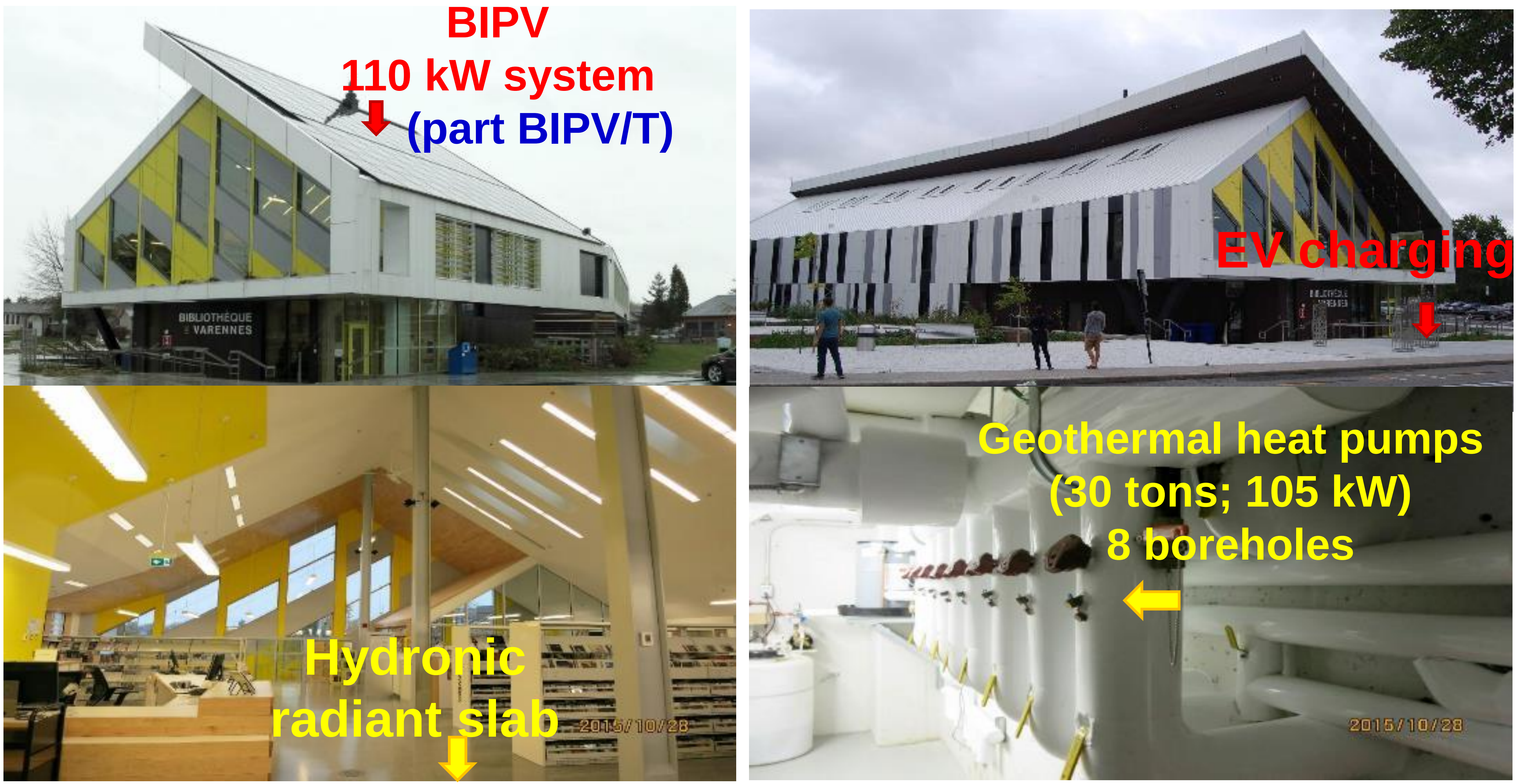
Illustration of different energy technologies that can be used to enhance flexibility in the operation of the Varennes library



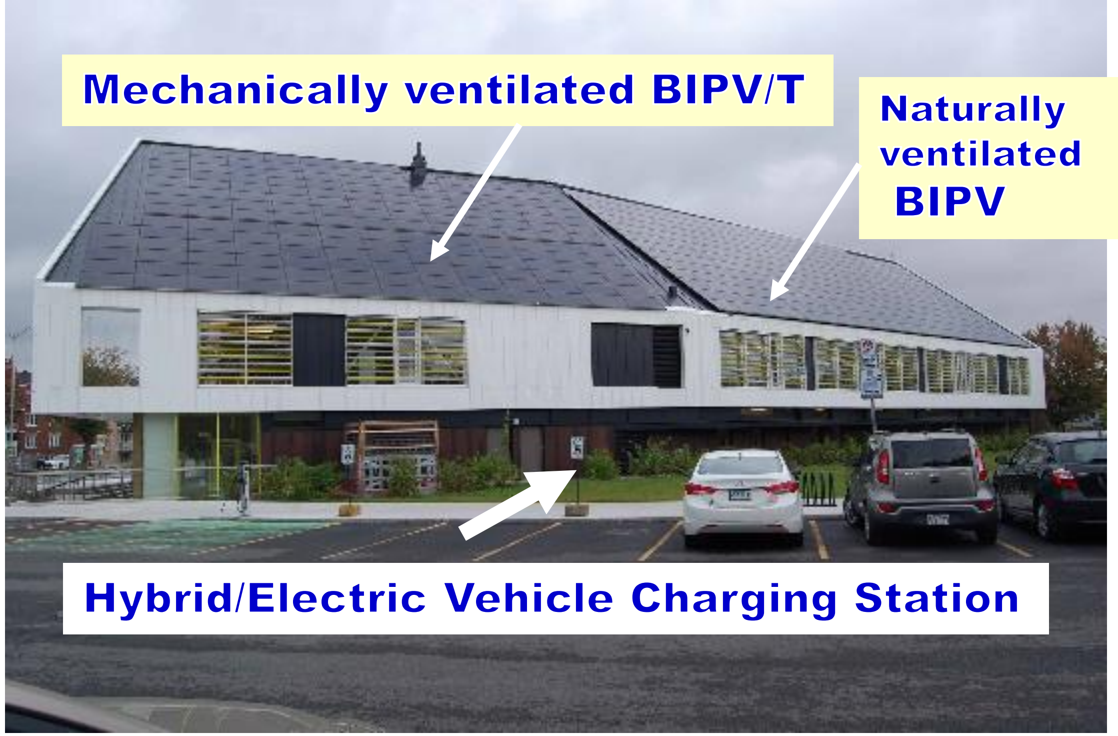
Load duration curve: [top] net consumption, [middle] net production and [Bottom] the energy exported free to grid

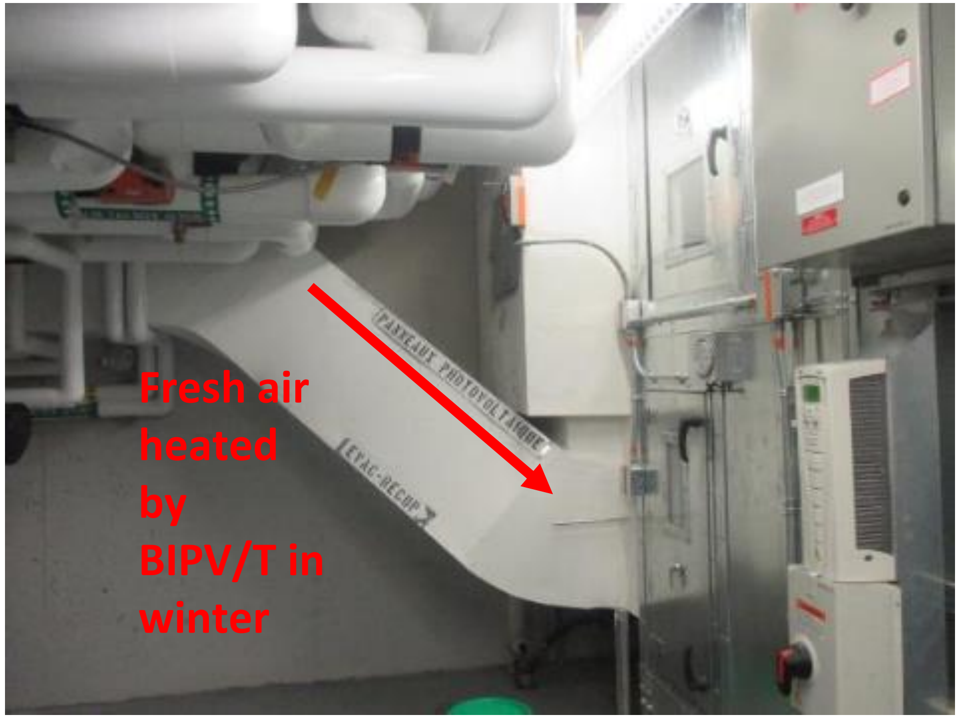
Note: grid will buy up to a max. of 50 kW from building

Varennes Library – key features



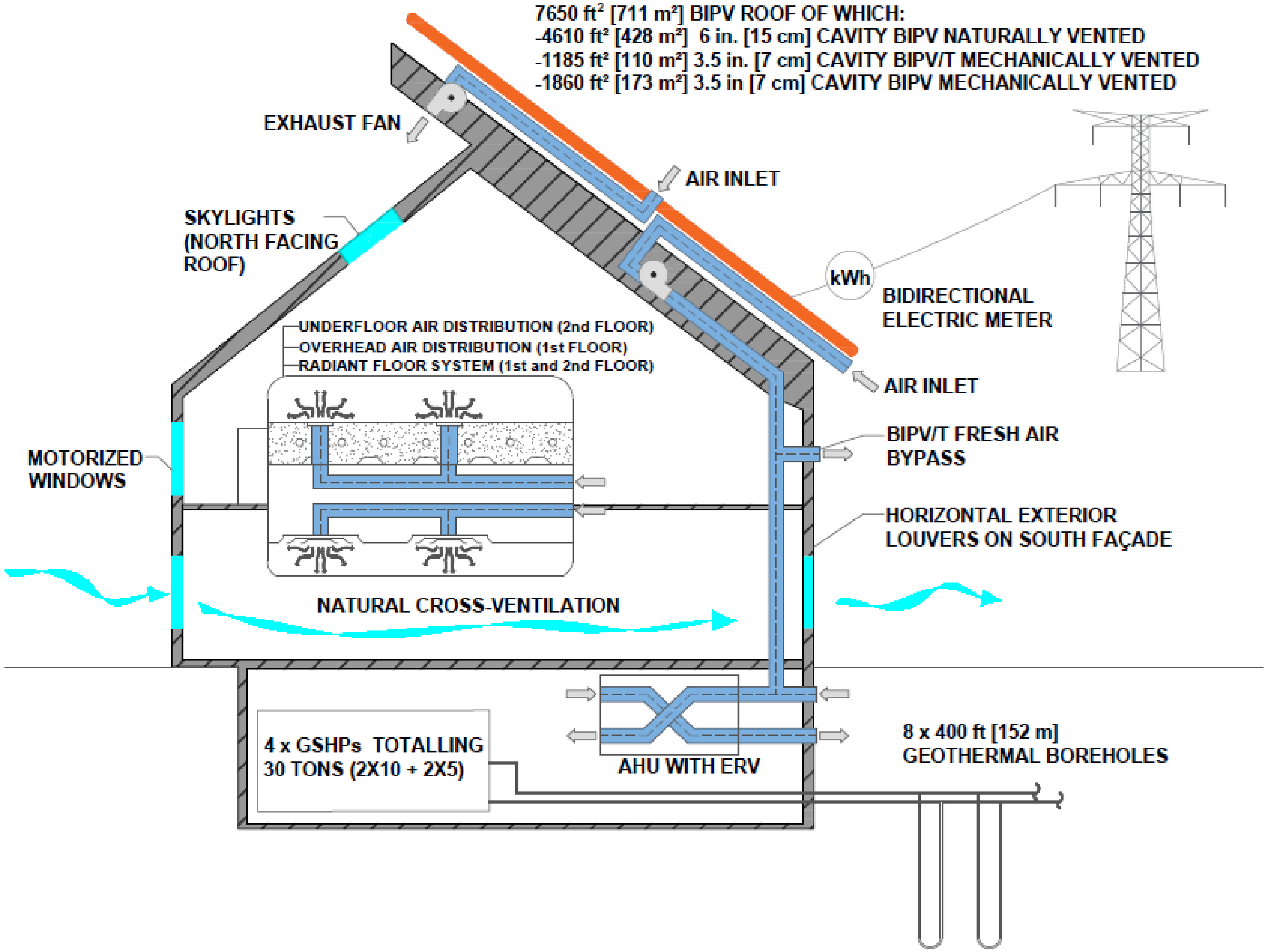
Reaches net zero   (primary energy factor for hydro about 1.4), consumption 60-70 kWh/m2/year



