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

Modelling, Design and Operation of Net-zero Energy Buildings and Lessons Learned

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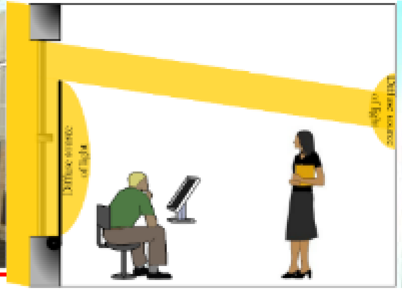
Major international trends in high performance buildings

- Adoption of net-zero energy (ASHRAE) as a long term goal; nearly zero or net-zero ready in some cases until 2030. Carbon-neutral 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; charging EV; 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

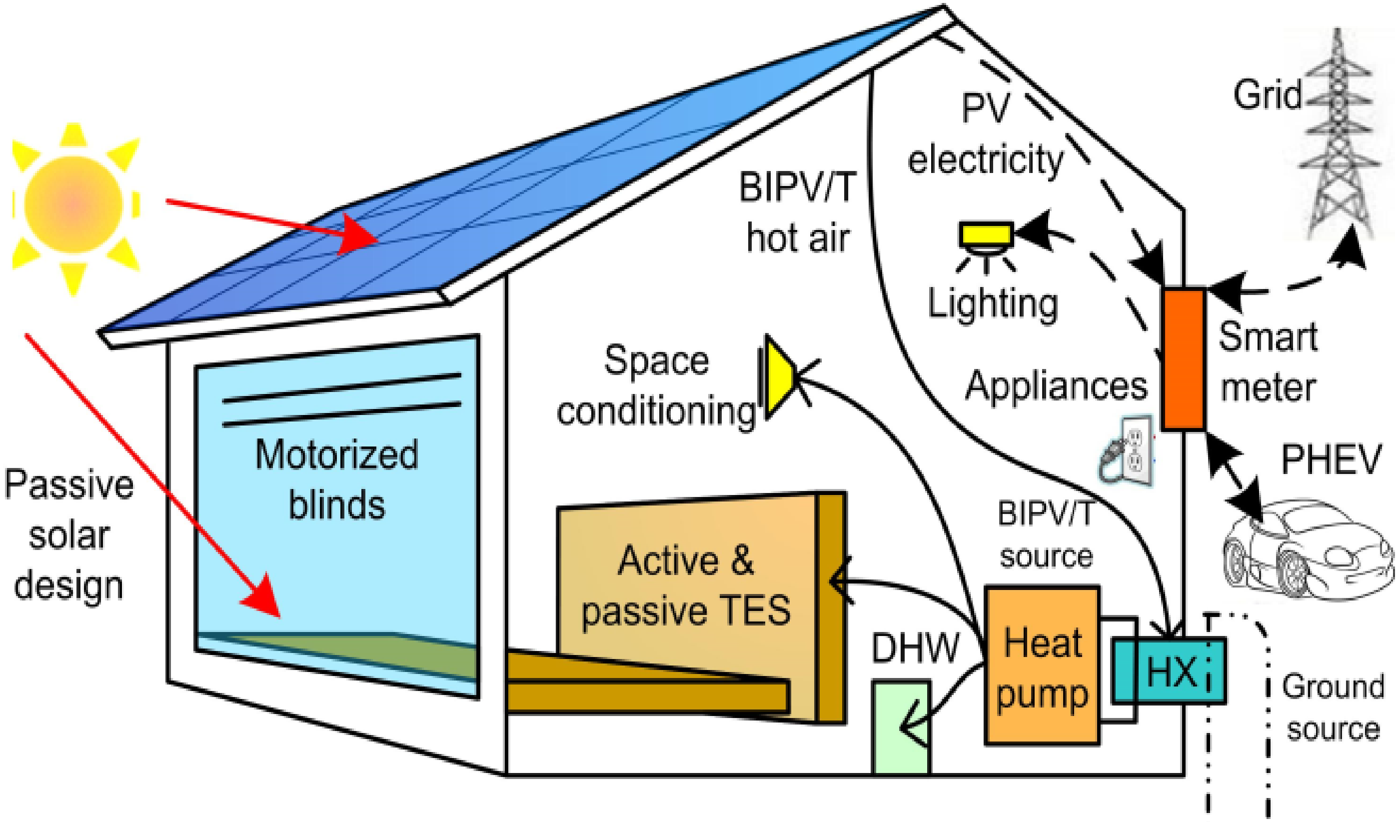
EcoTerra **BIPV/T**

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



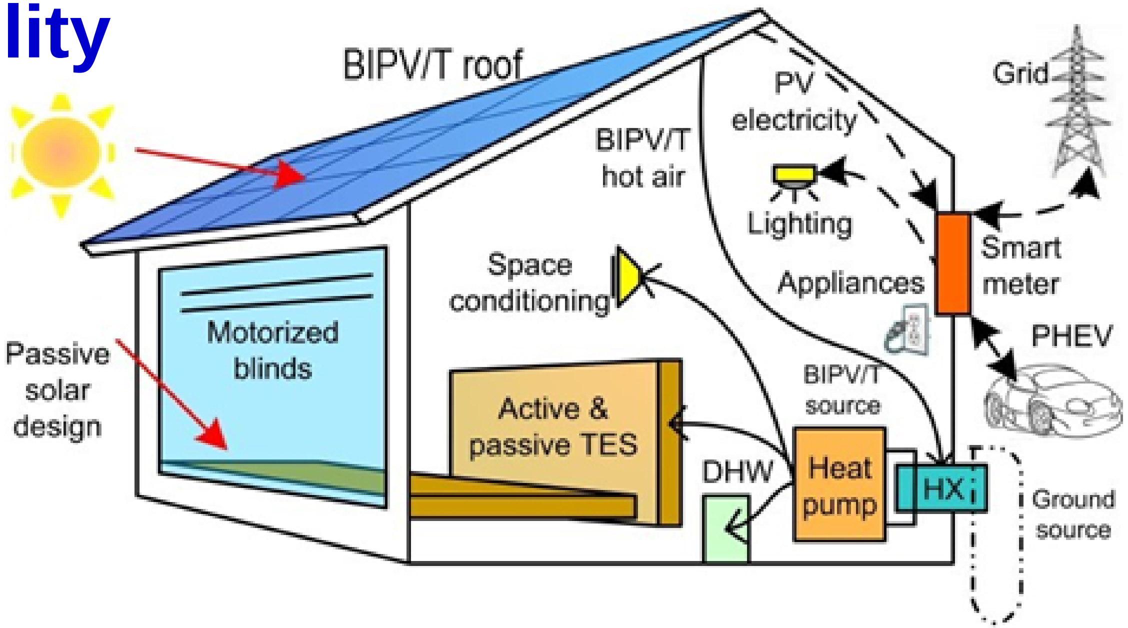
Integrated approach to **energy efficiency and passive design**

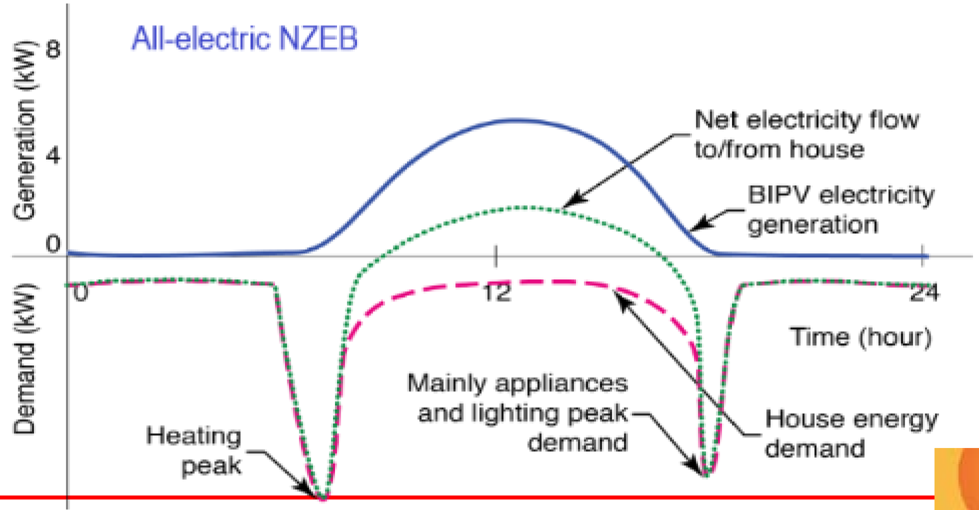
Integrated design & operation

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

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

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

