NSERC/Hydro-Québec Industrial Research Chair in Optimized Operation and Energy Efficiency: Towards High Performance Buildings

Overview and Flexibility Applications

- Varennes Netzero Library

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NSERC/Hydro-Québec Industrial Chair
Director, Concordia Centre for Zero Energy Building Studies (CZEBS)
Professor, BCEE Dept

IRC Research – 3 axes

- 1. **Model predictive control** and optimized responsive building operation;
- 2. **Building flexibility** for enhanced integration of distributed renewable energy resources and smart grid interaction
- 3. **Application case studies** that integrate the work of axes 1 and 2 in retrofit measures (including control strategies) for existing buildings.
- Predictive control methodologies and optimal operating strategies will be developed under Axis 1 to optimize interaction with smart grids, including peak shaving, cold load pickup after power outage, demand response implementation and integration of intermittent renewables.

PROJECTS

Axis 1: Model predictive control and optimized responsive building operation

- **1.1** Development of grey box/data driven models of building zones and main HVAC components
- **1.2** Development of a methodology for design of model-predictive control (MPC) for buildings
- **1.3** Implementation and calibration of MPC, real time use of energy flexibility
- **1.4** Optimal operation of existing buildings based on calibrated strategies and retrofits

Axis 2: Building flexibility for enhanced integration of distributed renewable energy resources and smart grid interaction

- **2.1** Building design to support energy flexibility, including occupant behavior
- **2.2** Study of integration of semitransparent photovoltaics into building envelope and impact on demand profile
- **2.3** Comparison of different types of building-integrated storage and isolated storage charging/discharging options
- **2.4** Characterization of the impact of solar radiation fluctuations on building power demand in heating conditions
- **2.5** Methodology for addressing power demand variations due to short term solar radiation fluctuations

Axis 3: **Application case studies**	
3.1 Application of MPC/optimal operation strategies to case study buildings	**3.3** Optimal operating strategies for a smart grid-responsive NZEB
3.2 Application of energy efficiency and flexibility measures in conjunction with MPC	**3.4** Energy and load management in school buildings

KEY RESEARCH FACILITIES

- Utilize building physics and data from buildings such as those monitored by Hydro Québec and the *Experimentation Houses for Building Energetics (EHBE)* develop a methodology for generation of reduced order models (ROMs).
- **Validate models in SSEC facility.**

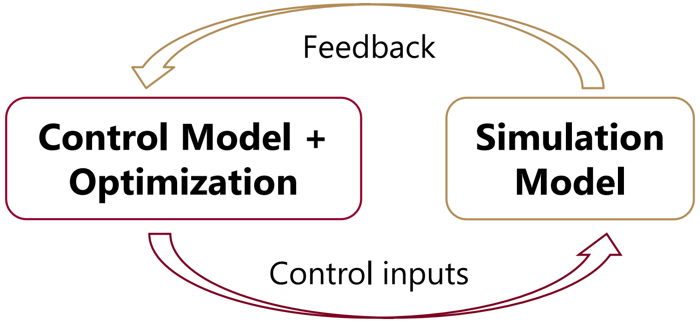
EHBE facility (HQ)

Solar simulator SSEC facility

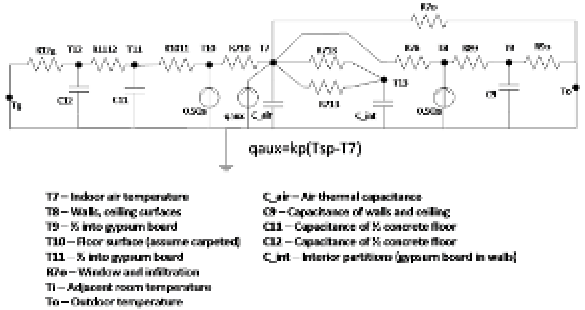
- ROMs form the basis of **predictive control strategies** that utilize weather forecasting up to 3 days ahead, **energy flexibility** and models for occupant behavior.
- A methodology for generating and calibrating simplified ROMs appropriate for real time control (typically 3rd order).

METHODOLOGY FOR PREDICTIVE CONTROL (JENNIFER)

- Model-based predictive control is studied as a strategy to reduce electricity bills for a bank building
- Numerical study based on two models of the building
  - A more detailed one for simulation
  - A simple one (control model) used in the optimization algorithm
- Implemented in Matlab/Simulink
- The **objective function**:



$$J = \underbrace{\left(\sum_{i=1}^{N} P_i \Delta t\right) \cdot (4.93\ ¢/\text{kWh})}_{\textbf{Energy charge \$}} + \underbrace{\max(\mathbf{P}) \cdot (14.37\ \$/\text{kW})}_{\textbf{Power charge \$}}$$



- A near-optimal temperature setpoint schedule over a relatively short prediction horizon (e.g., 1-2 days).

25% Reduction in Utility Cost

38% Reduction in Power Peak

Case study Varennes Library – Canada's first institutional solar NZEB

Officially opened May 2016

Market is ready for such projects provided standardized BIPV products are developed

Now modelling and optimizing operation and grid interaction under NSERC Hydro Quebec Chair

- 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**)

We played a key role in guiding energy design of the building

Varennes Library: living lab

Multi-Functional Library

First Public Canadian Solar NZEB

Rendering just before final design; note skylights

At a Glance

- Net Floor Area: 2100 m^2
- BIPV/T Roof: 110.5 kWp
- Solar Heat Recovery: 1142 L/s
  (pre-heated fresh air)

Thermal Storage

- **8x 150m geothermal boreholes**
- **Concrete slab, hydronic radiant**

Other Passive Solar Design Features

- Natural cross-ventilation
- Exterior fixed solar shading

Window to wall ratios

- North: 10%
- South: 30%
- East: 20%
- West: 30%

Building has become **a living lab**:
photo from class visit

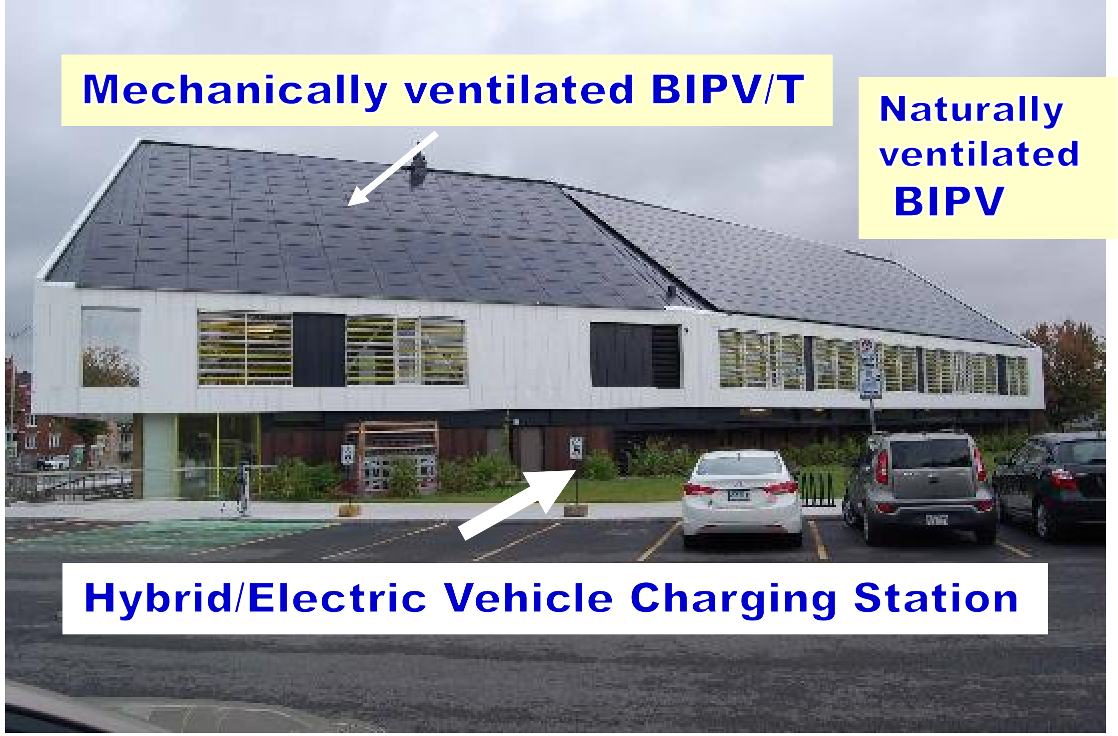
Skylights

Vegetation Screen (Growing)