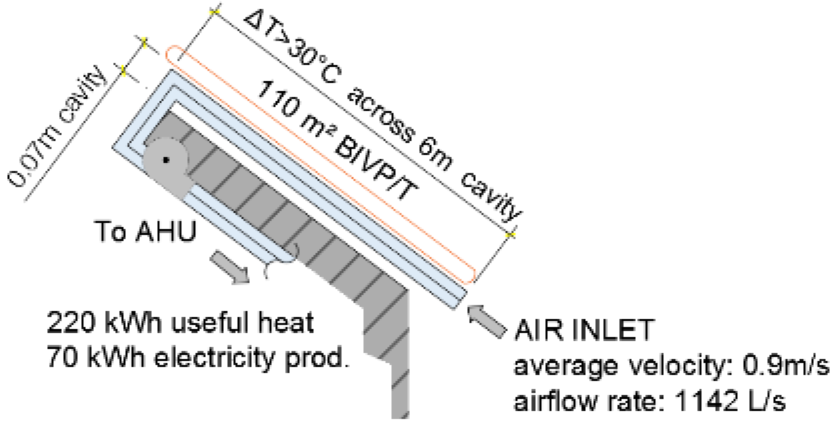


110 kWe BIPV (part BIPV/T)
Heat recovered on part of the array to supplement fresh air heating
38° slope, oriented South to South-East

LIBRARY SYSTEMS: HEAT PUMP, THERMAL STORAGE, BIPV/T, EV

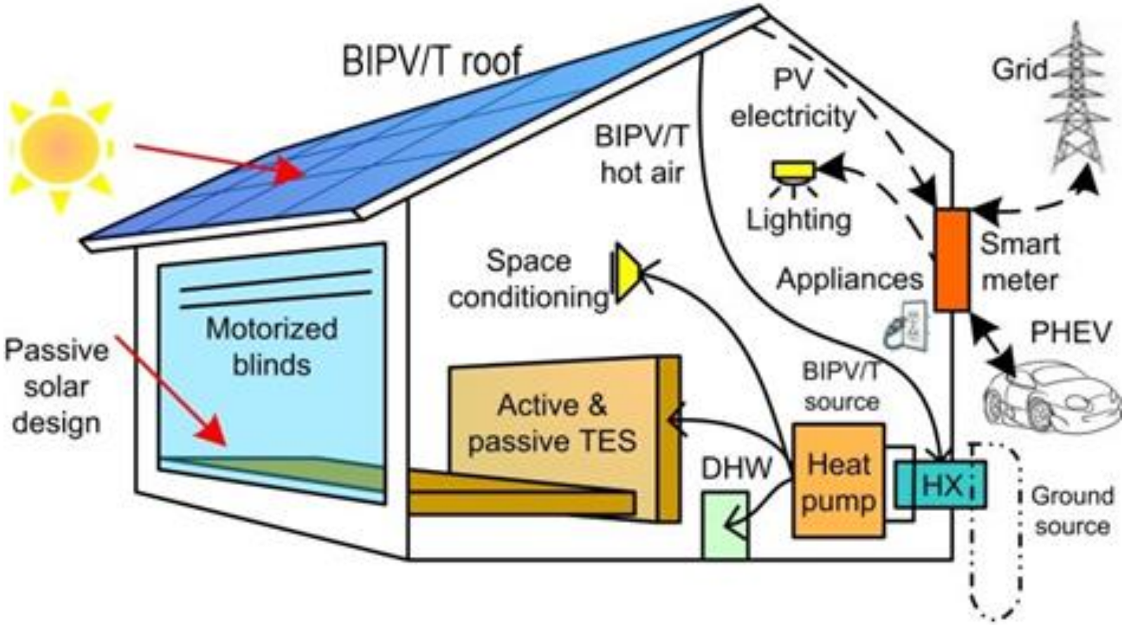


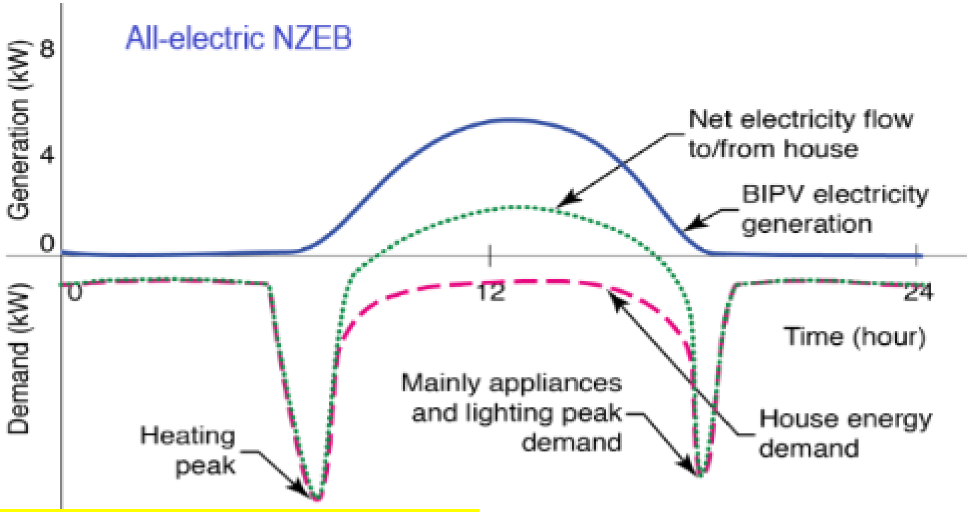
- Custom BIPV/T, one inlet
- Fan activated for outlet air temperature >25°C
- Rated electrical efficiency: 15.9% STC
- Combined efficiency up to ~60% (thermal + electrical)



Energy flexibility modelling based on measured data

Integrated smart solar building concept and grid integration – need for energy flexibility





Varennes Library, Canada's first net-zero energy Institutional building designed with our guidance (2016).

Currently studying/optimizing its grid interaction under NSERC/Hydro Quebec Industrial Research Chair

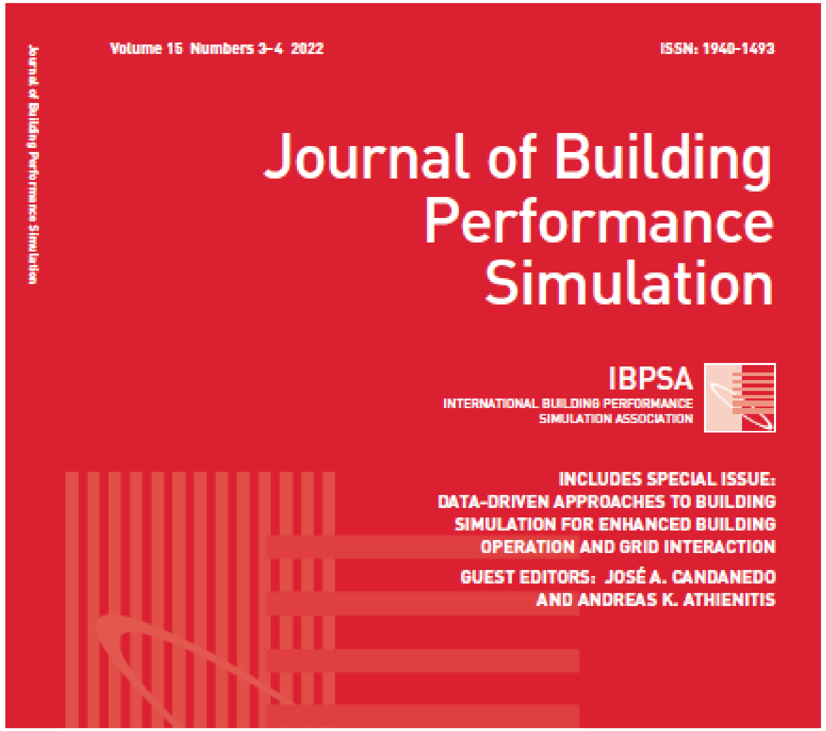
Energy flexibility needs to be quantified relative to a reference demand profile

Development of BEFI and Archetype RC Models

- Development of a Building Energy Flexibility Index (BEFI) and methodology applied to different types of buildings and time periods;
- Demonstrated through a series of papers that grey box reduced order models (ROMs) RC network models can be used to model archetype building zones and energy storage/HVAC archetype systems for MPC and BEFI prediction. Developed a paper on ROMs, Special Issue of JBPS Journal;
- The ROMs are to be automatically developed - data driven and to be calibrated in real time using reinforcement learning. The methodology for automated RC model generation has been applied to houses monitored by Hydro-Quebec;
- Demonstrated and quantified the important flexibility potential of buildings with a combination of storage and renewable energy systems such as the Varennes Library. Test with MPC and actual flexibility started.

JBPS special issue: Data-driven approaches to building simulation for enhanced building operation and grid interaction

Guest Editors: José A. Candanedo and Andreas K. Athienitis



Editorial

Leveraging data: a new frontier in building modelling and advanced control
José A. Candanedo and Andreas K. Athienitis

Articles

Control-oriented archetypes: a pathway for the systematic application of advanced controls in buildings
José A. Candanedo, Charalampos Vallianos, Benoit Delcroix, Jennifer Date, Ali Saberi Derakhtenjani, Navid Morovat, Camille John and Andreas K. Athienitis

Evaluation of data-driven thermal models for multi-hour predictions using residential smart thermostat data
Brent Huchuk, Scott Sanner and William O'Brien

Comparison of data-driven statistical techniques for cooling demand modelling of electric chiller plants in commercial districts
Mohammad Hassan Fathollahzadeh and Paulo Cesar Tabares-Velasco

Evaluating the suitability of regression-based emulators of building performance in practice: a test suite
Parag Rastogi, Mohammad Emtiyaz Khan and Marilyne Andersen

Estimating the value of jointly optimized electric power generation and end use: a study of ISO-scale load shaping applied to the residential building stock
Robert Cruickshank, Gregor Henze, Anthony Florita, Charles Corbin and Killian Stone

Control-oriented thermal network models for predictive load management in Canadian houses with on-Site solar electricity generation: application to a research house
Matin Abtahi, Andreas Athienitis and Benoit Delcroix

Developing machine-learning meta-models for high-rise residential district cooling in hot and humid climate
B. Jia, D. Hou, A. Kamal, I. G. Hassan and L. Wang

Building Energy Flexibility Index (BEFI)

A methodology for the definition and calculation of a dynamic as a state variable was developed.

The dynamic energy flexibility is defined as the capability for a building to:

(a) reduce its electricity demand during a critical period for the grid; and

(b) reduce or increase its electricity consumption anytime when needed for the grid.

BEFI in zone level:

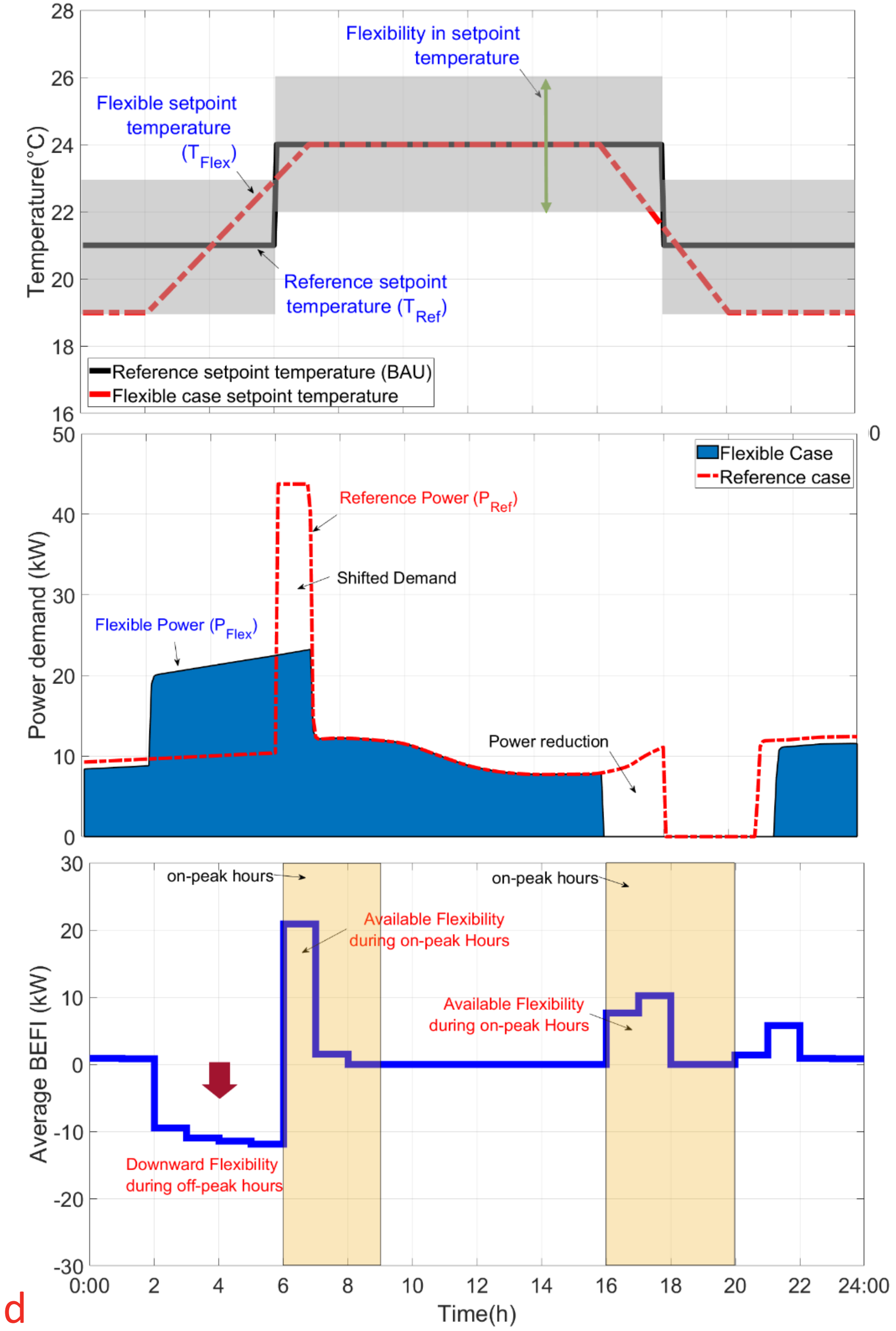
$$\overline{BEFI}(\mathrm{t},\mathrm{Dt}) = \frac{\int_t^{t+Dt} P_{\mathrm{Ref}} dt - \int_t^{t+Dt} P_{\mathrm{Flex}} dt}{Dt}$$