Smart Net-Zero Energy Buildings (NZEBs)

- Net-zero annual energy balance: many possible definitions depending on boundary: House? Community? Net-zero energy cost?
- Net-zero is an objective target that promotes an integrated approach to energy efficiency and renewables; path to net-zero is important
- Why smart? NZEBs must be comfortable and optimally interact with a smart grid
- NSERC **S**mart **N**et-zero **E**nergy **B**uildings Strategic **R**esearch **N**etwork (SNEBRN) – (15 universities and about 20 partners); helped accelerate research on Smart NZEBs in Canada

Solar Optimization and Integration

- The solar optimization process refers to optimization of form so as to:

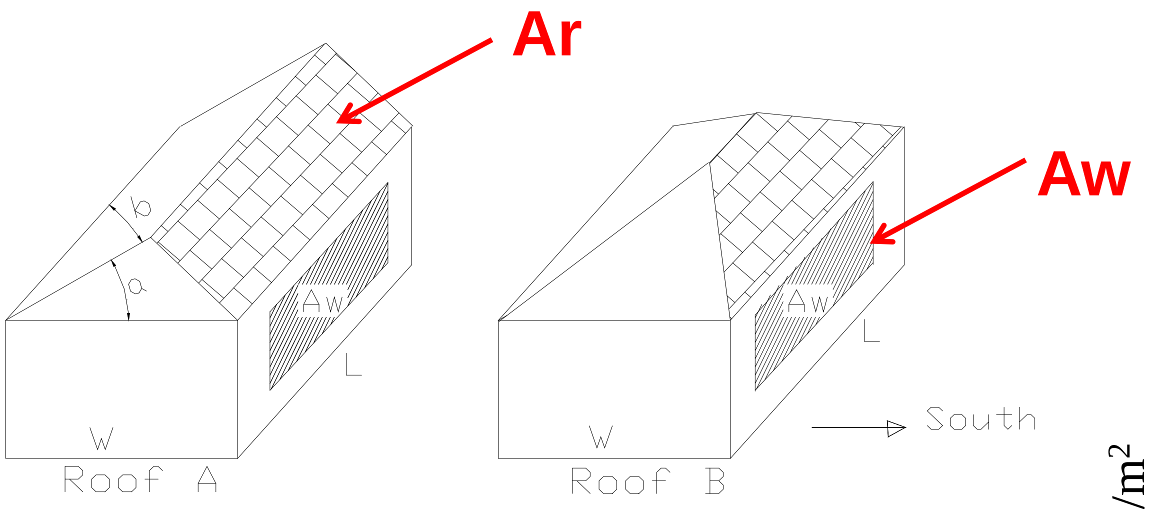
  (i) capture as much solar radiation as possible on the two main surfaces facing near south – a façade and a suitably oriented roof section,

  (ii) to utilize as much as possible of the captured solar energy as daylight and/or to be converted to electricity and heat.