Smaller triple glazed windows on North Side

Fixed solar shading on South side

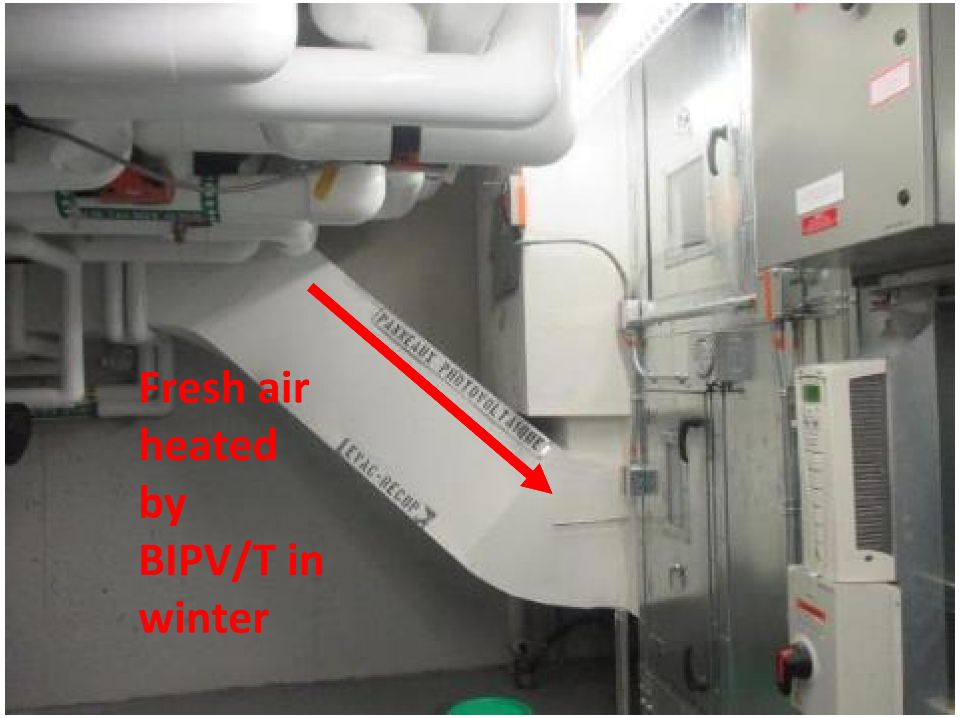
Geothermal Wells (8)



Mechanically ventilated BIPV/T

Naturally ventilated BIPV

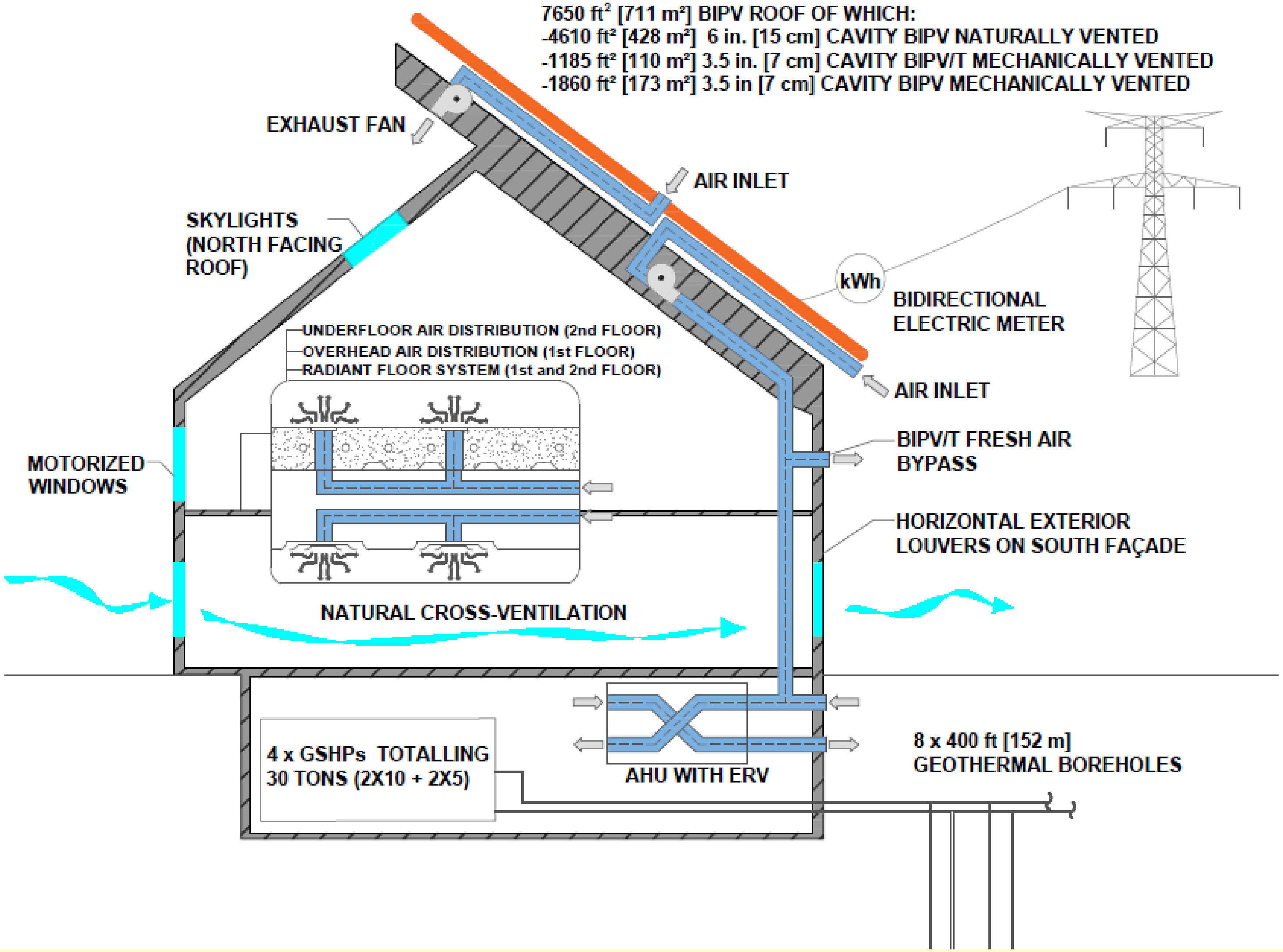
Hybrid/Electric Vehicle Charging Station



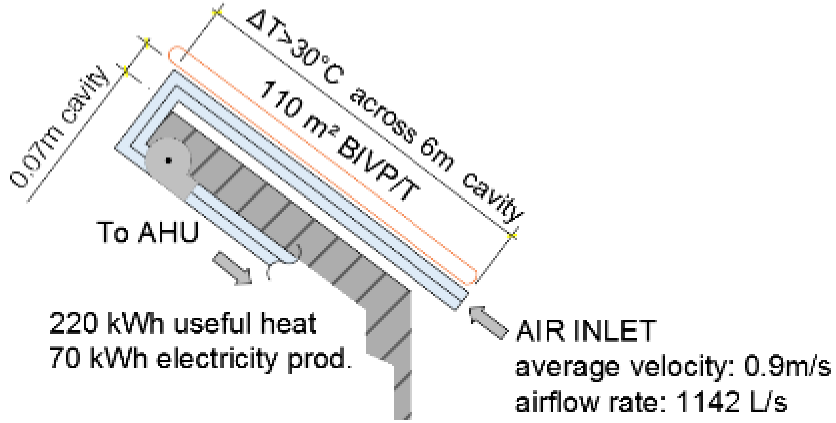
Fresh air heated by BIPV/T in winter

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 AND BIPV/T (PART OF ROOF)

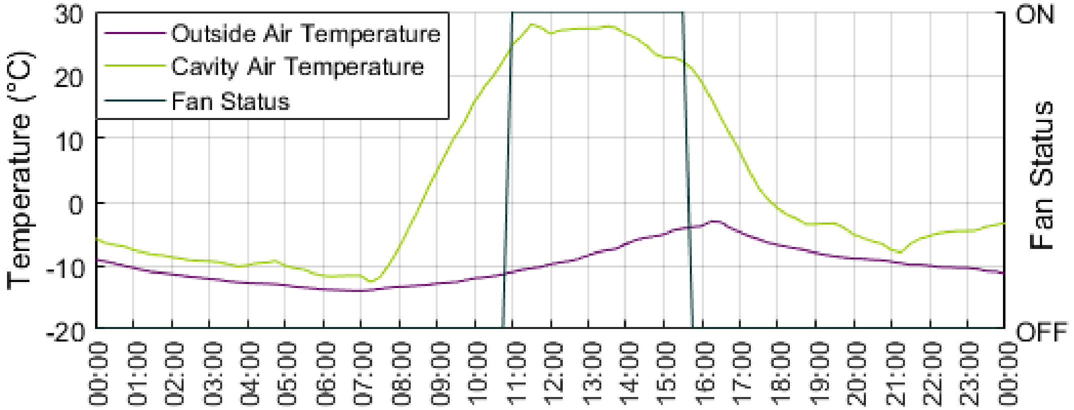


- Custom BIPV/T, one inlet
- Fan activated for outlet air temperature >25°C
- Rated electrical efficiency: 15.9% STC
- **Combined efficiency up to ~60% (thermal + electrical)**