BEFI as percentage:

$$BEFI\% = \frac{\bar{P}_{\mathrm{Ref}} - \bar{P}_{\mathrm{Flex}}}{\bar{P}_{\mathrm{Ref}}} \times 100$$

BEFI in Building level:

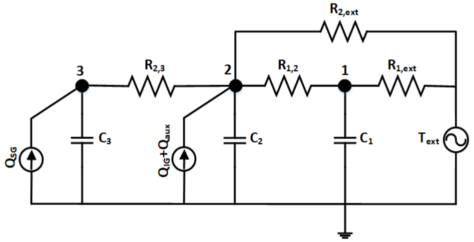
$$\overline{BEFI}_{\mathrm{Building}} = \sum_{1}^{n} BEFI_{\mathrm{Zone}}$$



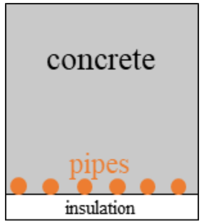
Reduce electricity consumption during peak (high price) periods or sell to grid

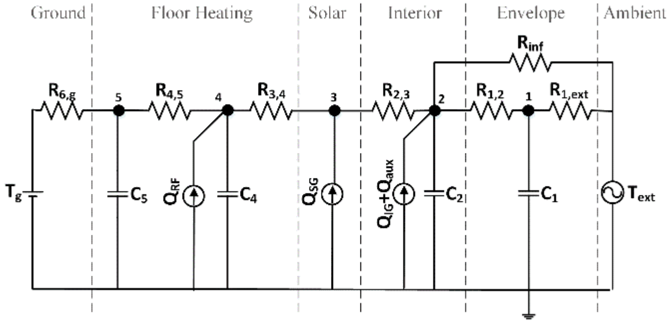
Archetype zones and archetype buildings – RC models and BEFI

Classroom heated with convective (forced air) systems – **3rd order RC model** and zone BEFI (school case study)



Thermal zone that includes radiant floor heating – 3rd – 4th order RC model and zone BEFI (school, Varennes Library)

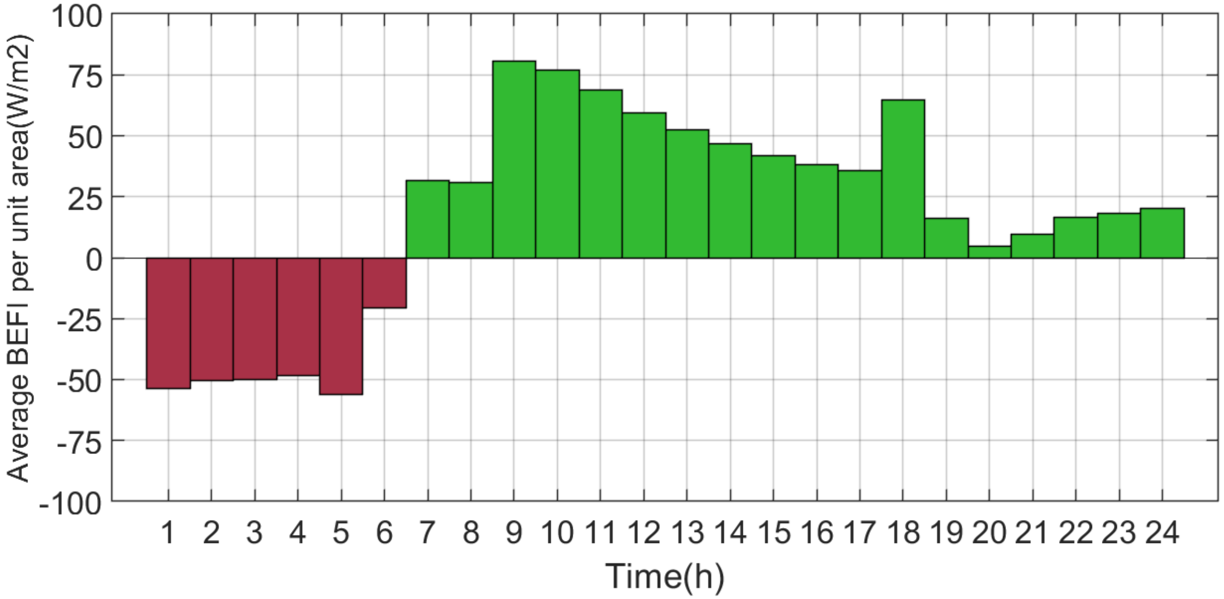




3rd order RC model archetype for 2-storey houses (baseboard convective heating); data driven models can be up to the number of controlled heat sources

System BEFI from building zones or group of buildings calculated from subsystem BEFIs; applied to school case study

Horizon du Lac School - Building level Flexibility – BEFI system preliminary results



The uncertainty of BEFI is determined by the **uncertainties** in both **model formulation** and **weather forecast**.

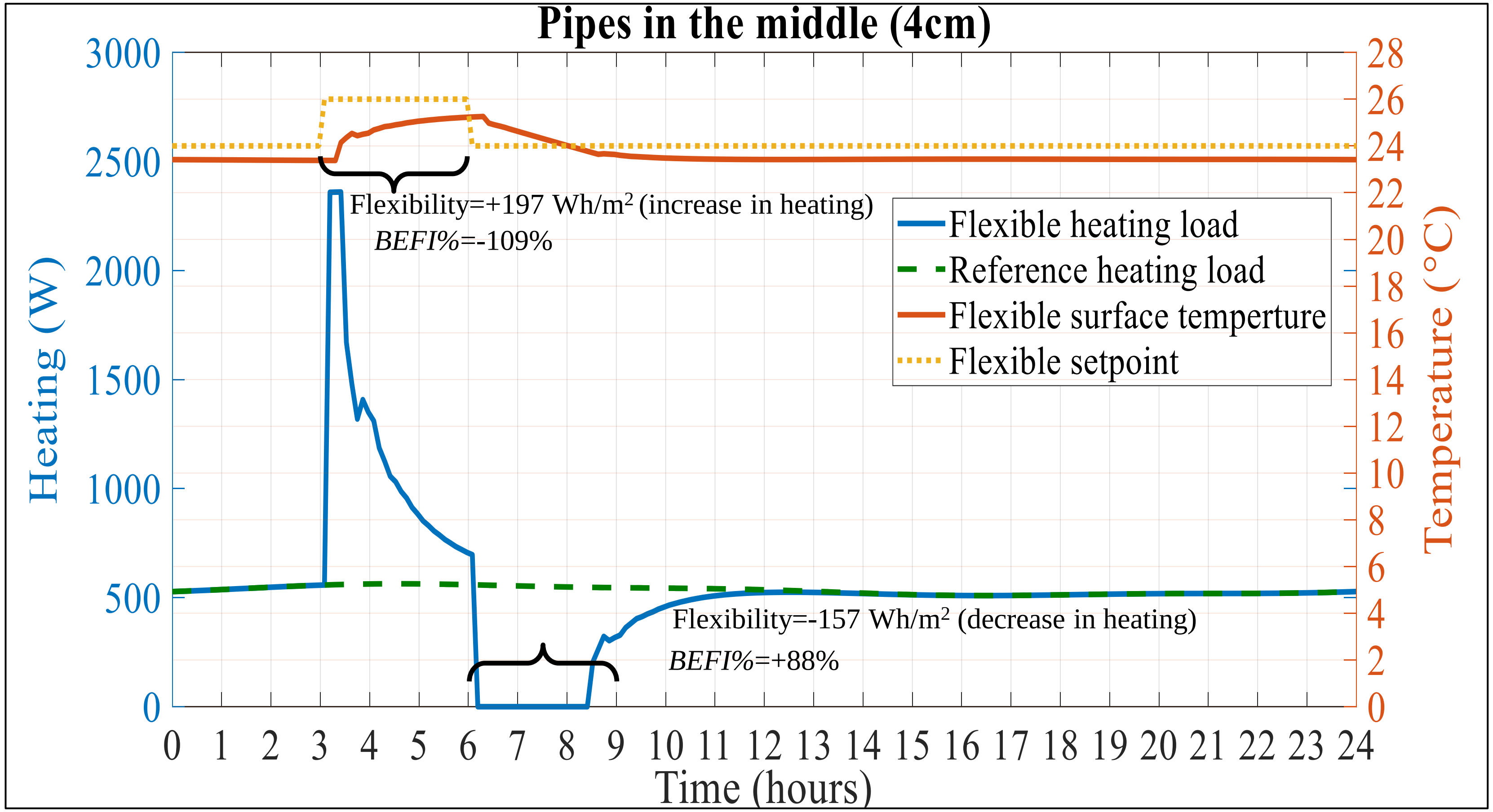
Uncertainty in modeling: ±15% for parameter identification

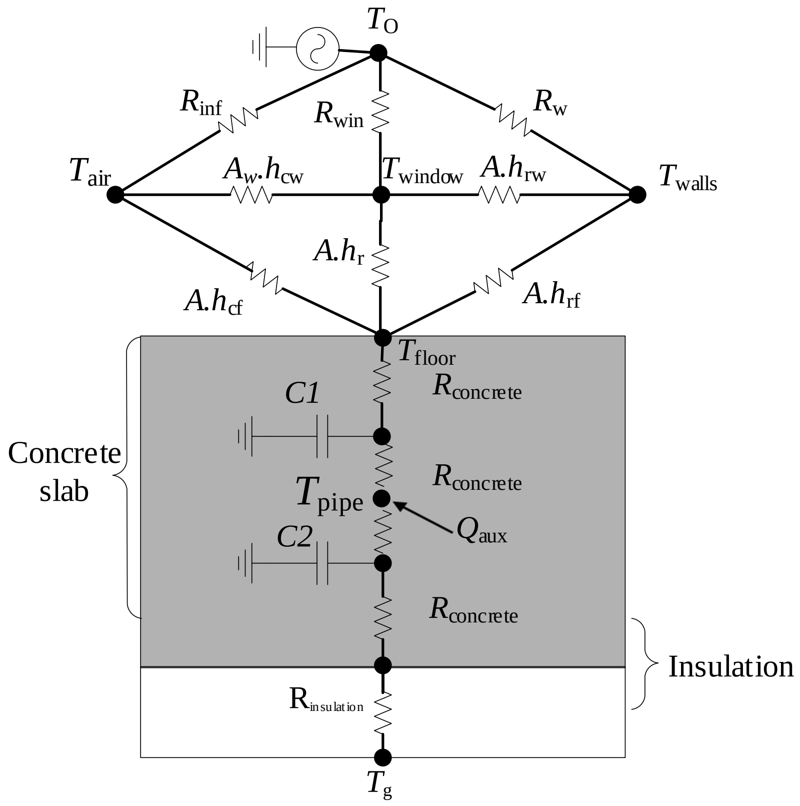
Uncertainty in weather forecast: ± 3% for one to three hours prediction

- The school has **potential flexibility of between 50 to 80 kW,** which represents between **40% to 65% building level energy flexibility.**
- Considering that there are more than 2,600 schools in Québec, there is potential flexibility of about **208 MW peak load reduction in the morning, and 130 MW in the afternoon when needed by the grid**.