  (iii) design for passive cooling

- Functional integration, architectural and aesthetic.

Optimization of buildings for solar collection

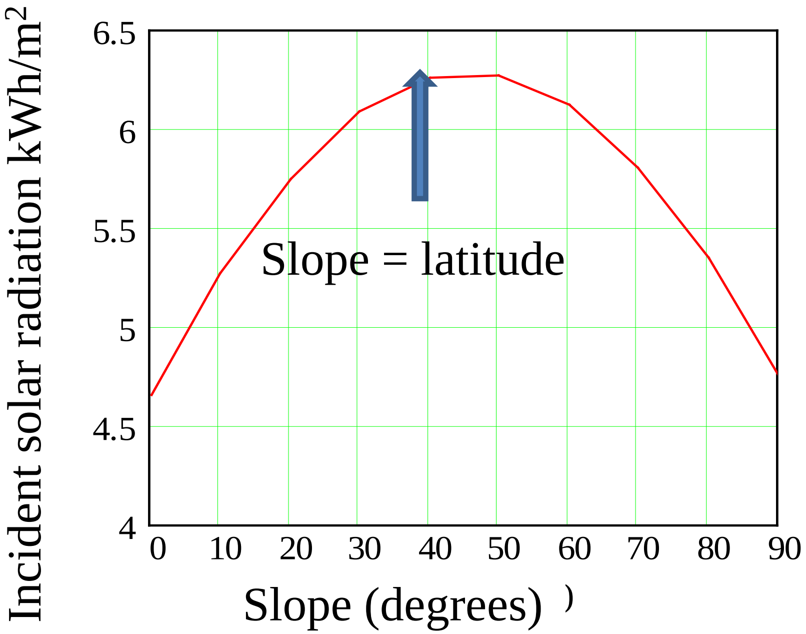


Two roof forms for the same floor plan

Important design variables:
Roof slope and aspect ratio L/W
Also window area

Slopes 40-50 degrees desirable
Aspect ratio higher than 1; around 1.3

Solar energy on roof – Montreal lat. 45 N



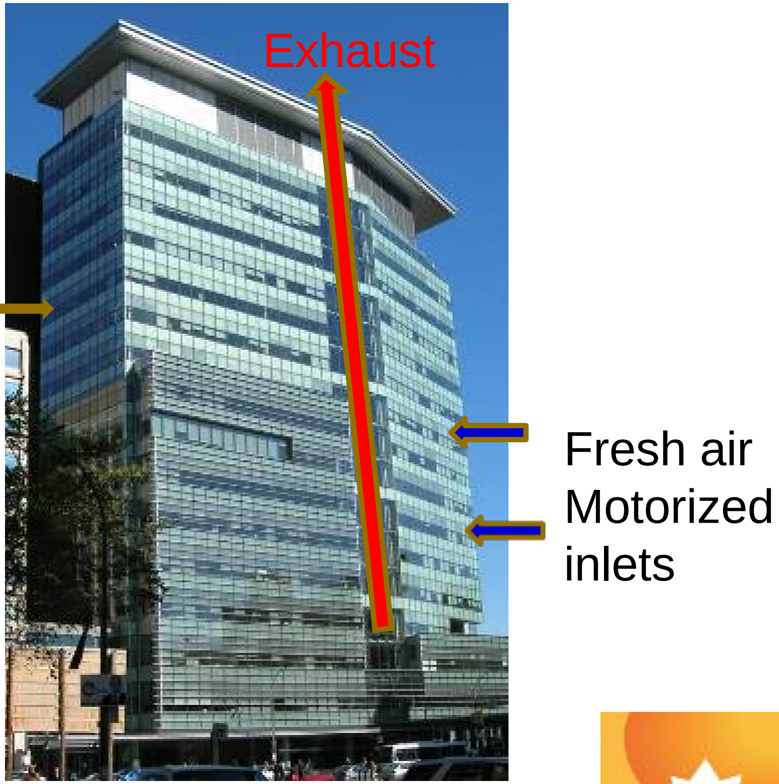
Optimize surfaces Ar and façade Aw simultaneously

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;



- **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!

Building Integration of PV

- Into roofs or facades, with energy system of building.
- **Roofs need to shed water: think of PV panels doing some of the functions of roof shingles**; shingles overlap hiding nails.
- Functional integration, architectural and aesthetic; recover heat (BIPV/T), and transmit daylight in semitransparent PV (STPV).

Not just adding solar technologies on buildings

*PV overhangs Queen's University (**retrofit**)*

Athienitis house (BIPV/T)

EcoTerra™ EQuilibrium™ House (Alouette Homes)
an SBRN-led demo project (2007)

2.84 kW Building-integrated photovoltaic-thermal system

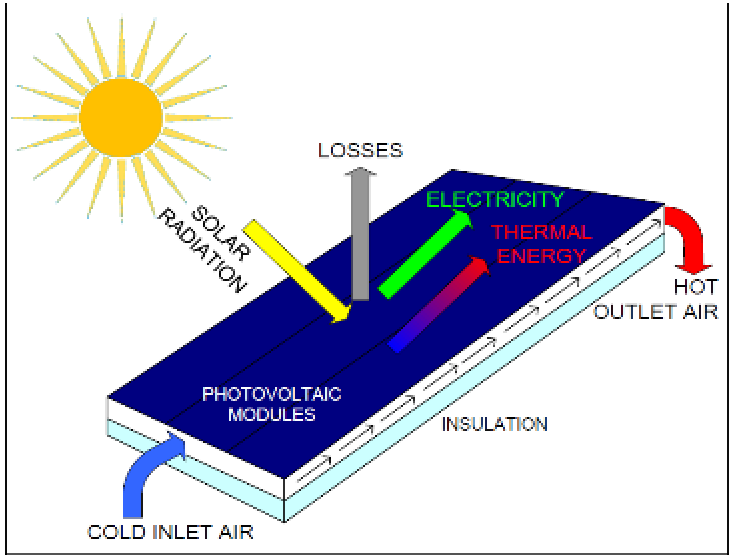
Passive solar design: Optimized triple glazed windows and mass