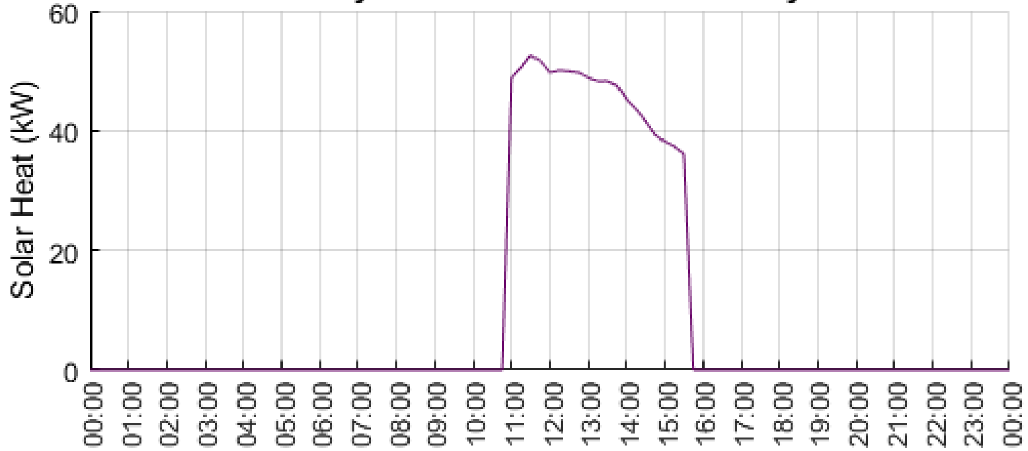


Flexibility provided by: thermal mass in floor slabs, BIPV/T heat, geothermal

BIPV/T System (winter clear day performance)

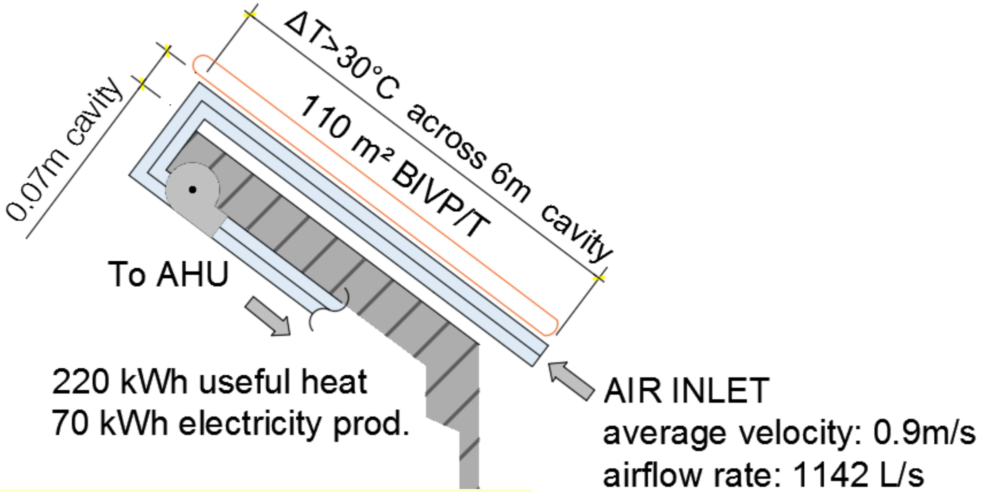


Daily Fan Operation, Air Cavity & Outside Temperature (°C) vs. Time February



Daily Solar Heat vs. Time February

- BIPV/T fan activated for outlet air temperature >25°C
- Rated electrical efficiency: 15.9% STC
- Combined efficiency: ~60% (thermal and elec.)



220 kWh useful heat
70 kWh electricity prod.

average velocity: 0.9m/s
airflow rate: 1142 L/s

Potential thermal and electrical flexibility

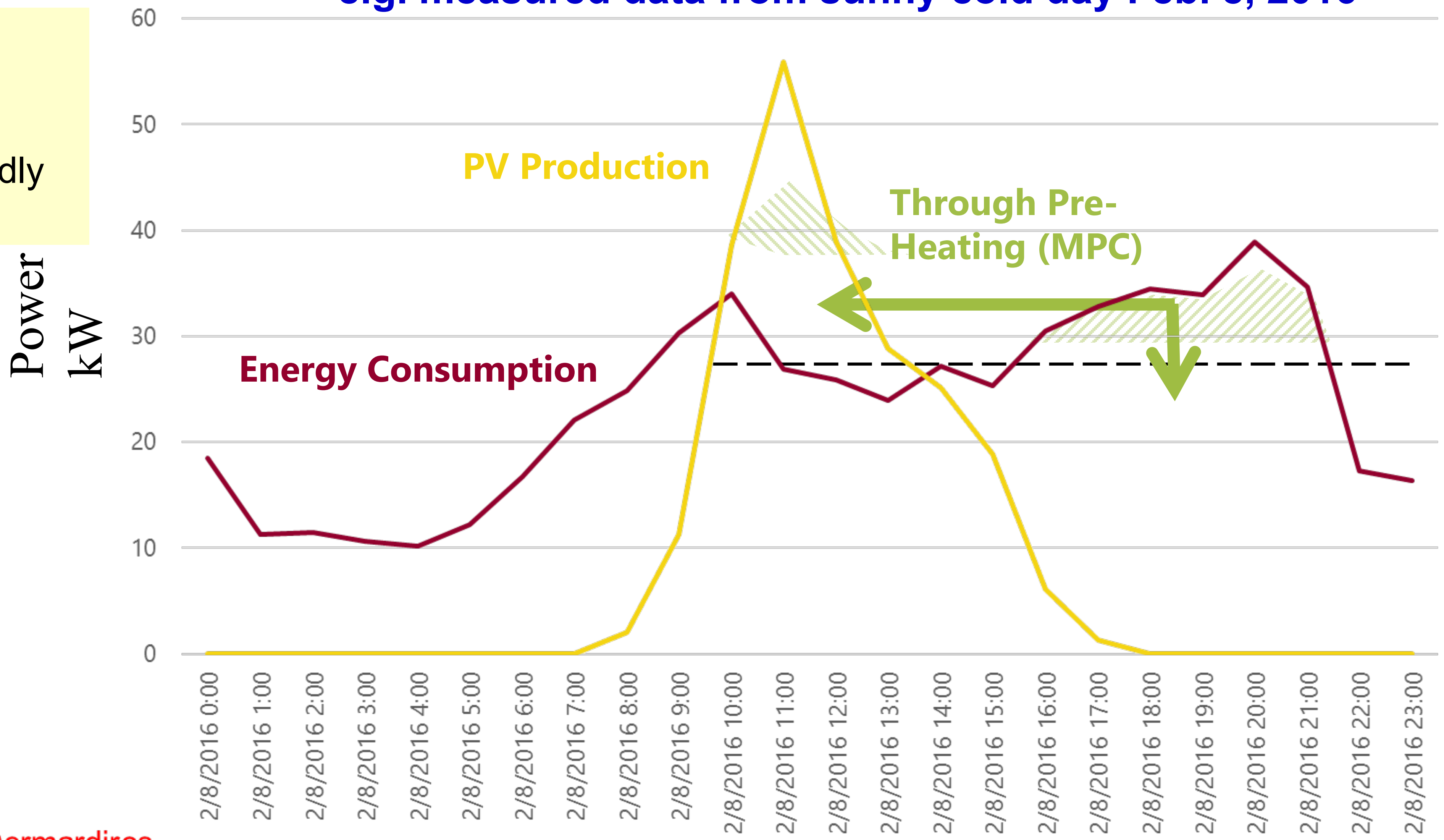
Production and Consumption Mismatch:

use predictive control to reduce peak demand during cold days

e.g. measured data from sunny cold day Feb. 8, 2016

Varennes Library:

Grid-friendly NZEB?