Navid Morovat

Radiant heat source at the middle of the slab and flexibility



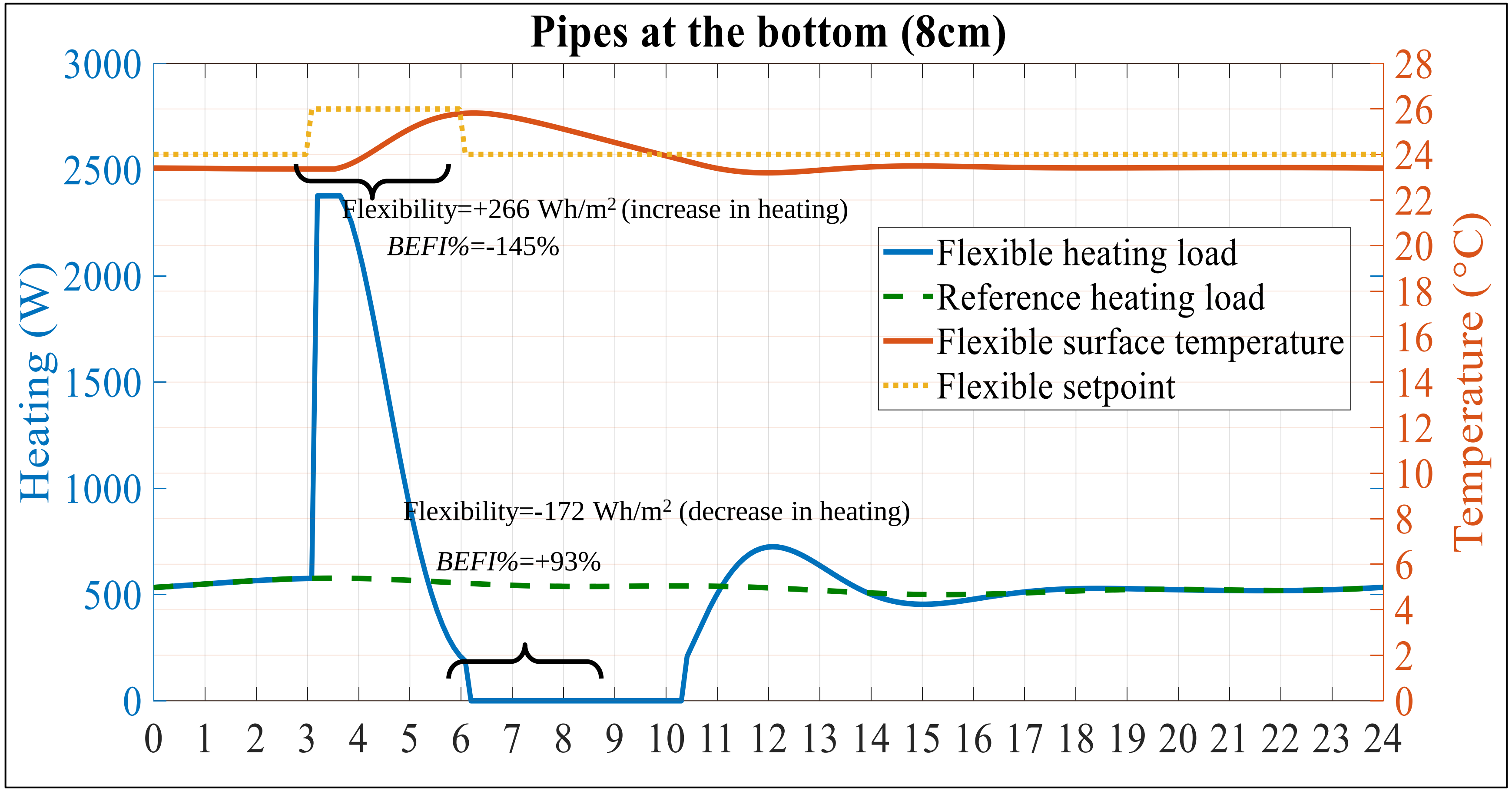


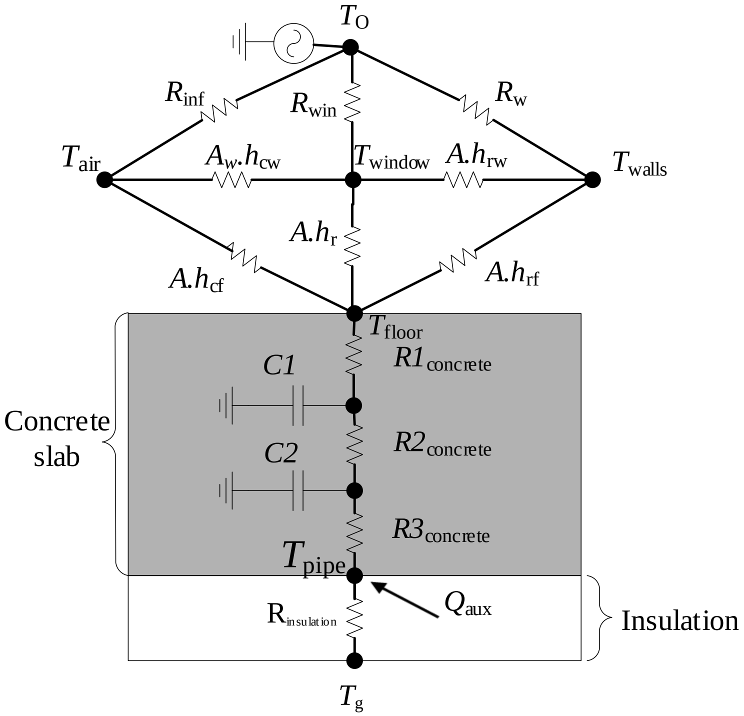
$$BEFI\% = \frac{\bar{P}_{Ref} - \bar{P}_{Flex}}{\bar{P}_{Ref}} \times 100$$

BEFI 88%

Power shifting period ≈ 2.5 hours (6am to 8.5am)

Radiant heat source at the bottom of slab and flexibility



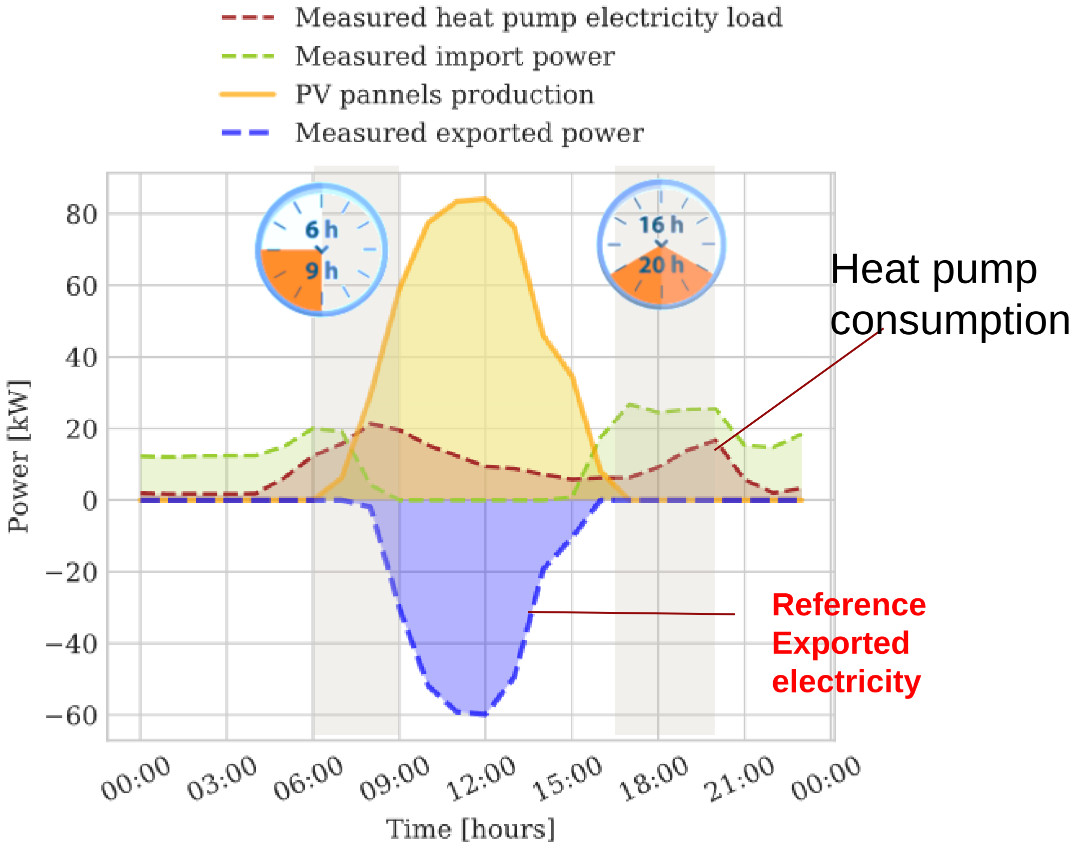


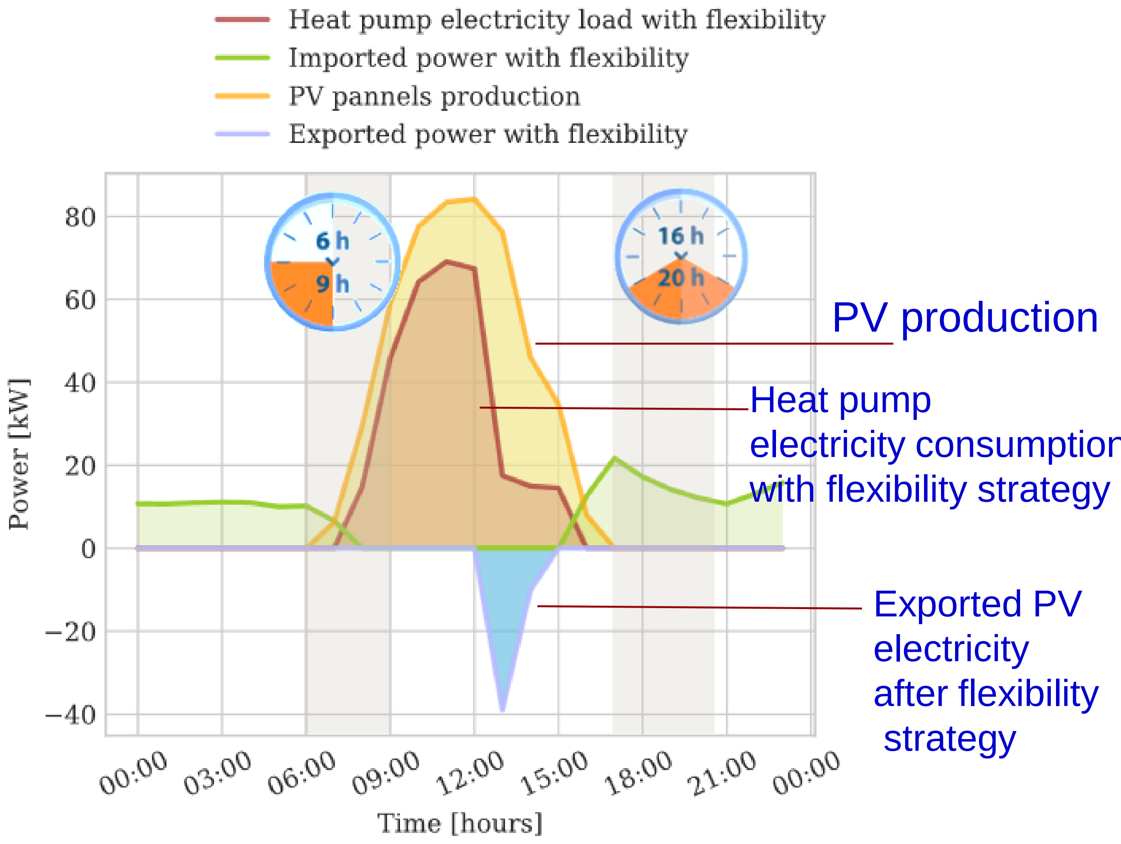
Case study applications
School
Varennes Library

$$BEFI\% = \frac{\bar{P}_{Ref} - \bar{P}_{Flex}}{\bar{P}_{Ref}} \times 100$$

BEFI 93%
Power shifting period ≈ 4.3 hours (6am to 10.3am)

VARENNES LIBRARY ENERGY FLEXIBILITY MODELLING WITH MEASURED DATA





Measured data as a reference scenario
sunny cold day on February 2, 2018

Energy flexibility quantification and use:
sunny cold day on February 2, 2018

To reduce consumption during peak periods of the grid and **increase self consumption** of PV electricity (outside peak periods)

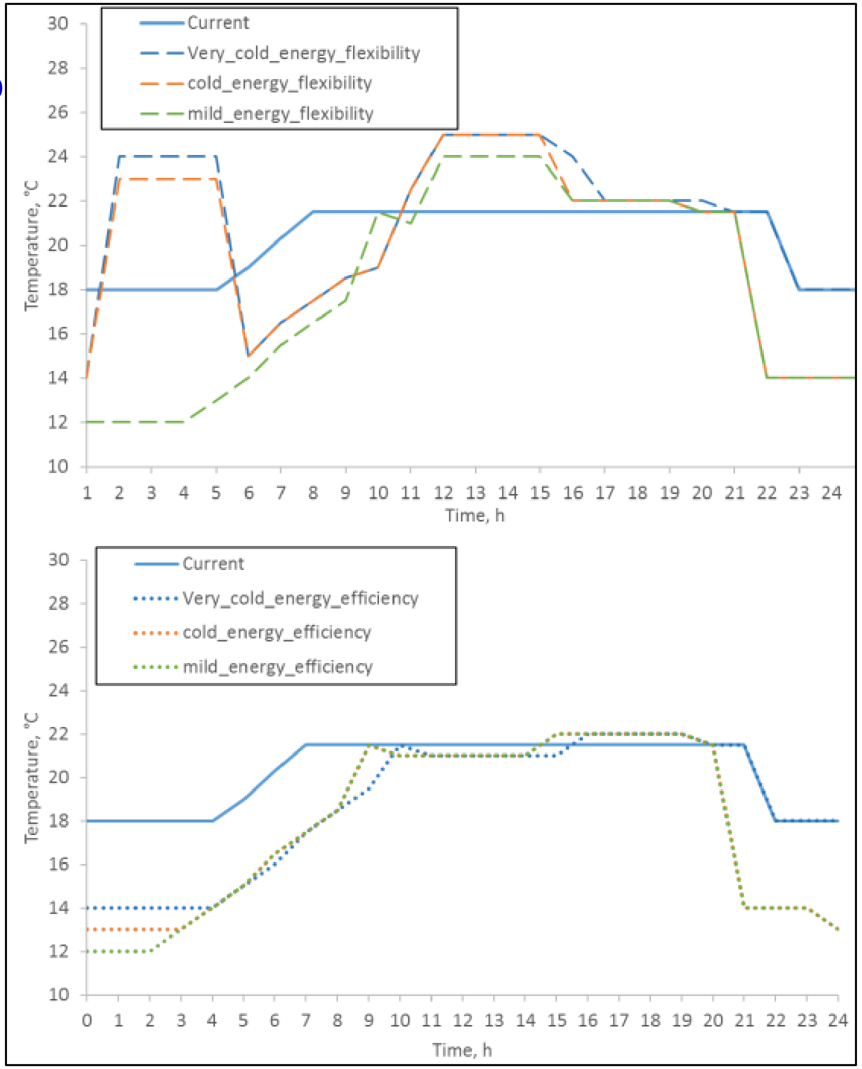
How much can we **reduce peak demand and consumption during peak periods for the grid?**