Ground-source heat pump

BIPV/thermal – integration in EcoTerra House

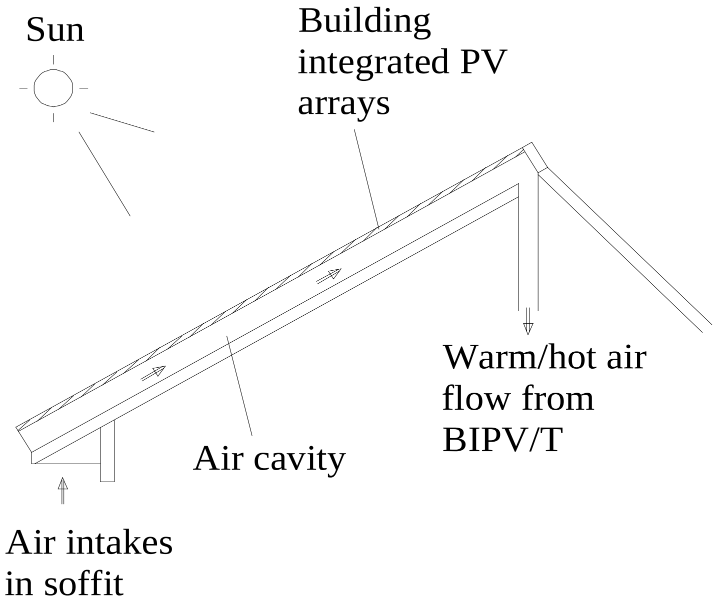
- Building integration: integration with the roof (envelope) and with HVAC
- BIPV/T – (photovoltaic/thermal systems): heat recovered from the PV panels, raising overall solar energy utilization efficiency
- Heat recovery may be open loop with outdoor air or closed loop with a circulating liquid; possibly use a heat pump
- **Open loop air system** used because it can work for a long time with little maintenance and no problems

EcoTerra™



Open loop air BIPV/T

BIPV/T roof construction in a home builder factory as one system – a Canadian innovation under the NSERC Solar Buildings Research Network



Based on research and simulation models developed and BIPV/T prototypes tested outdoors

Partnership included university researchers and students, prefabricated home builder, utility and government lab

Prefabrication: Assembly of House Modules (in about 5 hours)




Prefabrication (pre-engineered) of NZEBs can reduce cost of BIPV through integration

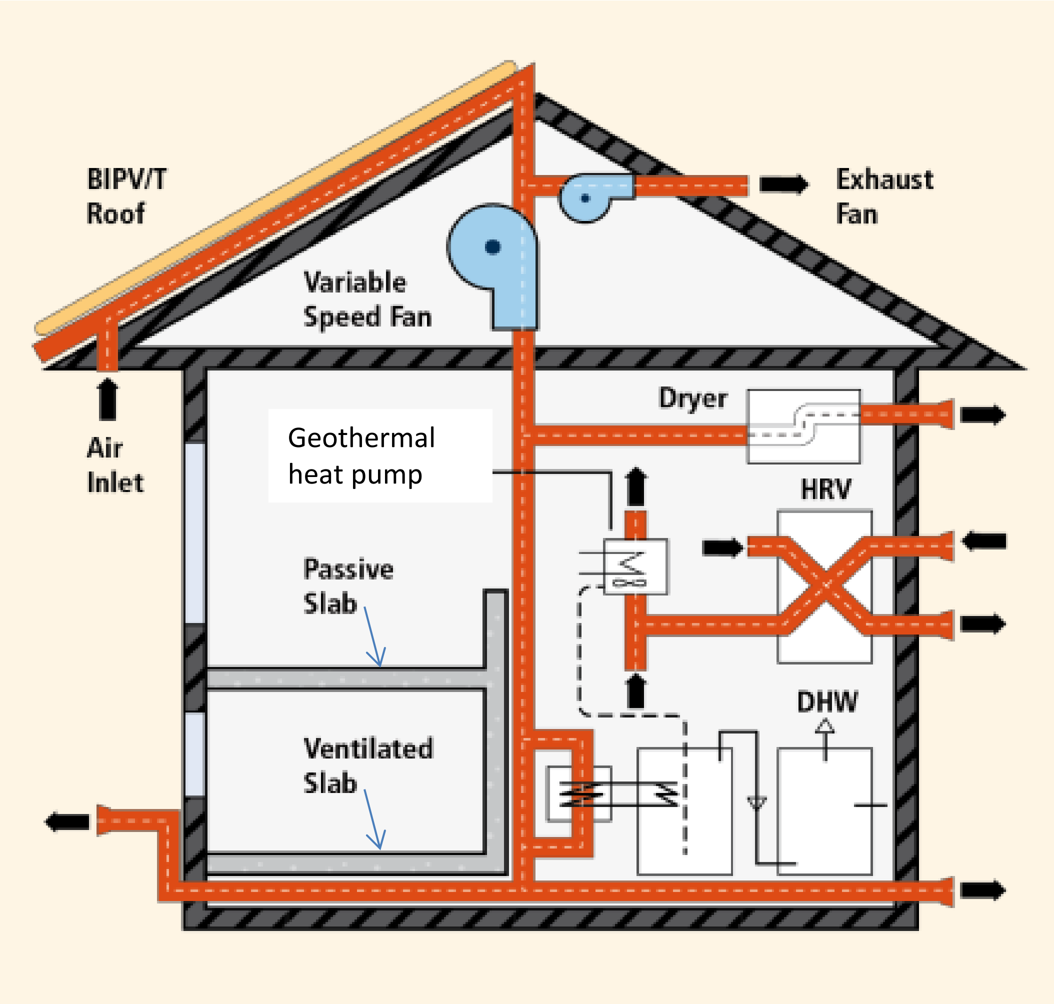
Quality of installation is enhanced

Passive design and integration with active systems

Near net-zero house; a higher efficiency PV system covering same area would result in net-zero.