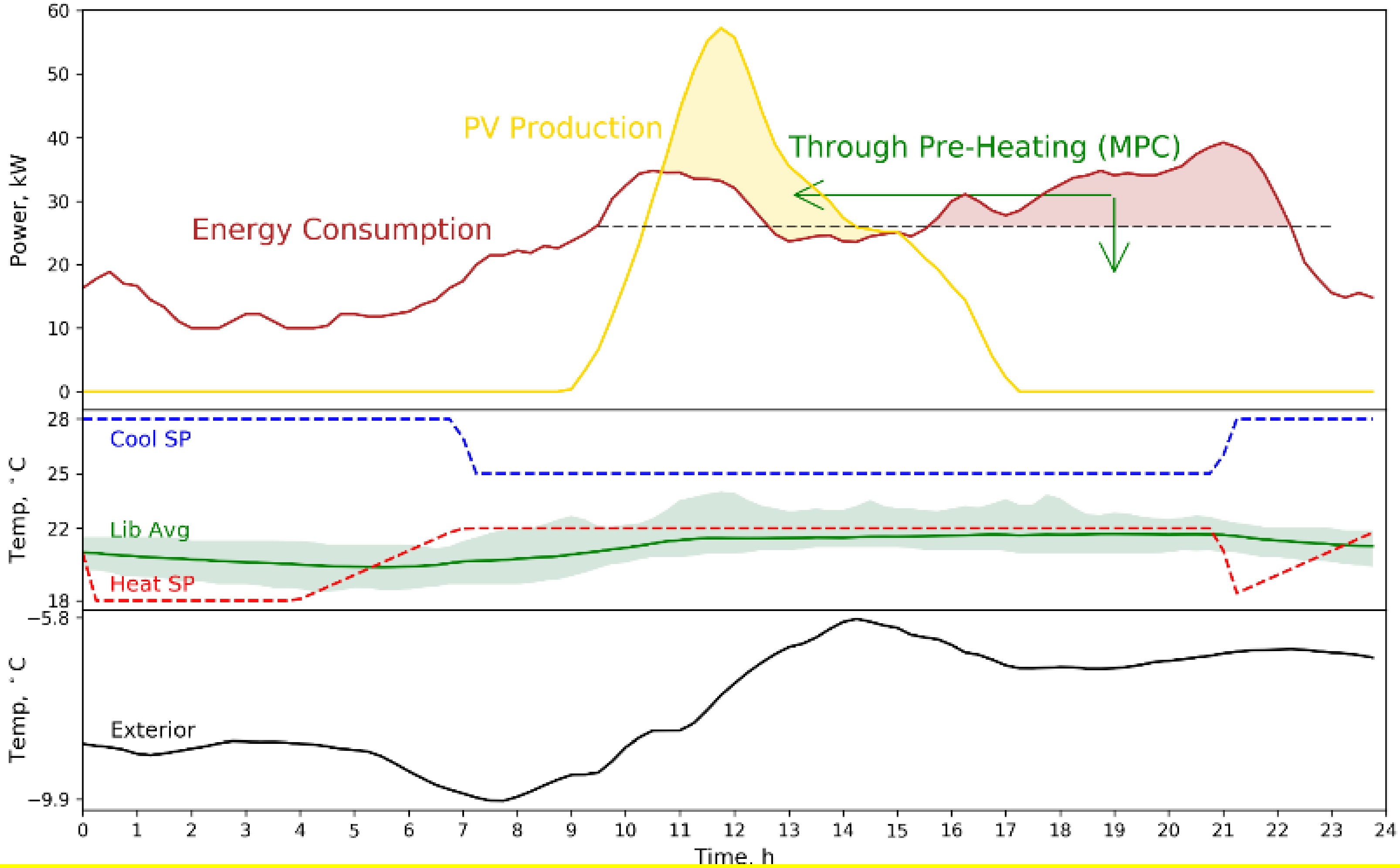


Smart NZEB can become **tool of the grid through MPC**

Harness energy flexibility

Vasken Dermardiros
PhD Student

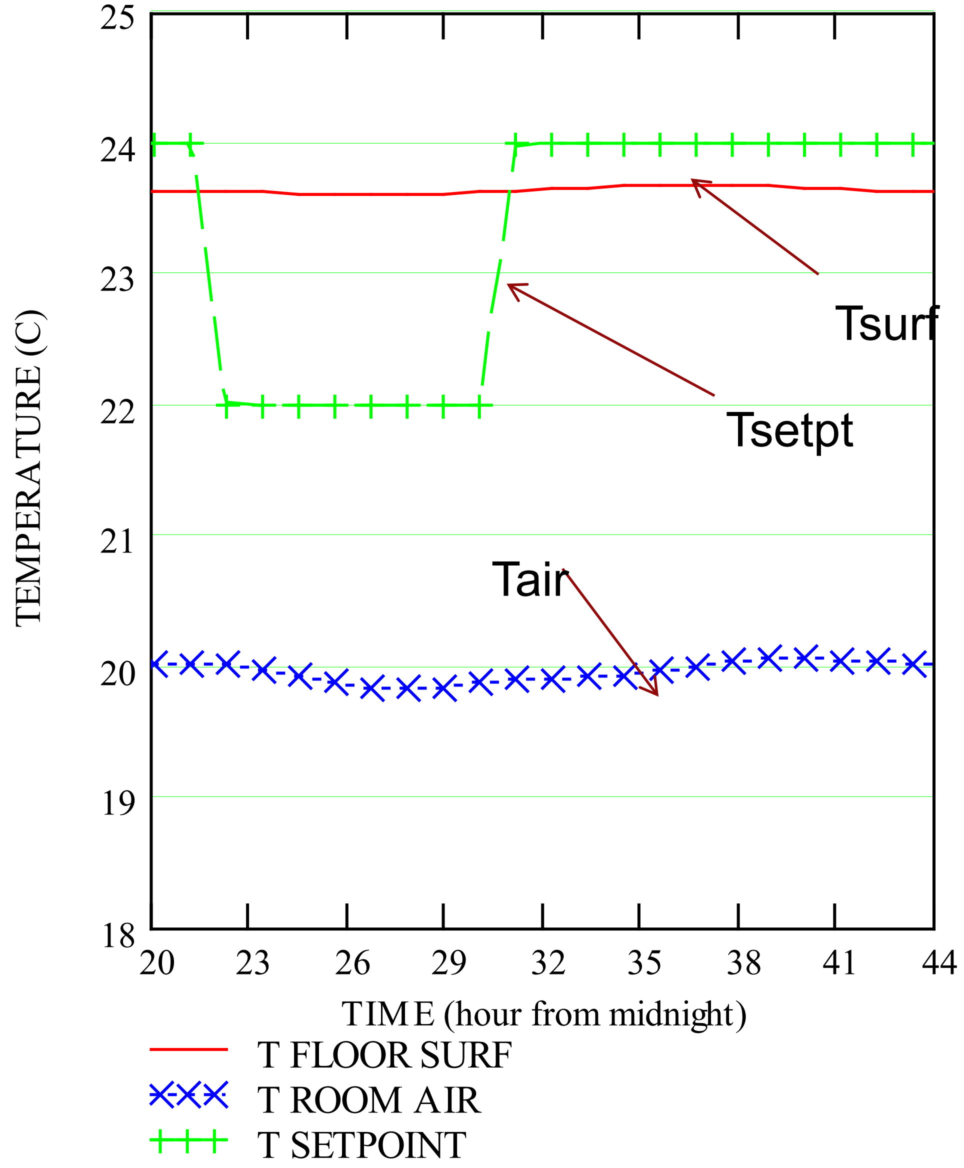
Predictive control design for winter sunny cold day - near optimal setpoint profiles shown