Heuristic MPC – Varennes Library and Implementation

- Based on 6-10th order RC model (3rd to 5th order for each floor).
- Expected weather conditions are clustered into **9 possible scenario** and each scenario, **two sets of predictive setpoint profiles** are developed with targets to maximize: **i) Energy-efficiency** and **ii) Energy flexibility**.
- Objective of the **energy-flexibility case:** shift load at two peak demand periods for the grid at Quebec based on weather forecast.
- Considered weather scenarios are:

Ambient Temperature	Cloudiness		
	Sunny	**Semi-cloudy**	**Cloudy**
Very Cold Minimum: -20°C Maximum: -10°C Average: -15°C	Scenario 1	Scenario 4	Scenario 7
Cold Minimum: 10°C Maximum: 0°C Average: -5°C	Scenario 2	Scenario 5	Scenario 8
Mild Minimum: 0°C Maximum: 10°C Average: 5°C	Scenario 3	Scenario 6	Scenario 9

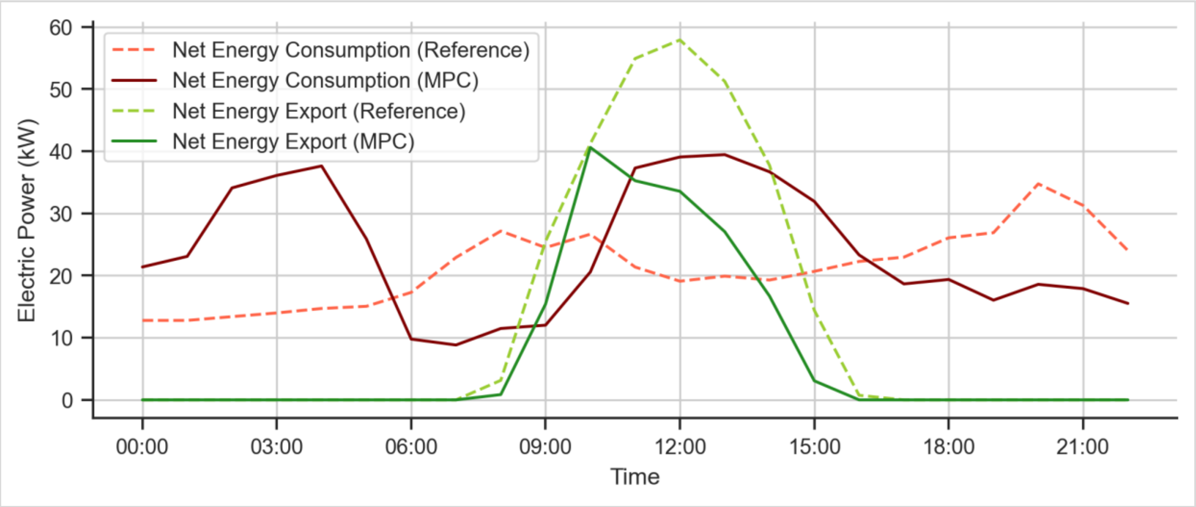
Near-optimal heating setpoint profile on sunny day

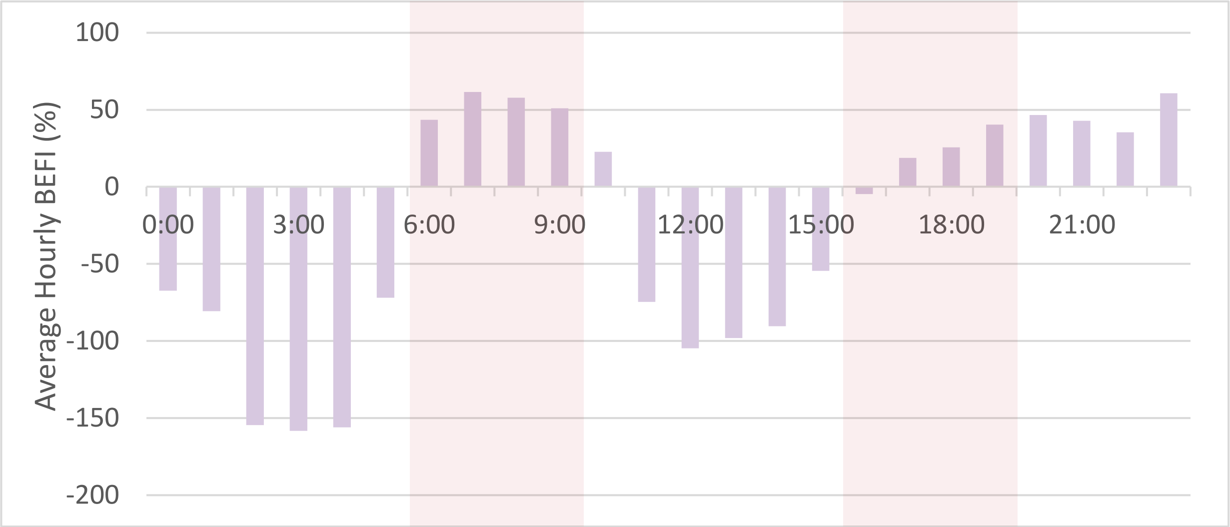


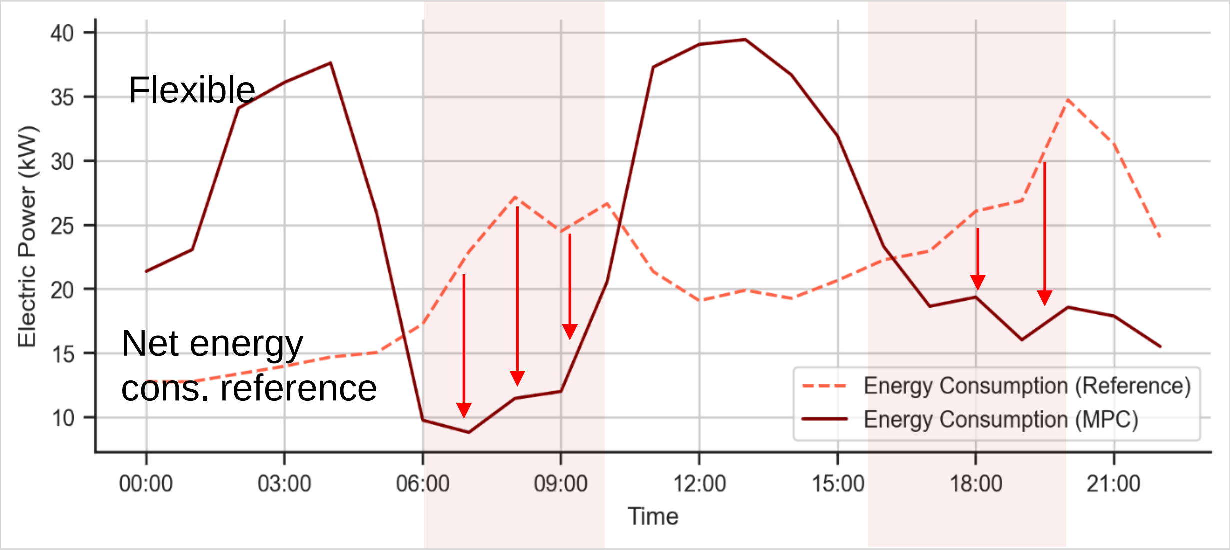
Canadian case study IEA Annex 81

❑ **Preliminary version of MPC was implemented during winter 2022 initially when Library is closed. Will apply also to school building**

Heuristic MPC Test at Varennes Library (23/12/21 to 03/01/22)







- Morning Peak Reduction: **- 50 kWh**
- Evening Peak Reduction: **-20 kWh**

Self-consumption of PV electricity was increased by about 40%

COLD SUNNY DAY (-20ºC)

CONCORDIA CAMPUS SOLAR AND HYBRID VENTILATION PROJECTS AND SOME KEY TEST FACILITIES

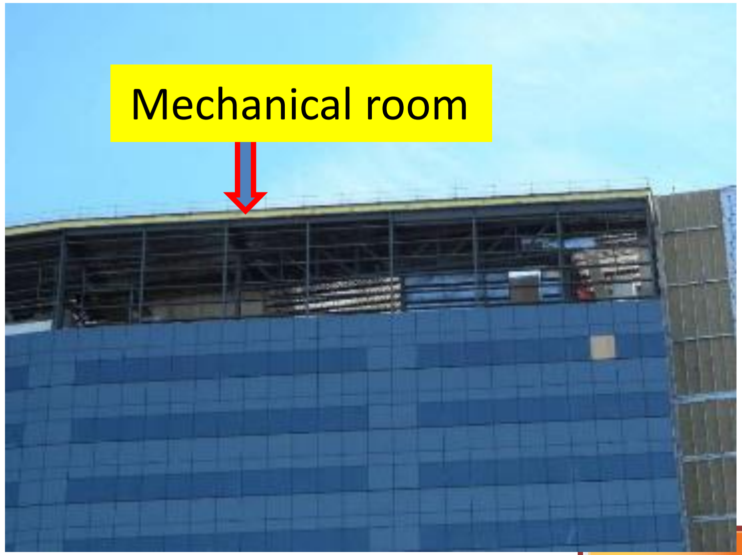
- JMSB Building-integrated photovoltaic/thermal system

- Engineering building hybrid ventilation system

- Solar Simulator
- Future Buildings Lab

JMSB BIPV/T SYSTEM (Concordia University 2009)

- Building surface ~ area 288 m^2 generates both solar electricity (up to 25 kilowatts) and solar heat (up to about 75 kW of ventilation air heating);
- **BIPV/T system** forms the exterior wall layer of the building; it is not an add-on;
- Mechanical room is directly behind the BIPV/T façade – easy to connect with HVAC
- Total peak efficiency about 55%;
- New system developed recently that simplifies design and has inlets in PV frames.



Occupant behavior:

Note shade positions

IoT with smart sensors can *facilitate automation of shades*

More R&D needed to make design of such systems routine; develop systems for retrofit

Steps for comfortable and healthy solar-optimized buildings

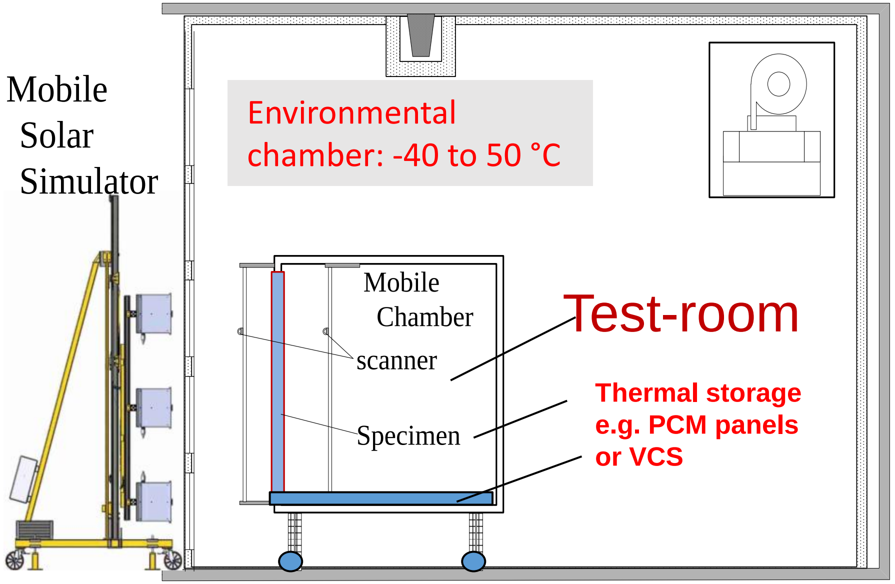
- Set **high targets for amount of fresh air to limit spread of viruses** by using solar air heating in winter and hybrid ventilation in cooling season
- Ensure **daylight availability in all offices**; enhances productivity and health
- Optimize **thermal comfort** through smart predictive control
- **Safety**: use **renewable energy for deicing sidewalks**
- Design **buildings for access and safety of people with disabilities**

EV building
hybrid ventilation system

MAJOR TEST FACILITIES:
ENVIRONMENTAL CHAMBER AND MOBILE SOLAR SIMULATOR

A **two-story environmental chamber** with a mobile solar simulator lamp field used to test building technologies under controlled environmental conditions (from arctic to desert).

- Temperature: -40 to +50°C
- Relative humidity: 20 to 95%
- Sunlight produced by a 6-lamp mobile solar simulator enters chamber via windows.