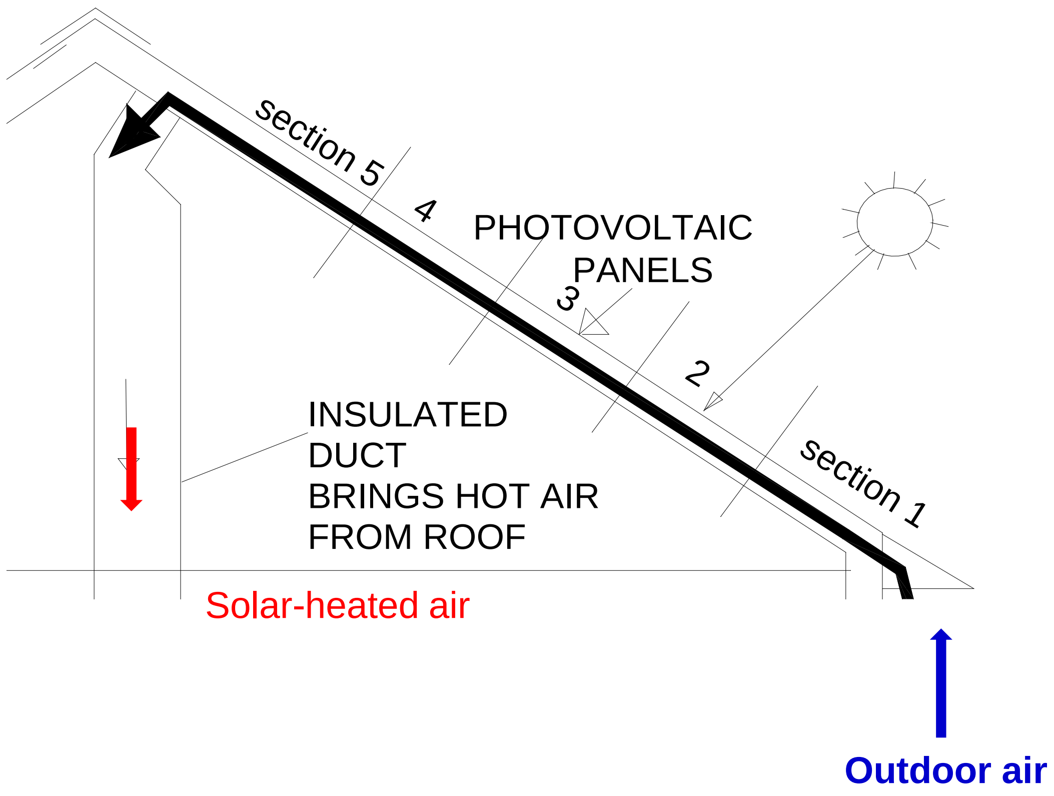
Study of occupancy factors indicated importance of controls.