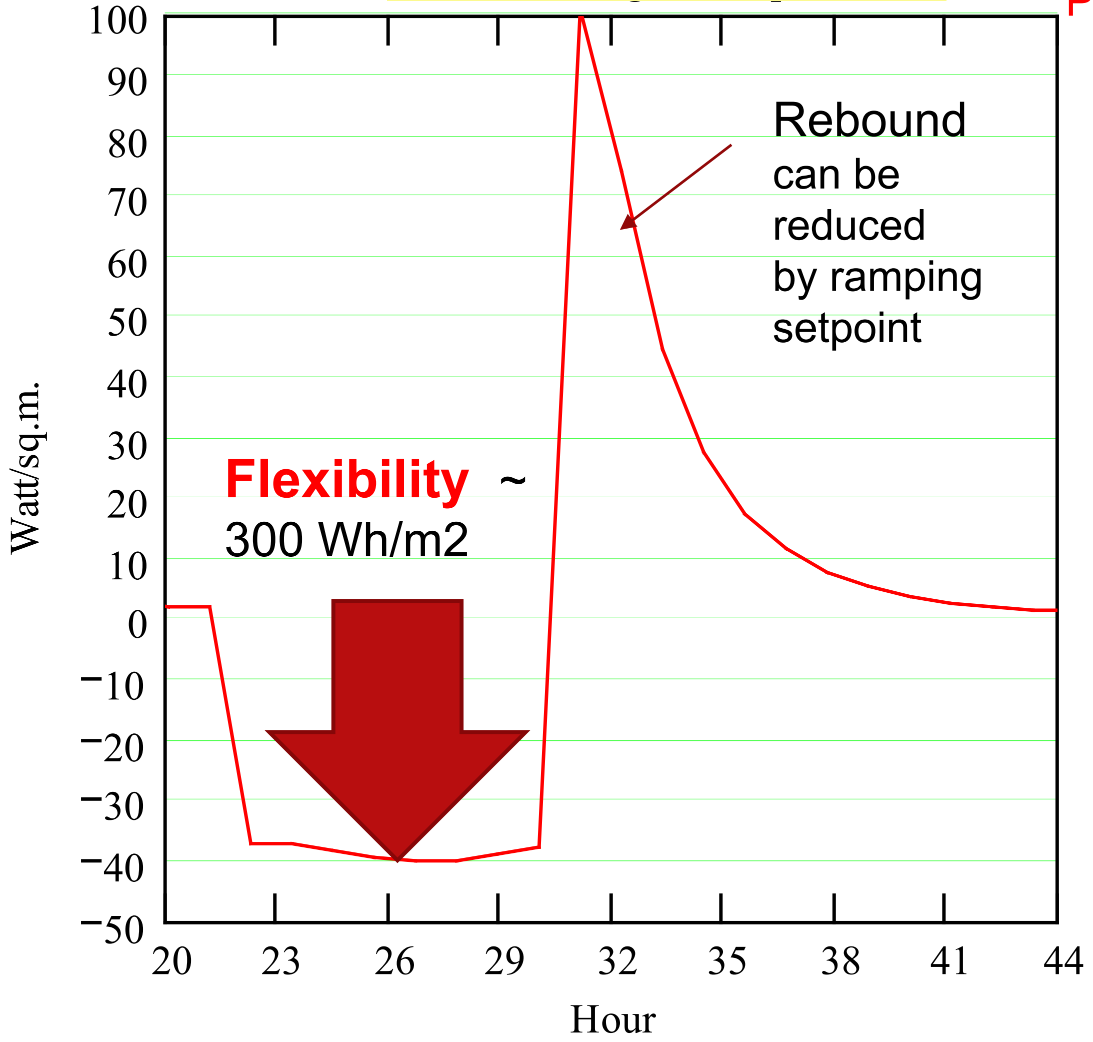
Preheat during daytime the radiant slab to reduce two demand peaks;
Electric grid utility will buy a maximum of 50 kW (net-metering)

Floor heating in perimeter zone
Setpoint reduced by 2 C

Ali Saberi,
PhD student



Floor heating reduction



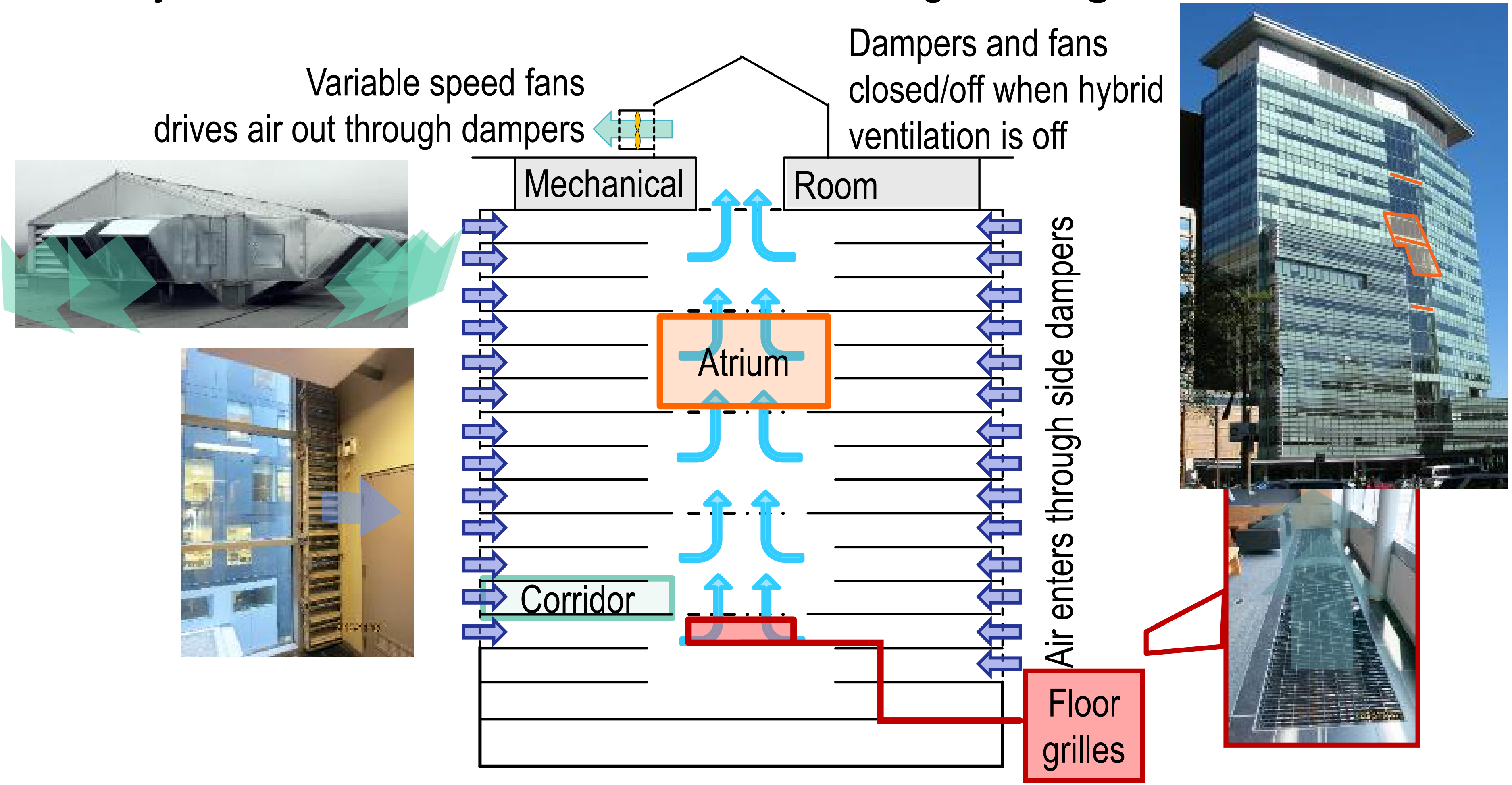
Flexibility ~ 300 Wh/m2

Rebound can be reduced by ramping setpoint

- **3rd order thermal network model** for perimeter zone with floor slab 15 cm. **Proportional control of floor surface.**
- Floor heating pipes in middle   Cold day in Feb. -11 C average

Case study: EV building – hybrid ventilation and its predictive control

- Concordia University (Montreal, Canada), EV building
- Hybrid ventilation of an institutional building with **high thermal mass**



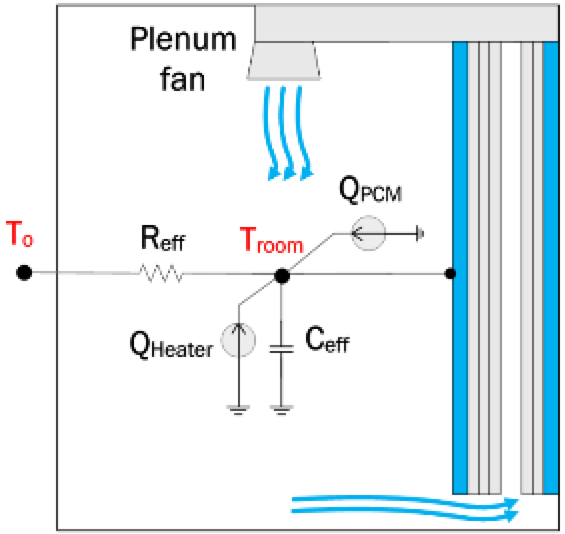
Variable speed fans drives air out through dampers