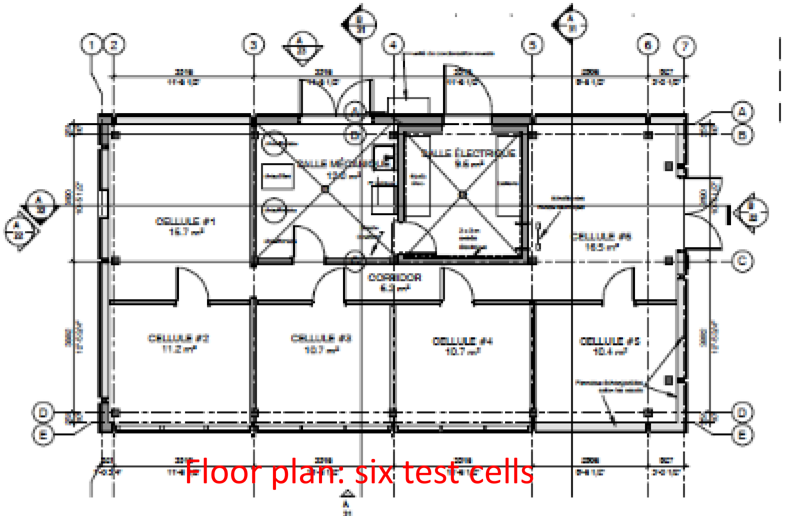


CONCORDIA FUTURE BUILDINGS LAB

- Develop and test innovative building and energy technologies
- Test and optimize the integration, operation and energy management of multiple power sources and energy storage
- Develop and advance net-zero energy building practices by optimizing integrated building and energy system performance under real weather operating conditions.
- Lead the building industry towards intelligent net-zero energy buildings of the future
- Northern and Indigenous sustainable buildings

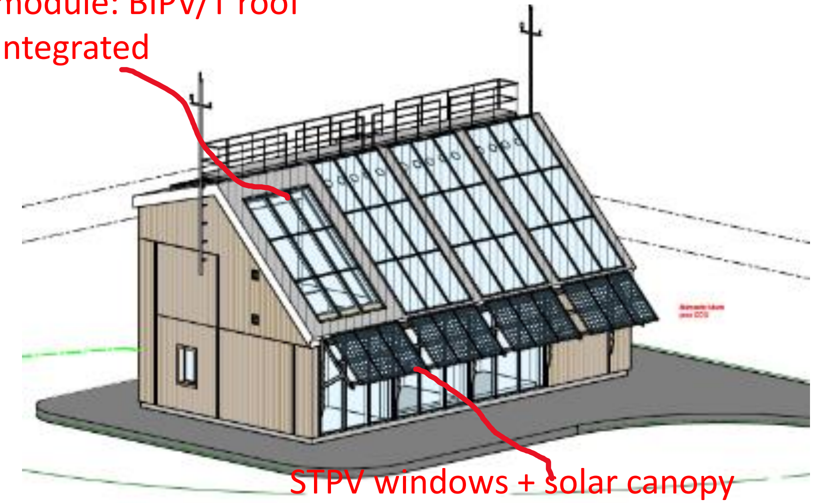
Research capabilities

- Various envelope and mechanical systems
- Interaction between envelope, indoor environment and HVAC systems
- integration/interaction of renewables: solar, wind, fuel cells
- Capabilities to test interaction of buildings with grid, nano-grid



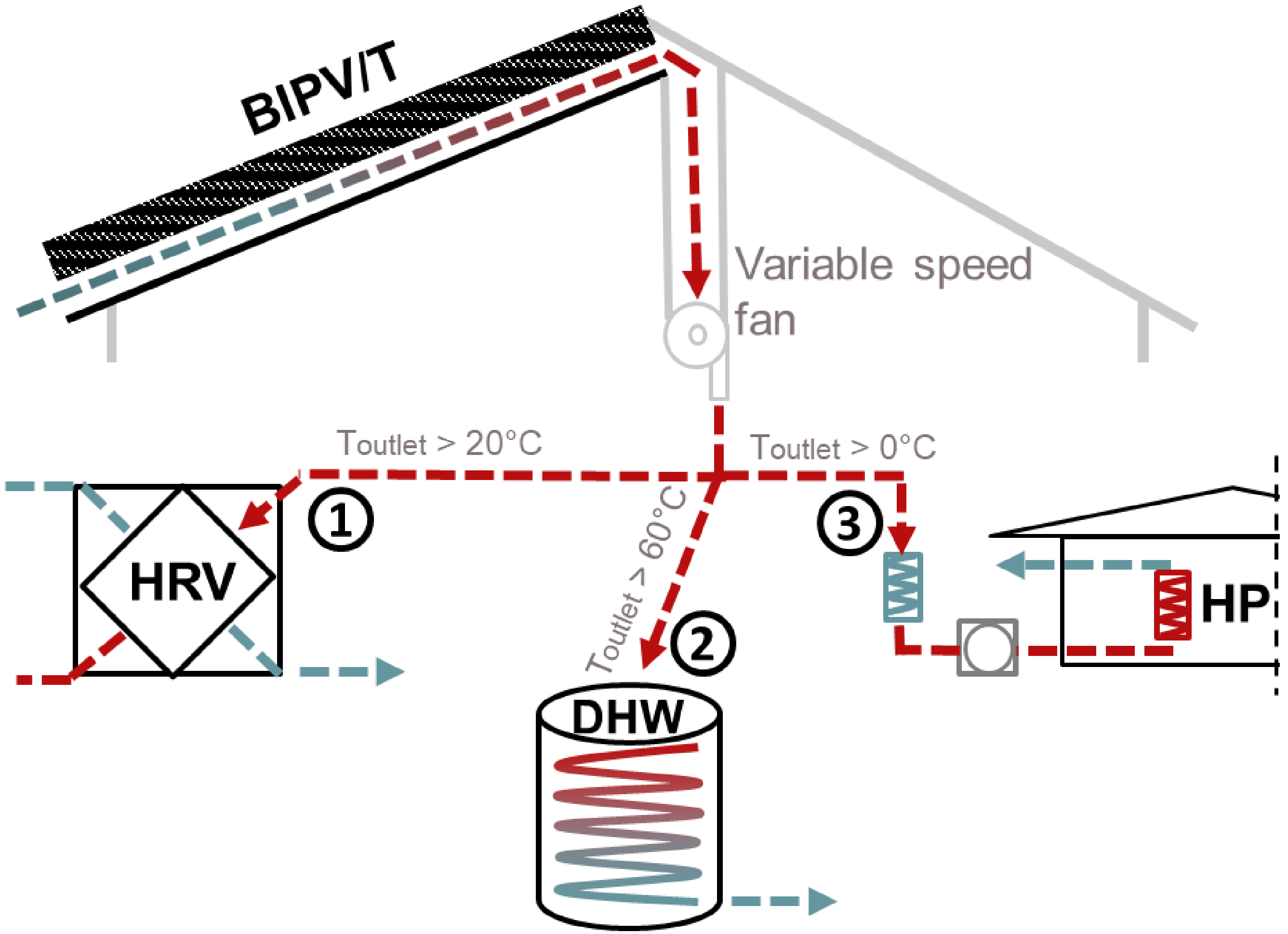
Floor plan: six test cells

Changeable roof module: BIPV/T roof integrated



STPV windows + solar canopy

BIPV/T coupling with Building HVAC
Local subsystem MPC and supervisory MPC



1) **Preheated ventilation air** (with or without an HRV)

2) **For DHW** (summer application)

3) **Supply for an air-source heat pump** (COP enhancement)

A control algorithm is required to regulate the BIPV/T flow rate, depending on the:

i. supply air temperature requirements

ii. flow requirements

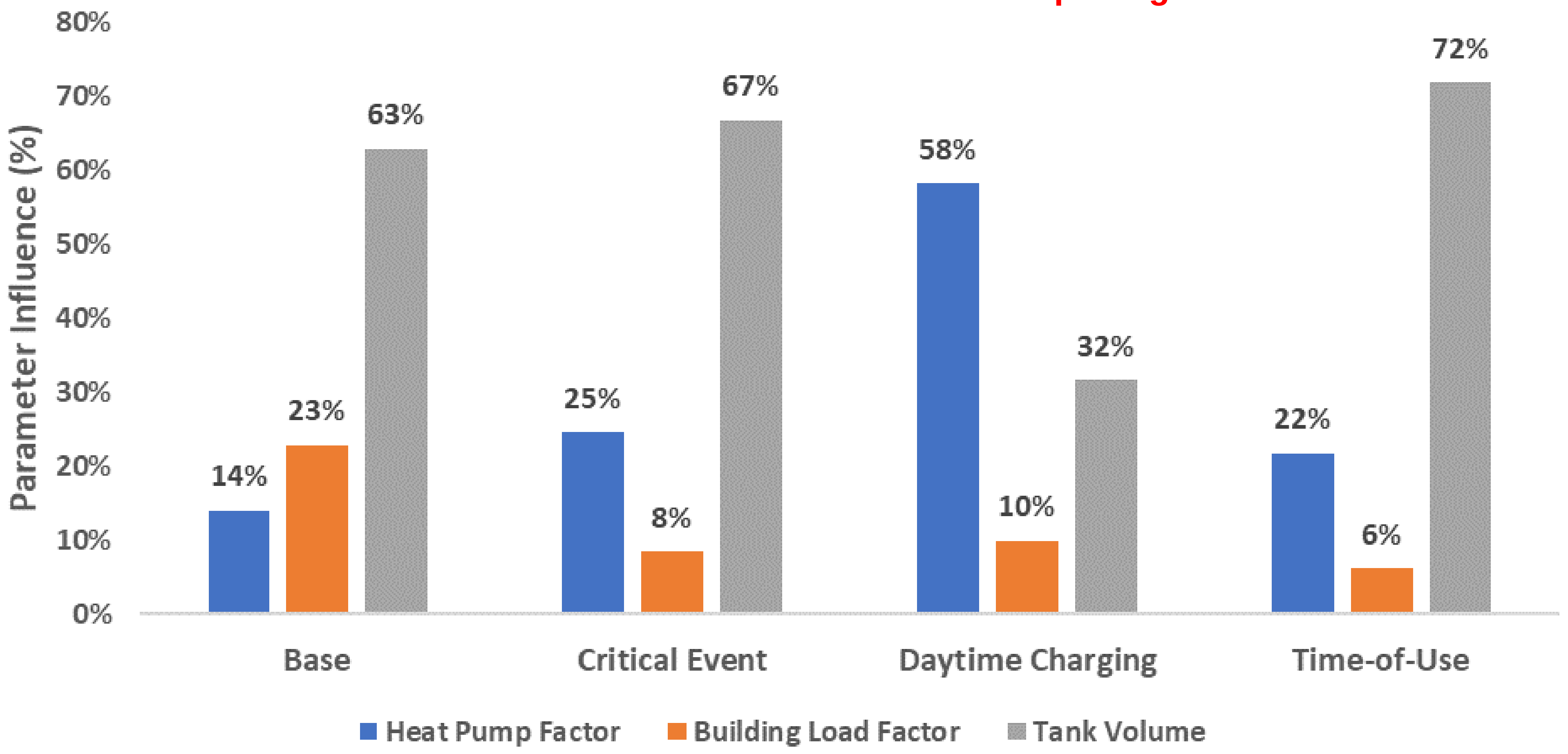
iii. environmental conditions

Anna-Maria Sigounis

BIPV/T + Heat Pump: Thermal Storage Size Influence on Energy Flexibility

- **Tank volume** has the largest impact on the flexibility; **Heat pump size** has the highest influence for daytime charging

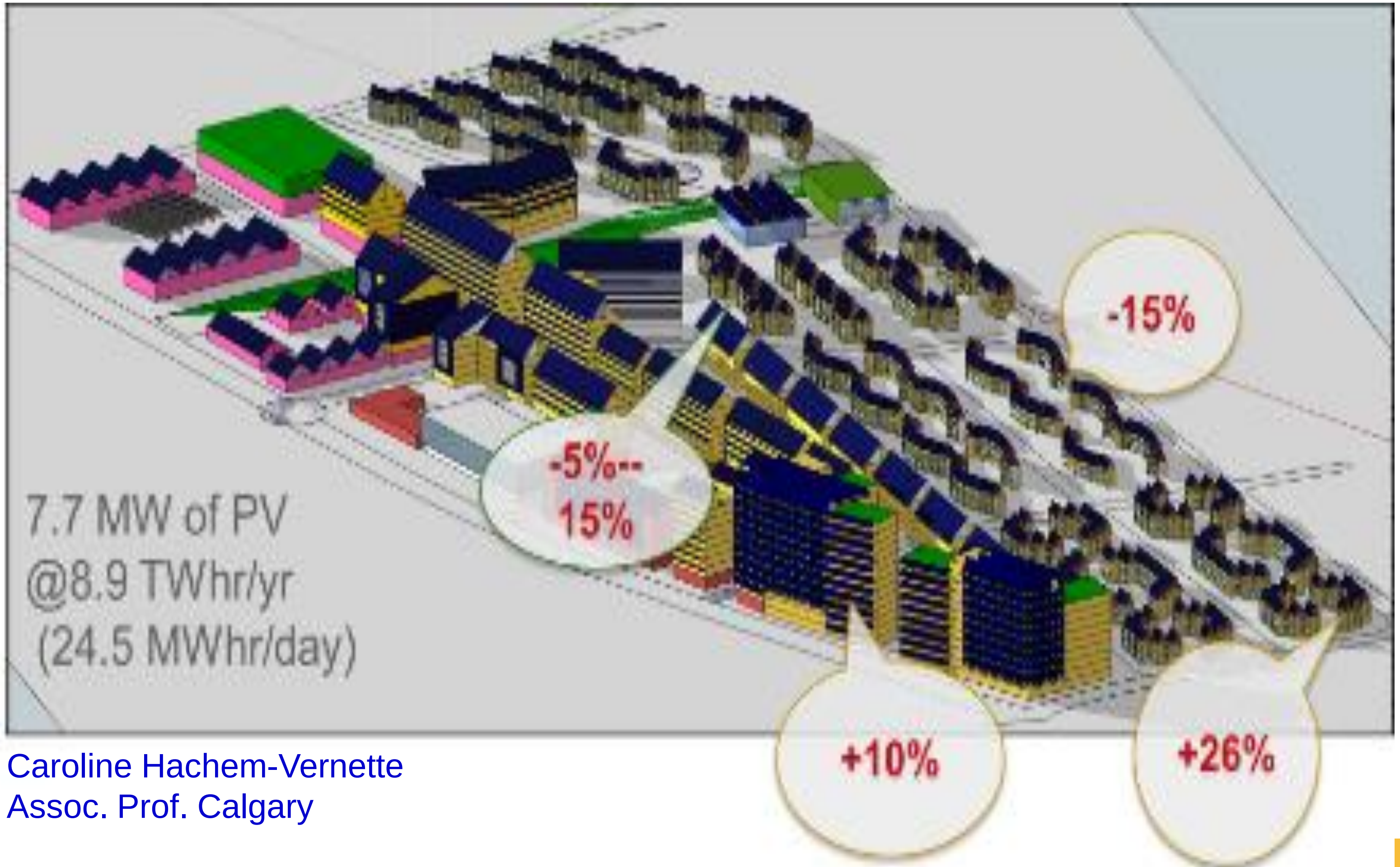
- **Optimal tank volume** ranged from 250 – 1000 L
  - 250 L typical with no demand response (base case)
  - 1000 L for time-or-use
  - 350 – 600 L for daytime charging and **critical peak pricing**