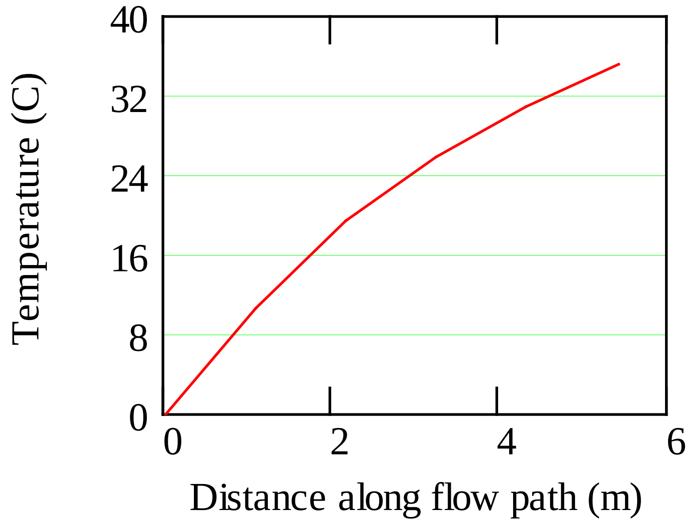
IEA Task 40 case study



EcoTerra energy system

BIPV/T roof in 5 sections for analysis - Energy model

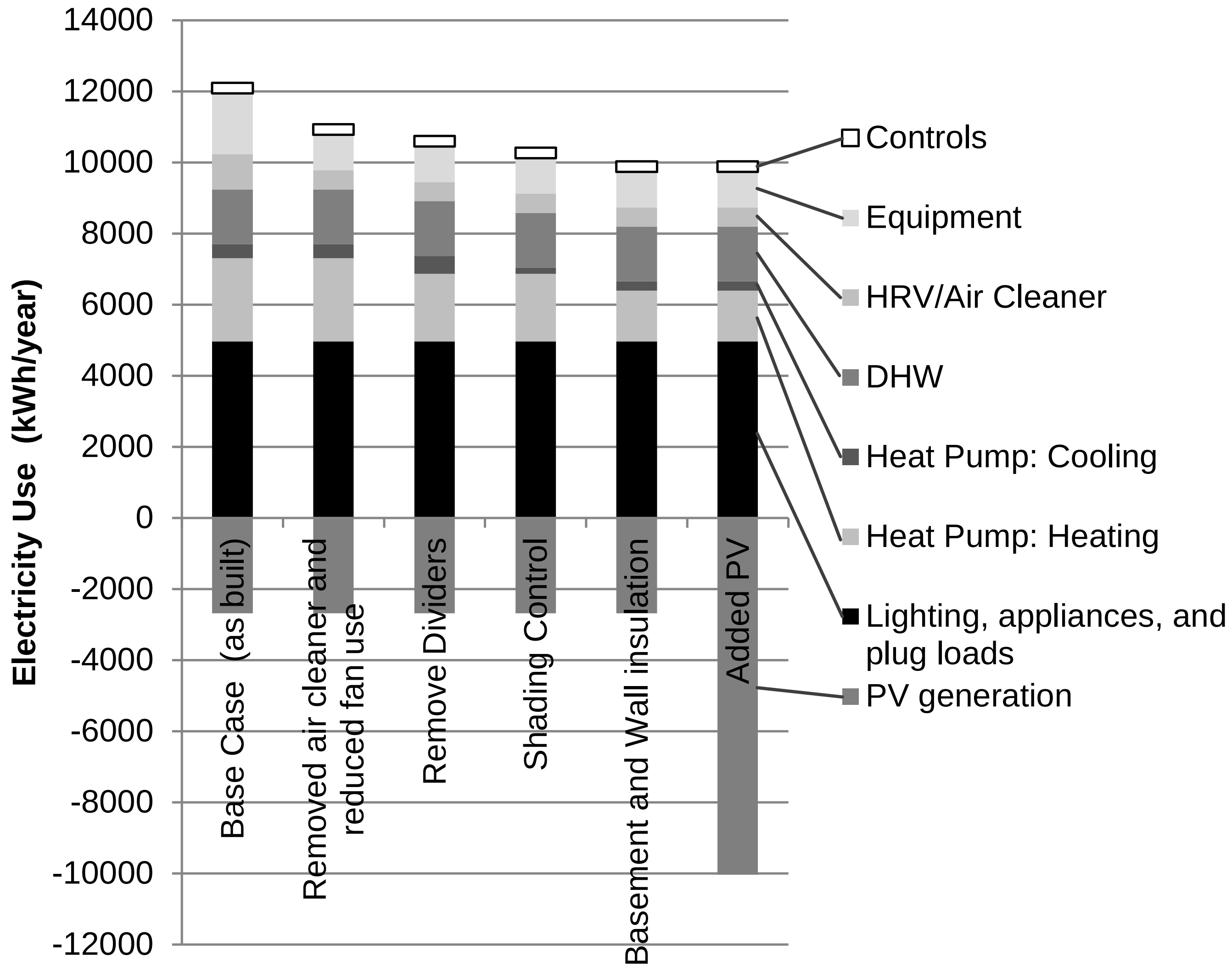


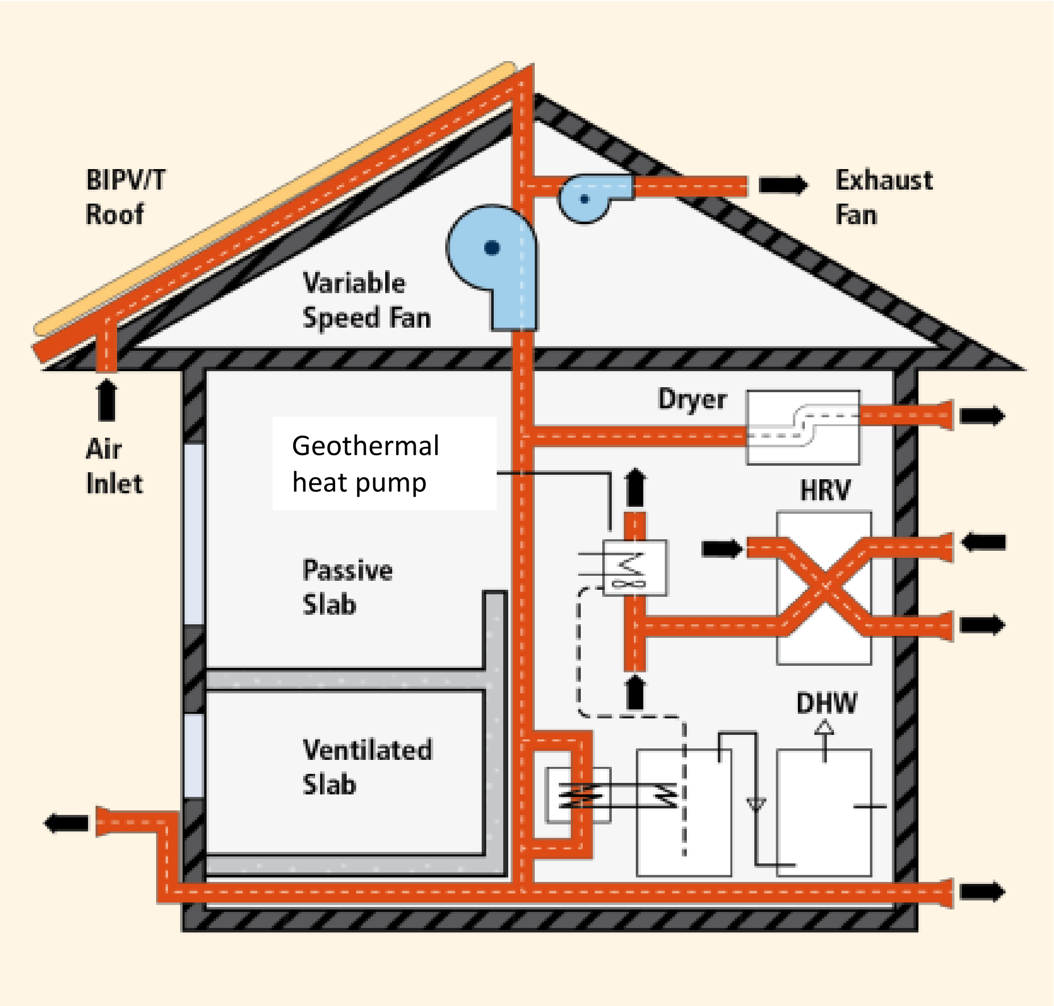


An open loop air system is utilized for the BIPV/T system as opposed to a closed loop to avoid overheating the photovoltaic panels