Dampers and fans closed/off when hybrid ventilation is off

Air enters through side dampers

H. Vallianos
D. Qi
L. Wang

Active thermal storage reduced order models



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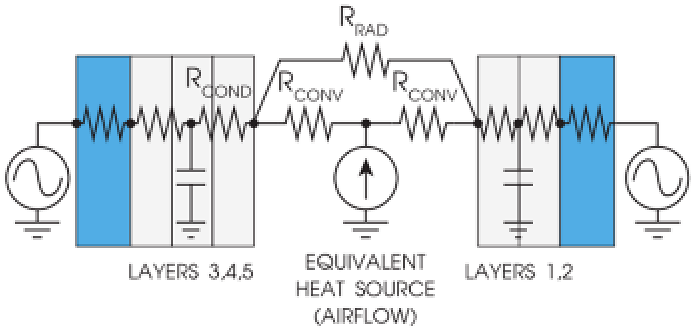
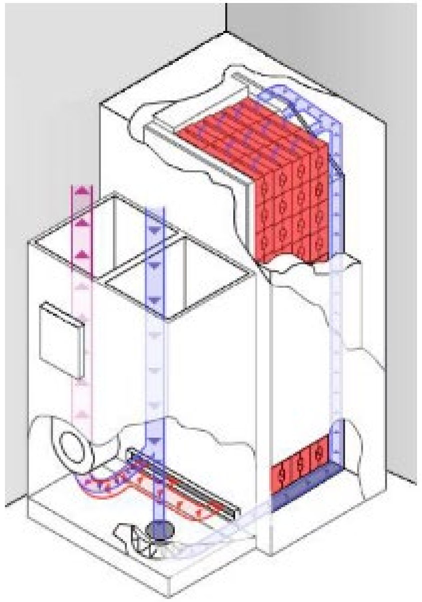


b

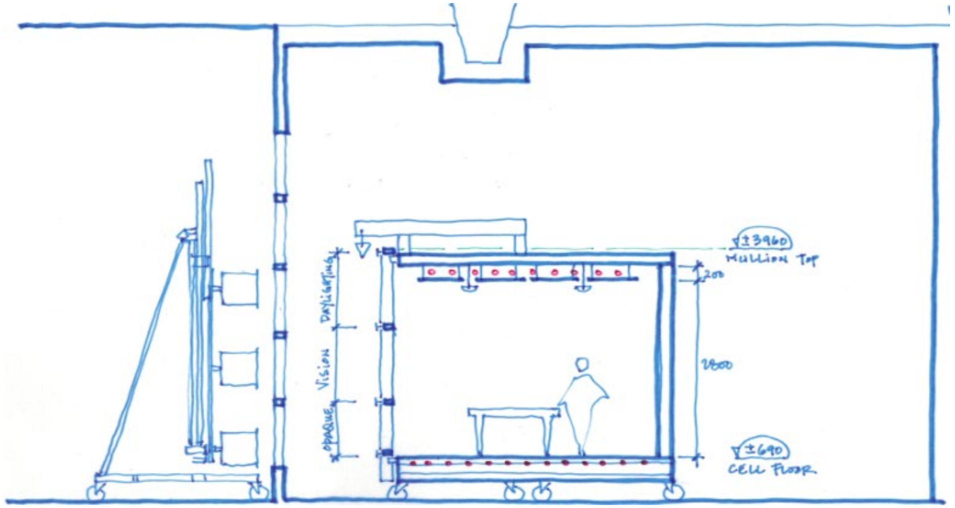
Reduced order models
to harness energy flexibility
and for MPC

1. Active PCM wall with airflow (Vasken, Tasos, Jennifer)
2. Thermelect high temperature storage in HVAC systems (Jen)
3. Floor heating/cooling (Ali)

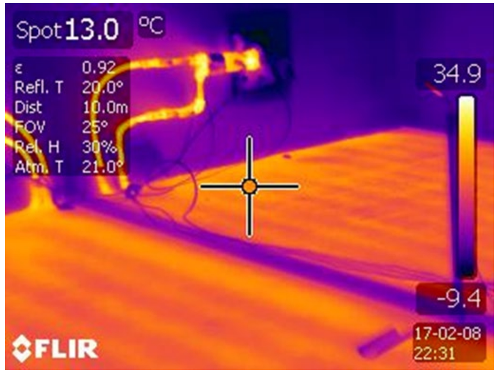


Development of theoretical transfer function models for different building and zone types

- Development of detailed theoretical frequency domain thermal network models.
- Distributed parameter elements employed to represent transient heat storage in building fabric layers.
- Models utilized to produce fundamental results on the frequency response characteristic of major transfer functions.
- **3rd order models found to be adequate for most purposes (e.g. MPC) – validated in SSEC (see example below for convective heating).**



$$\tilde{G}_{SG}(s) = \frac{2.27\times10^{-6}s^2 + 4.21\times10^{-10}s + 3.12\times10^{-14}}{s^3 + 4.17\times10^{-3}s^2 + 2.48\times10^{-7}s + 7.06\times10^{-13}} \quad [\mathrm{K/W}]$$



NSERC Smart Solar Buildings and Communities (SSBC) Strategic Research Network (2018-2024)

www.solarbuildings.ca

Andreas Athienitis
Scientific Director

Liam O'Brien
Associate Director

SSBC builds on the NSERC Smart Net-zero Energy Buildings Strategic Research Network (2011-2017) and the Solar Buildings Research Network (2005-2010)

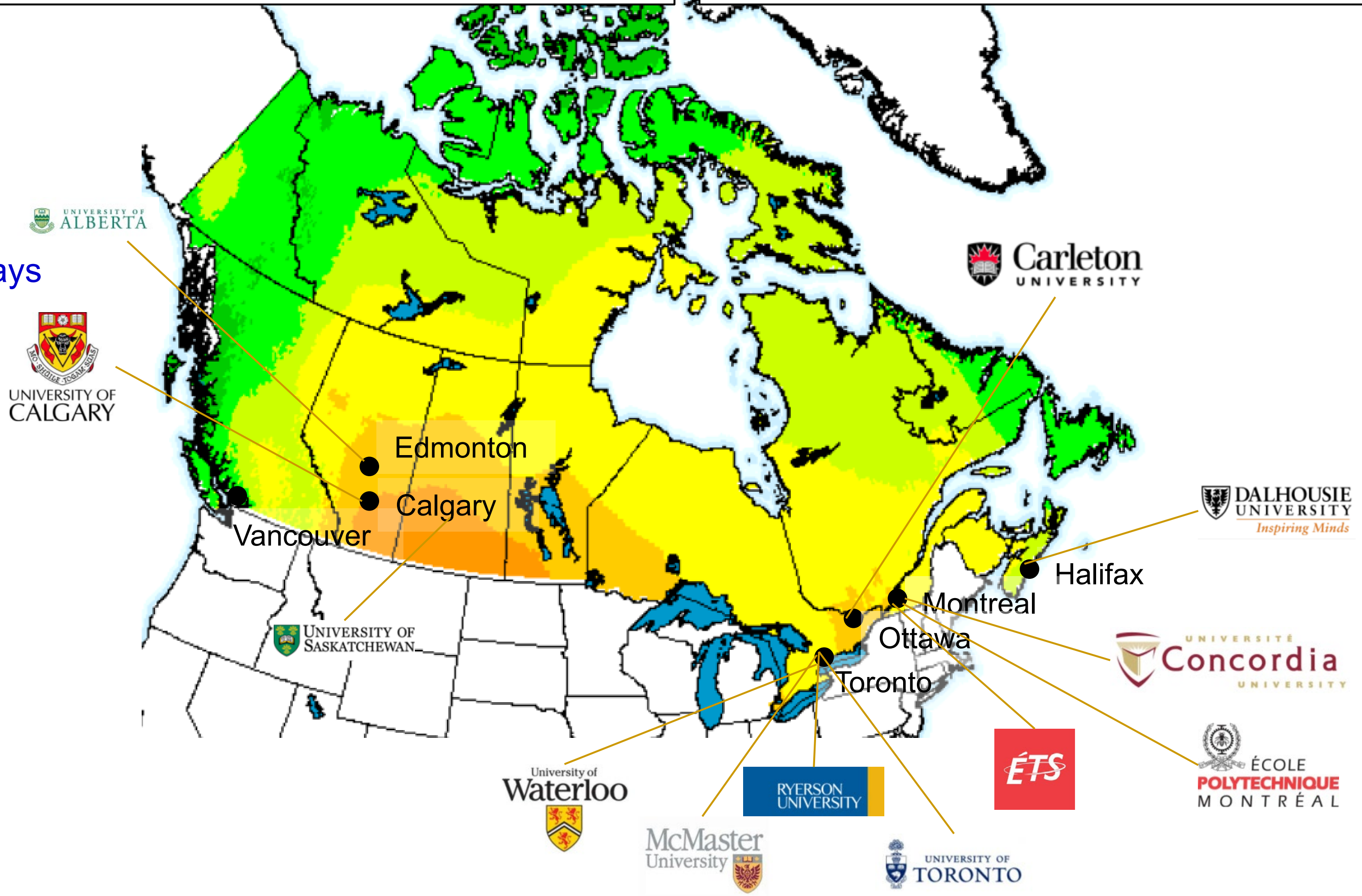
Background - SNEBRN

- **26 top researchers from 12 Universities**
- Building and energy industry leaders; key government partners – NRCan, Hydro Quebec, local distribution companies