Heat pump Water heater Connectable to Air BIPV/T

An ambitious Canadian Net-zero Energy Community: West 5 - case study with s2e (partner) in London, Ontario

- Optimized for solar energy utilization to reach net-zero
- Integration of electric vehicles owned by the community
- Energy storage at the building and community levels



Caroline Hachem-Vernette
Assoc. Prof. Calgary

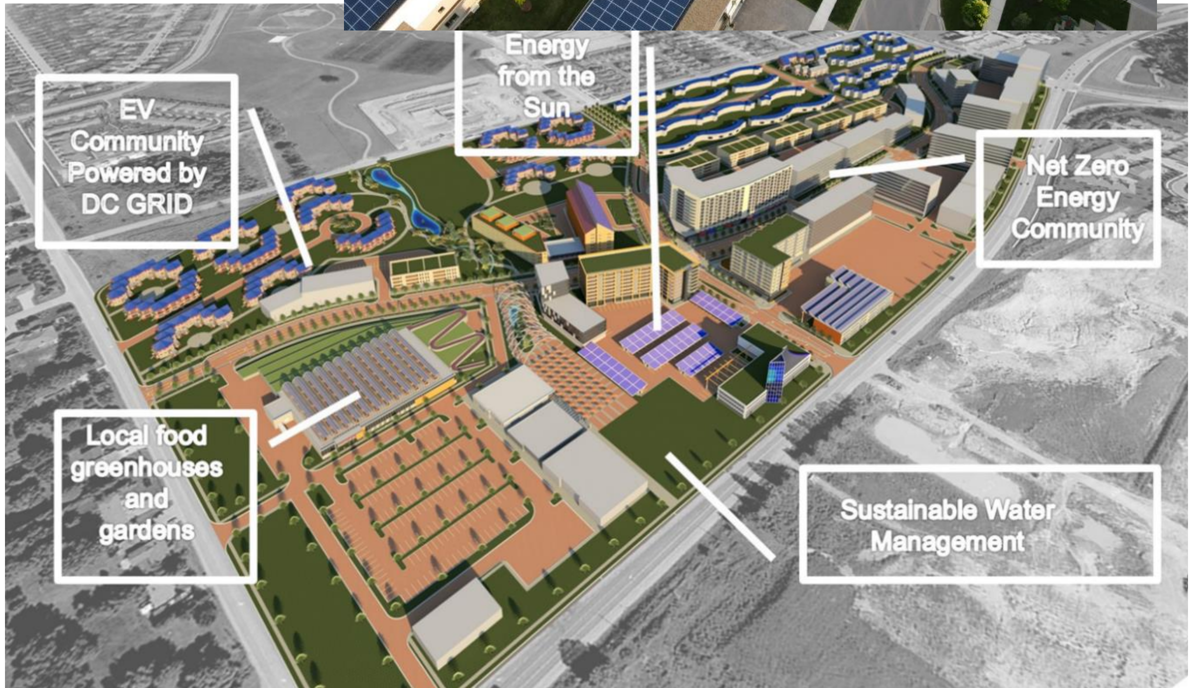
Major Case Study for CAE Roadmap

An ambitious Canadian Net-zero Energy Community: West 5 - case study with s2e (partner) in London, Ontario

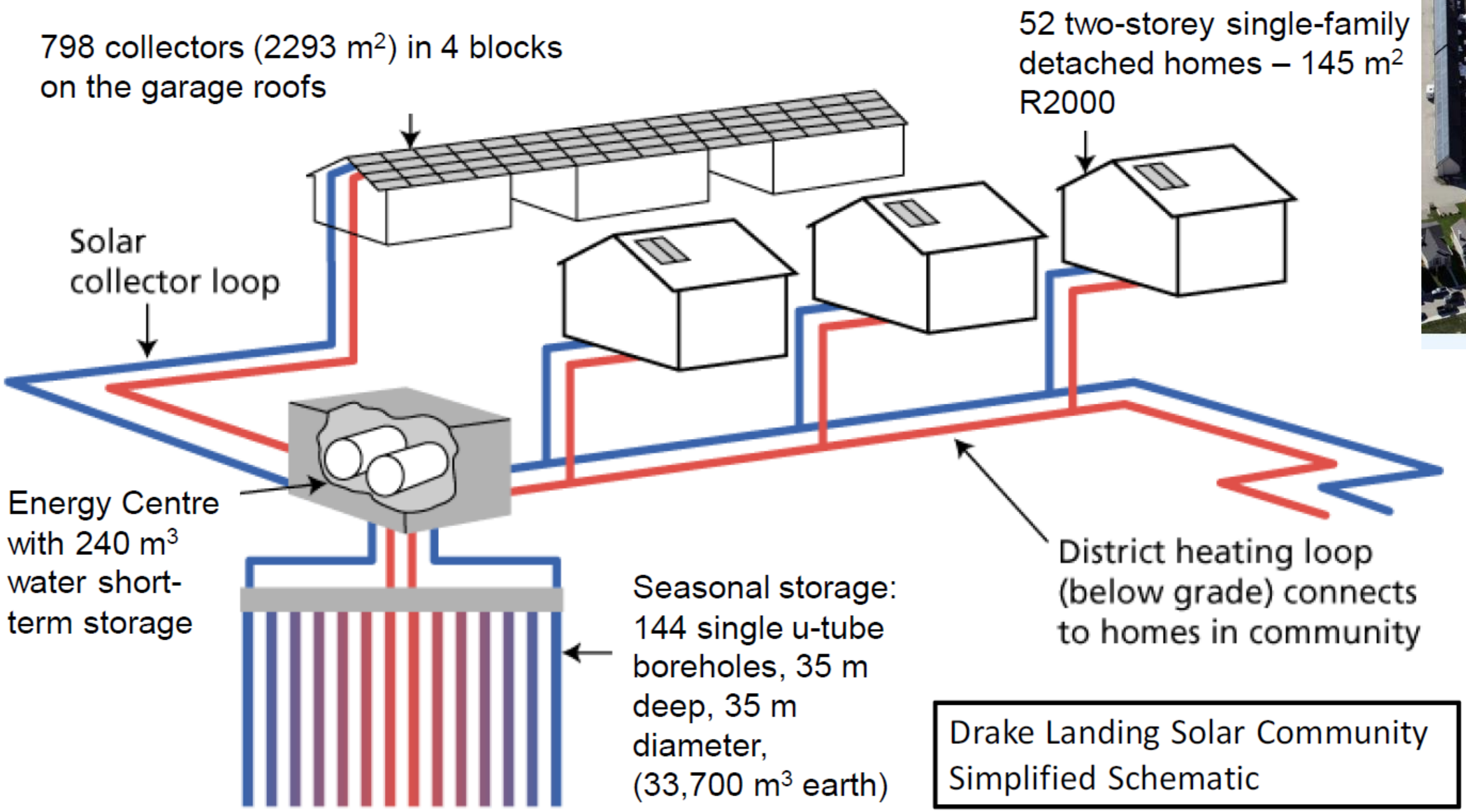
- Micro Utility Business Model
- Micro Utility owns all energy generation equipment and major loads such as heat pump, hot water heater, appliances.
- Homeowner pays a smart fee lower than energy cost is a traditional home.
- Future proofs against rising energy

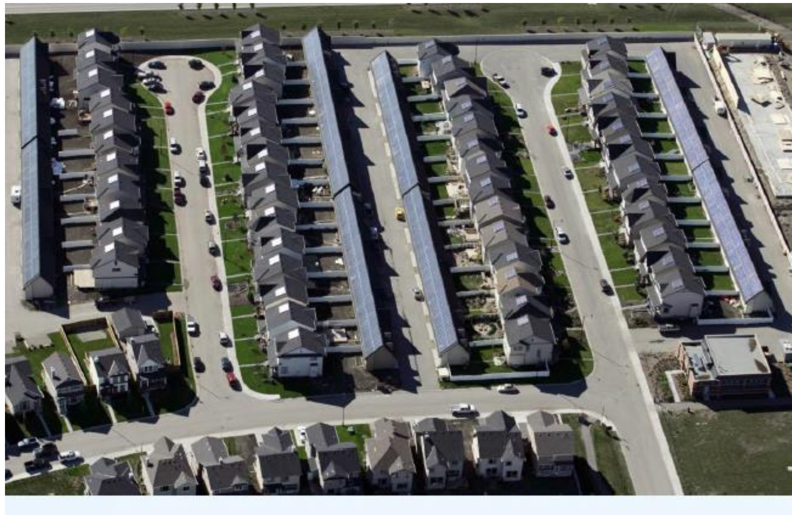
Development 20% completed

Original concept



Drake Landing Solar Community (Alberta) Seasonal solar heat storage in borefield





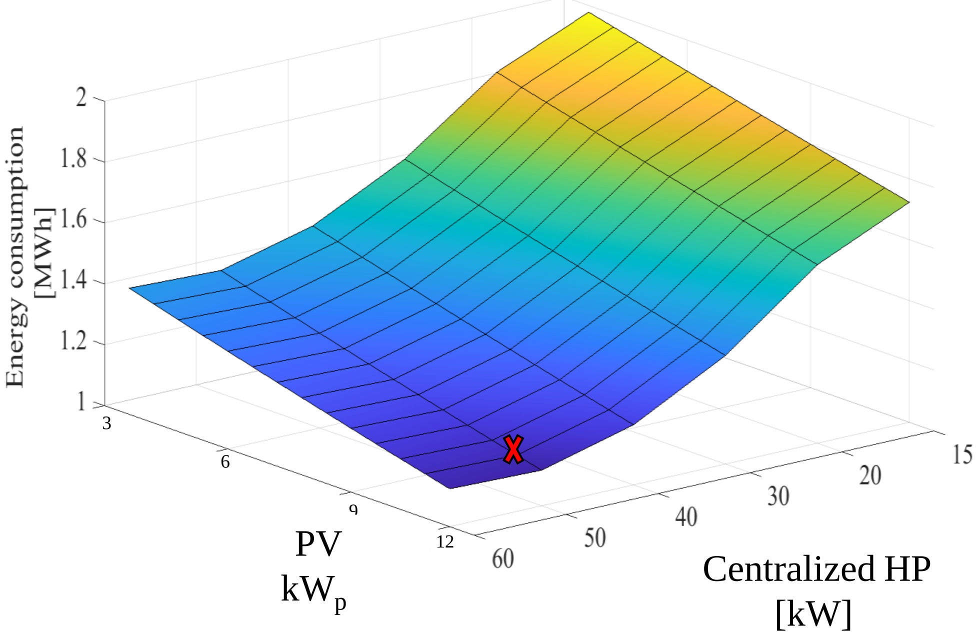
Average solar fraction > 90%
In 2015/16 100%

Source: Bill Wong, NRCan

Flexibility-oriented design for the retrofitting of a virtual energy community in Québec: Techno-economic analysis

Case study scenario investigation:

- Reference scenario.
- Implementation of PVs with a variable penetration rate.
- Implementation of Centralized heat pump.
- **Implementation of BIPV/T + Centralized heat pump (solar source heat pump).**



Identification of the optimal combination

Optimum will change depending on constraints, energy storage and with EV integration