Electrical and thermal models are linked since electrical efficiency of PV is a function of temperature (increases with lower temperatures of PV)

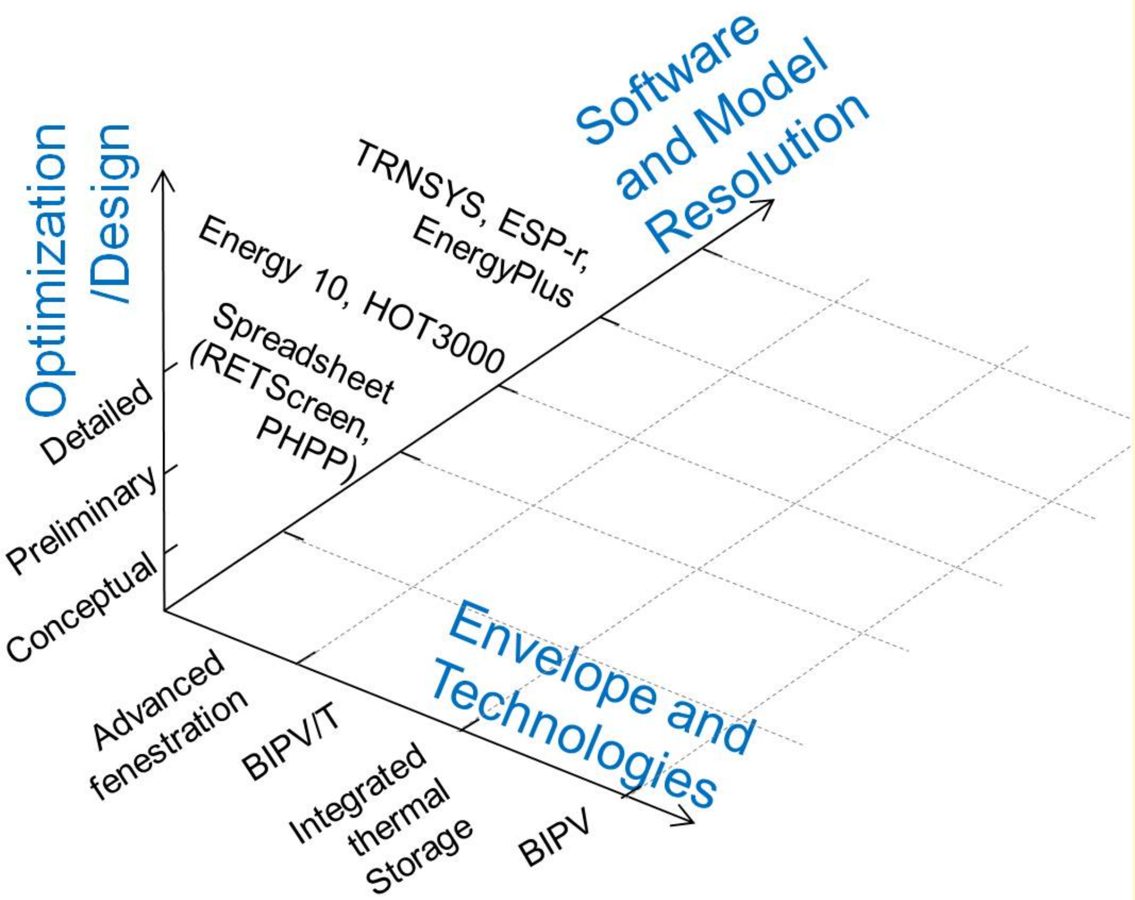
EcoTerra archetype redesign simulation studies



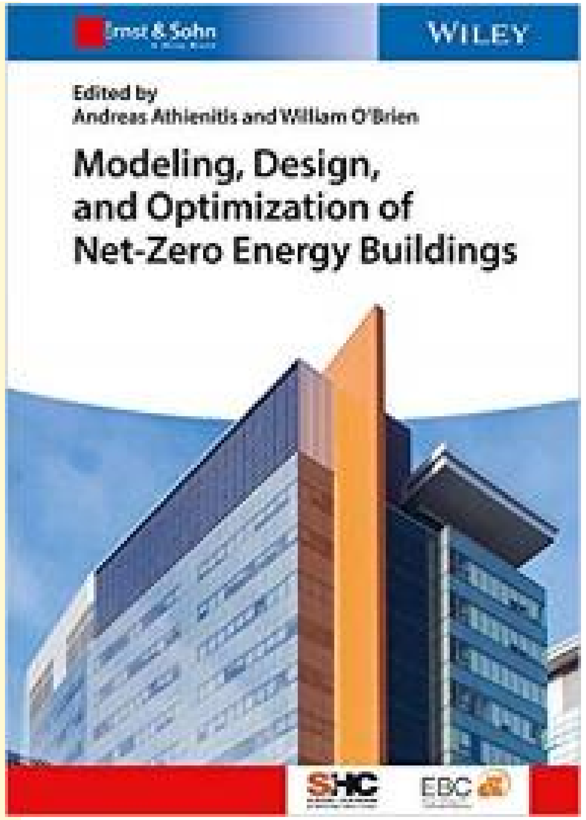


Replacement of roof PV (amorphous Si) With high efficiency C-Si makes house net-zero