Some important facts

- Most of Canada is quite sunny, with cold winters
- Ground temperatures 6-10 °C in most populated areas (lat 42-53° N)

Lat 53° N
Heating degree-days
5212



Legend

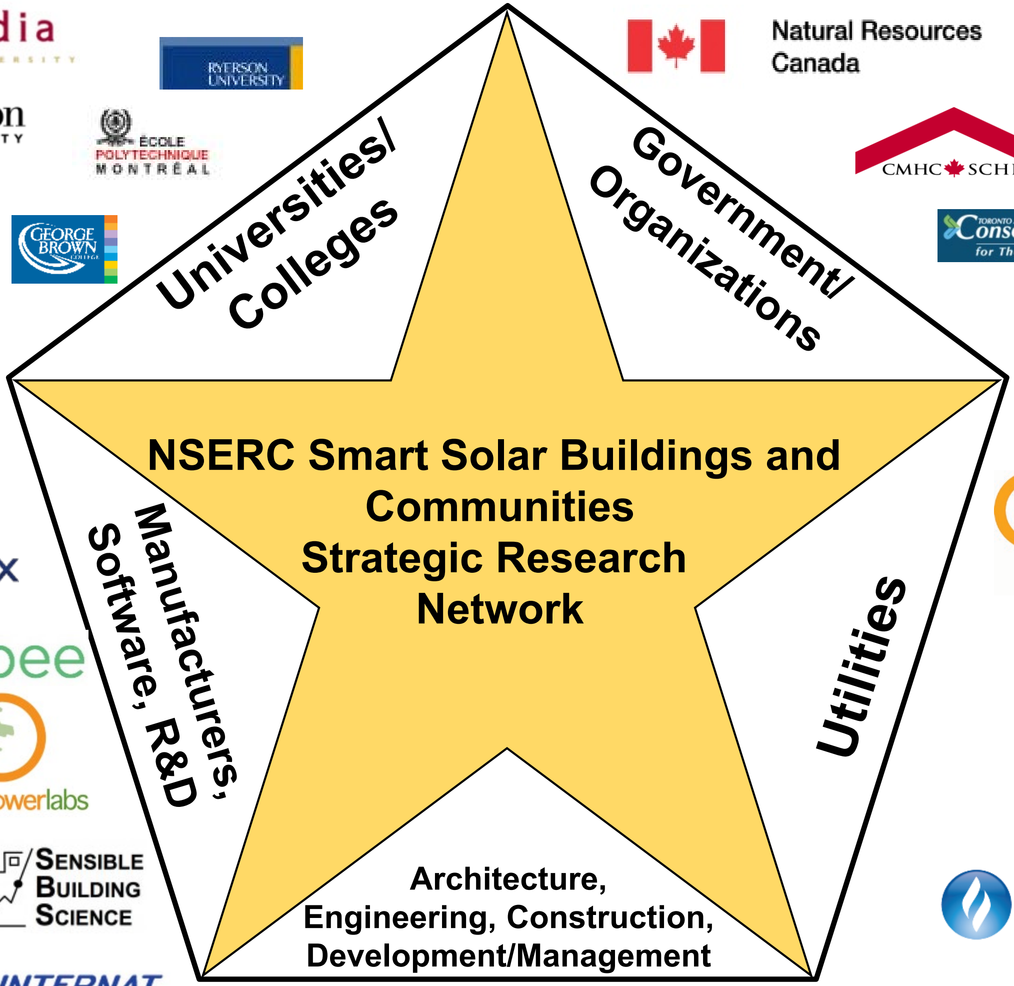
Photovoltaic potential (kWh/kW) South-facing, tilt=latitude Annual

🟦	0 - 500 kWh/kW
🟦	500 - 600
🟦	600 - 700
🟦	700 - 800
🟩	800 - 900
🟩	900 - 1000
🟩	1000 - 1100
🟨	1100 - 1200
🟨	1200 - 1300
🟧	1300 - 1400
🟥	1400 +

Lat 45° N
Heating degree-days
4519

PV potential map of **Canada with** location of the 12 SSBC Universities

Partnerships



Universities/ Colleges

Government/ Organizations

Utilities

Architecture, Engineering, Construction, Development/Management

Manufacturers, Software, R&D

NSERC Smart Solar Buildings and Communities Strategic Research Network

Dalhousie University Inspiring Minds

Université Concordia University

Ryerson University

Carleton University

McMaster University Inspiring Innovation and Discovery

École Polytechnique Montréal

University of Calgary

ÉTS

George Brown College

University of Waterloo

University of Saskatchewan

University of Alberta

Natural Resources Canada / Ressources naturelles Canada

CMHC SCHL

Canadian Home Builders' Association

Arctic Energy Alliance

Toronto and Region Conservation for The Living City

UQROP

City of Burlington

NRC·CNRC

Varennes

Hydro Québec Institut de recherche

HCE Energy Inc.

uniongas An Enbridge Company

CanadianSolar

ecologix

ecobee

Autodesk

greenpowerlabs

RYCOM

Sensible Building Science

Internat Energy Solutions

s2e

PageauMorel

Regulvar

Noventa Reimagining Energy

Landmark Homes it's what's inside

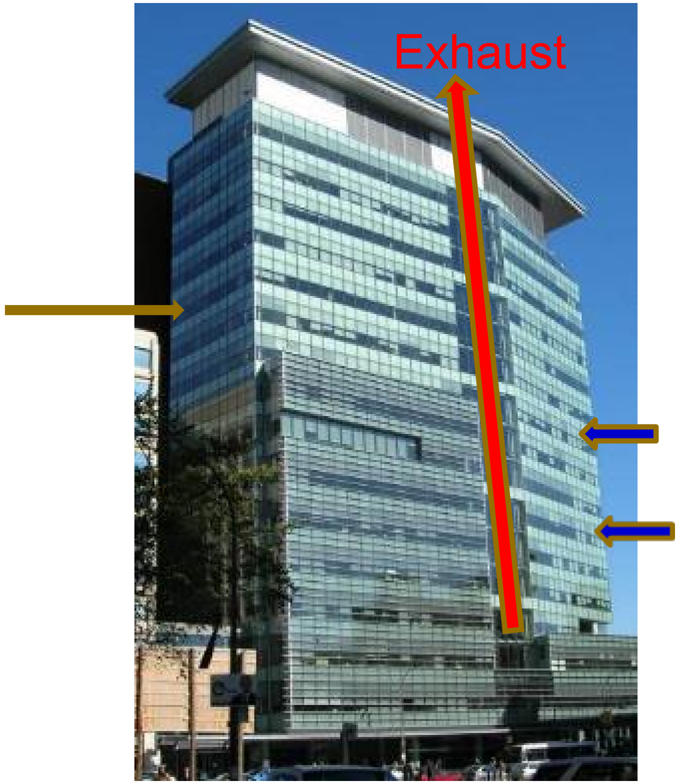
3One Structure

Killam Apartment REIT

PCL

Commercial/Institutional Buildings: some trends

- Electric lighting: transformation in building design that moved towards **smaller window areas until the 1950s;**
- Followed by evolution to air-conditioned “glass towers” with **large window areas**: more daylight – but higher cooling and heating requirements; now LED lighting;
- Currently: renewed interest in daylighting and natural/hybrid ventilation; eg **hybrid ventilation system** at Concordia EV building & predictive control (NSERC/HQ IRC);
- **Building-integrated photovoltaics (BIPV)**, possibly with heat recovery (BIPV/T) or semitransparent PV windows (STPV);
- PV modules have dropped in price by 90% in last 10 years! Can be used as building envelope element! But BIPV products needed.