A. Petrucci

Residential Densification: Case Study in Montreal area

Old house (bungalow) replaced with two low-energy 2-storey solar houses

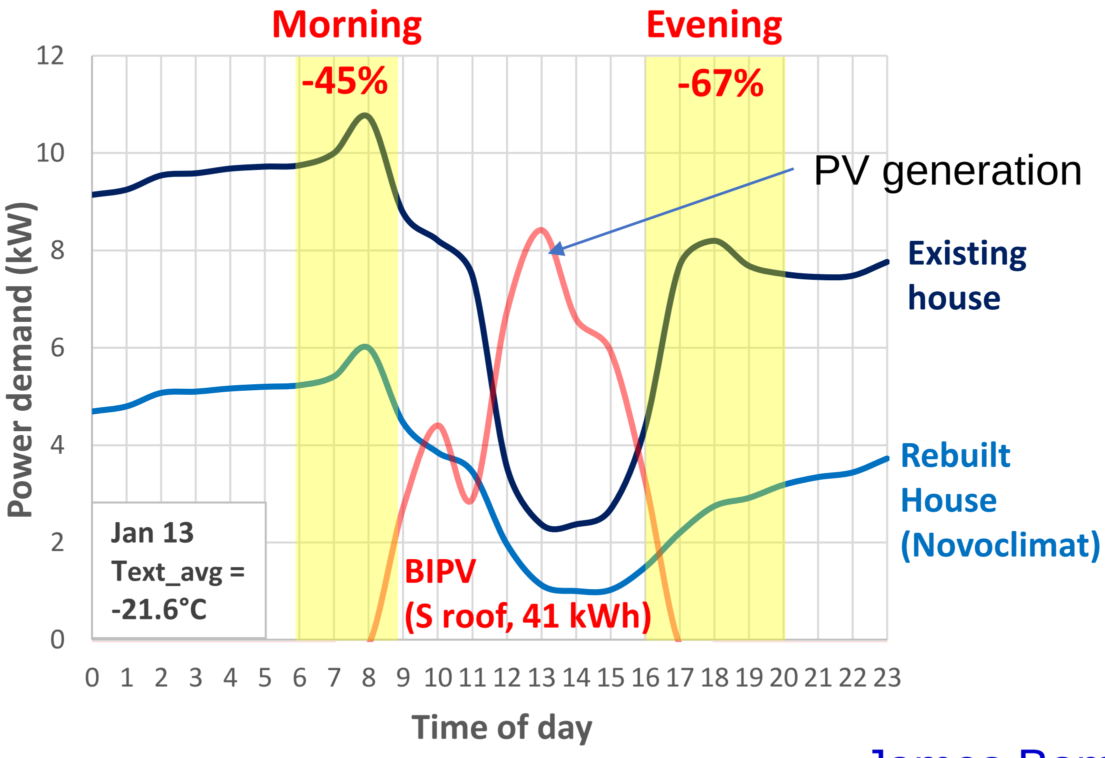
- **Residential densification reduces land and energy use (house operation & mobility)**
- **Shift from consuming 6,000 kWh/yr/pers to producing 3,500 kWh kWh/yr/pers**
- **84% of PV energy can be exported to decarbonize or self-consumed (flexibility)**

Existing single detached house

Two new low-energy solar houses (built on the same land lot)

Average PV system size to be installed on typical house for the proposed solution (10 kWp)

Power demand reduction on a very cold sunny day

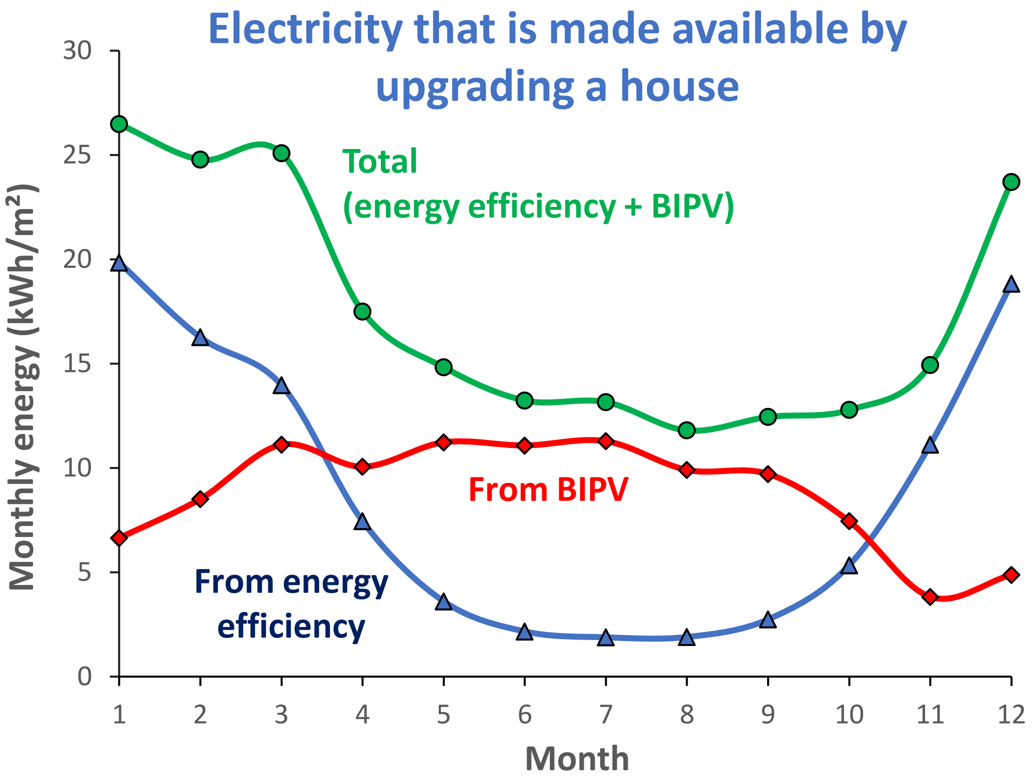


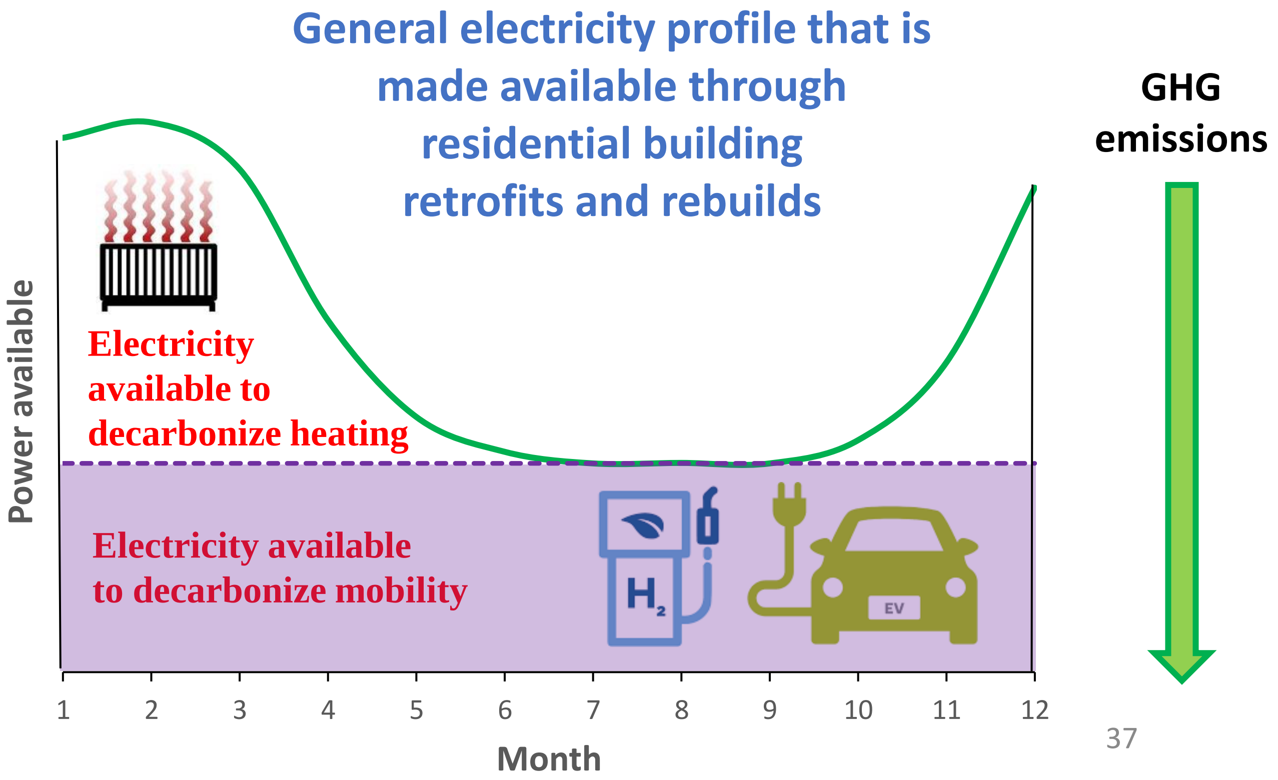
Upgrading **35% of single detached houses** in Québec (all houses built before 1978) could provide about **2700 MW peak demand reduction**

Possible Source of Energy for Decarbonization in Québec

Electrify heating & mobility through low-energy solar buildings

- **Heating electrification requires energy in winter (provided mainly by energy efficiency)**
- **Mobility electrification requires approximately the same energy supply year-round**
- **Energy efficiency + BIPV matches the needs for electrifying heating and mobility**
- **Their combination almost doubles electrification potential (compared to separately)**



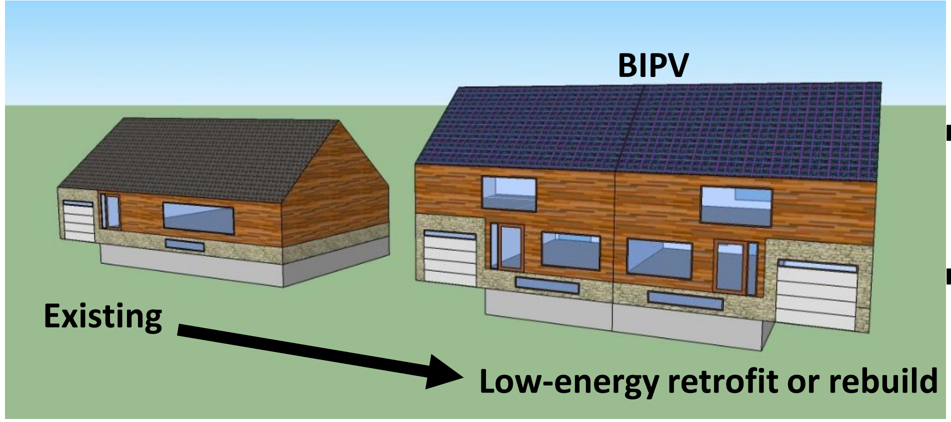


Decarbonizing Heating and Mobility in Québec

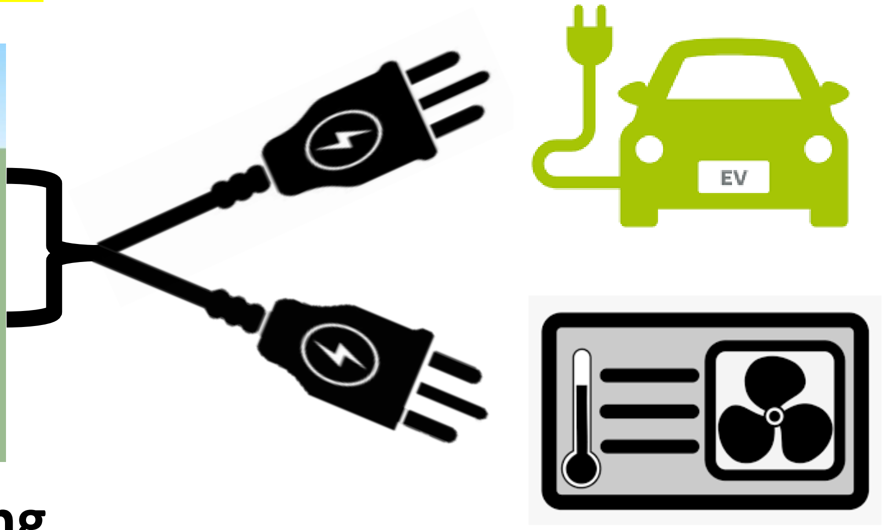
Impact of upgrading houses that use electric resistance heating

- Potential for upgrading 42% of single detached houses to low-energy solar houses
- 33.4 TWh of electricity is made available for decarbonization (19% of current use)

- Additional 7.9 TWh available to decarbonize natural gas used for building heating
- Electrify mobility: 83-100% converted to EVs
- GHG emissions payback time is 3-4 yrs for retrofits and 6-11 yrs for rebuilds
- Up to 34% reduction in GHG emissions



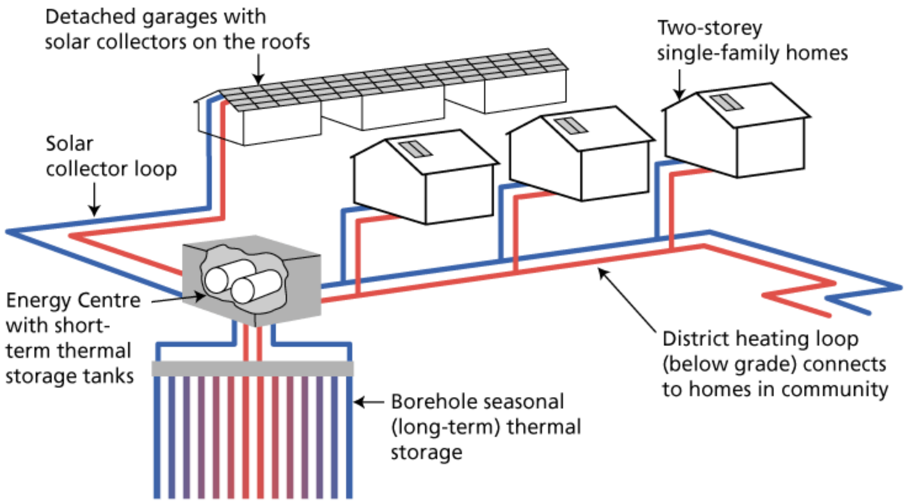
Upgrade to low-energy solar building



Different pathways to net-zero

- Different mixes of renewable energy technologies depending on location and local climate (e.g. seasonal solar energy storage in boreholes – in very cold locations)
- High energy efficiency (although not excessive as it increases cost more than adding renewables).
- Producing electricity for EVs and optimizing smart grid interaction.
- Always need healthy and comfortable indoor environment.

West 5 Community, London Ontario (about 25% developed) smart microgrid



Drake Landing Solar Community (Alberta)