Fresh air
Motorized
inlets

John Molson School of Business building at Concordia: **Novel BIPV/T system under NSERC SBRN network (2009)**

PV panels are same width as the curtain wall; spandrel sections could accommodate more PV

Just 288 m^2 was covered
Imagine possible generation with 3000 m^2 BIPV/T

Shades could be automatically controlled

Occupant behavior:

Note shade positions

IoT with smart sensors and machine learning can *facilitate automation of shades*

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

Smart Solar Buildings and Communities: The vision

- **Integrated (electricity and thermal energy flows)**: at the building and at the community level

- **Exploiting local renewable energy**: BIPV, BIPV/T, STPV, solar thermal, seasonal heat storage with heat pumps

- **Resilient**: interconnected micro-networks where one part of the network can go down without affecting the rest; survive emergencies largely based on solar and geothermal energy; apply to infrastructure (e.g. bridges, tunnels, roads, public spaces); application to Arctic and remote communities

- **Intelligent**: Advances in sensors, **information and communication technologies** (e.g., IoT) and **artificial intelligence** offer opportunties to develop systems capable of **auto-optimization, auto-learning, and auto-correction**

Theme 1: Building integration of photovoltaics, active building envelope systems and HVAC

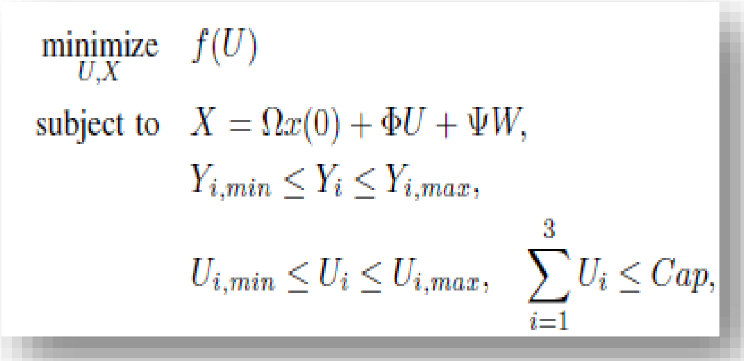
Co-leaders: Ian Beausoleil-Morrison (Carleton), Hua Ge (Concordia)
C. Simonson, C. Cruickshank, M. Collins, Y. Chen, U. Berardi, T. Stathopoulos, N. Kherani, A. Athienitis
Partners: Canadian Solar, Unicel….

- BIPV: BIPV/T, semitransparent PV windows
- Active daylighting systems
- Solar thermal systems; integration with heat pumps and thermal storage
- Heat pump, HVAC and BIPV/T integration and optimization

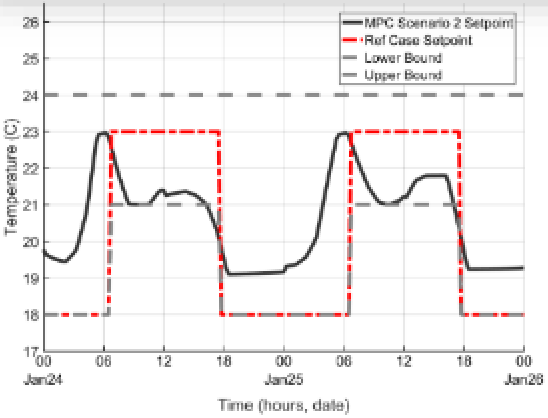
Theme 2: Optimal operation of smart, comfortable and energy-flexible buildings

Co-leaders: Alan Fung (Ryerson) and Jose Candanedo (NRCan)
W. O’Brien, R. Zmeureanu, M. Kummert, B. Gunay, A. Athienitis
Partners: Canmet, Regulvar, HQ….

- Smart building with occupant-centric control strategies
- Model-based controls
- Forecasting and predictive controls at the zone and single building level
- Building energy flexibility and grid interaction

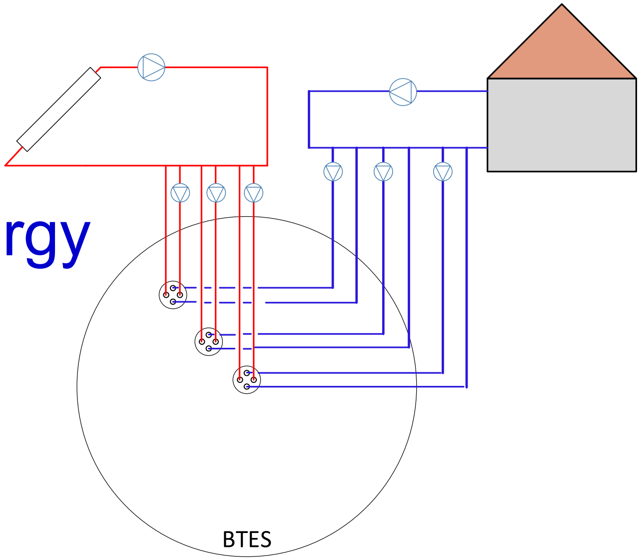


$$\begin{aligned} \underset{U,X}{\text{minimize}} \quad & f(U) \\ \text{subject to} \quad & X = \Omega x(0) + \Phi U + \Psi W, \\ & Y_{i,min} \leq Y_i \leq Y_{i,max}, \\ & U_{i,min} \leq U_i \leq U_{i,max}, \quad \sum_{i=1}^{3} U_i \leq Cap, \end{aligned}$$



Theme 3: Community energy systems that optimize utilization of distributed renewable energy sources

Co-leaders: Michel Bernier (Polytechnique) and Jim Cotton (McMaster)
M. Lightstone, L. Swan, S. Bucking, P. Pillay, B. Kankar
Partners: Canmet, HQ …..

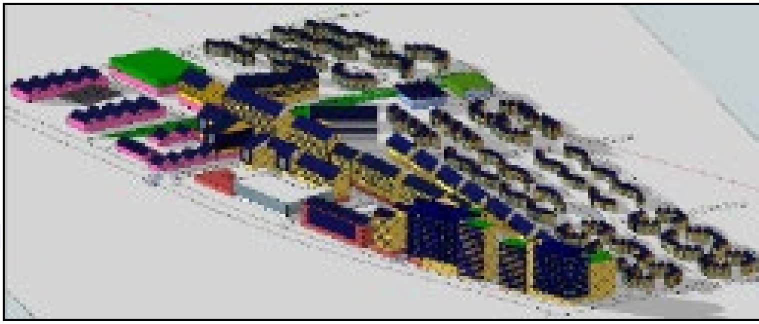


- Community level design of thermal and electrical storage; energy flexibility
- Islanded operation during emergencies such as ice-storm '98
- Multi-building interactions and optimization
- Seasonal energy storage; apply to infrastructure and public spaces
- Community level energy management – apply AI to develop self-adaptive optimal strategies; integrate building level models, reduced order community models
- Application to northern and remote communities

Theme 4: Integrated building/community modelling, design and operation, input to national policy

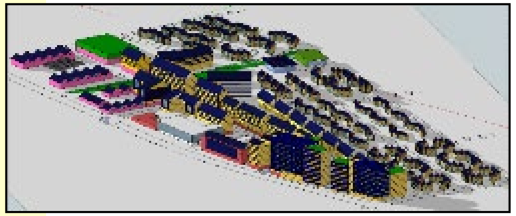
Co-leaders: Michaël Kummert (Polytechnique) and Andreas Athienitis (Concordia)
L. Wang, K. Bhattacharya, P. Pillay, T. Stathopoulos, C. Hachem-Vermette
Partners: s2e, Canadian Solar, Municipalities, CHBA, CMHC, CanmetENERGY

- Promising clean energy and smart technologies and their integration will be studied to provide input to national policies – e.g. potential towards GHG reduction until 2050 while **achieving energy resilience**;
- **Occupant behavior models and renewable energy incentive measures** to optimize the demand and renewable energy generation profiles from communities/building clusters;
- Study of **long-term built environment solar design strategies for deep reductions in GHG emissions and resilience**;
- Techniques such as **predictive control** based on weather forecasting and **energy flexibility** applied on a large scale to aid community planning; integration of Evs.



Towards smart high performance resilient buildings

BUILDING SYSTEMS	**CURRENT BUILDINGS**	**FUTURE SMART BUILDINGS**
Building fabric	Passive, not designed as an energy system	Optimized for passive design and integration of active solar systems
Heating & Cooling	Large oversized systems	Small systems optimally controlled; integrated with solar, CHP; *Communities: seasonal storage and district energy; smart microgrid, EVs*
Solar systems	No systematic integration – an after thought	Fully integrated: daylighting, solar thermal, PV, hybrid solar, geothermal systems, biofuels
Building operation	Building automation systems not used effectively	Predictive control to harness energy flexibility; online demand prediction; grid-friendly.
Integration with design	**Operating strategies not optimized with design**	**Integrated design that considers optimized operation; optimize form and basic features in early design**



Smart community