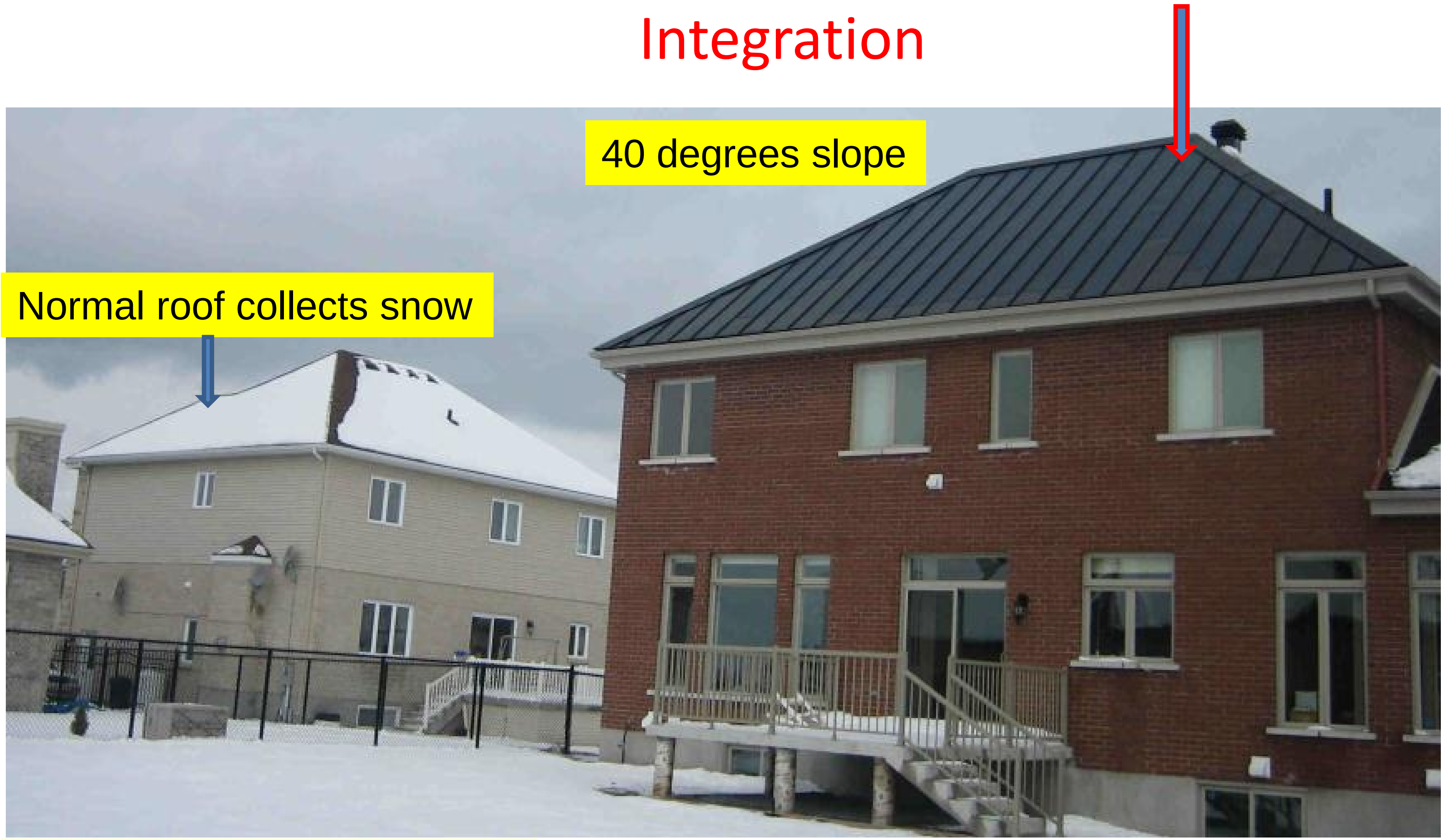
Model resolution in building simulation and design



- What is the appropriate **model resolution** for each stage of the design?
- What is **the role of simple spreadsheet-based tools** versus more advanced **detailed simulation?**
- What other tool **capabilities are needed to model new technologies such as building** fabric-integrated storage (PCMs), and active envelopes (e.g. BIPV/T)?



Resilience: Note snow melting from BIPV/T roof Integration



Note difference in south facing window areas

Athienitis house, Domus award finalist

Passive air circulation in BIPV/T melts snow in winter.

Private project

Athienitis House (2006)
Domus award finalist

Integration – BIPV/T (1.9 kW_e)
Passive solar – **superior comfort**
Geothermal system (2-ton)
Efficient controls

Passive solar design + BIPV/T + Geothermal + efficient 2-zone controls

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

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

New Varennes Municipal Library (2016) – Solar NZEB - DESIGN

South elevation – before final

Official opening:
May 16, 2016

2017 sq.m. NZEB

First public institutional designed solar NZEB in Canada
110 kW BIPV (part BIPV/T), Geothermal
Radiant heating/cooling, passive solar

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.**

PRESENTLY MONITORING PERFORMANCE & OPTIMIZING OPERATION

Varennes Library: living lab

Multi-Functional Library

First Public Canadian Solar NZEB

Rendering just before final design; note skylights

EV charging

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

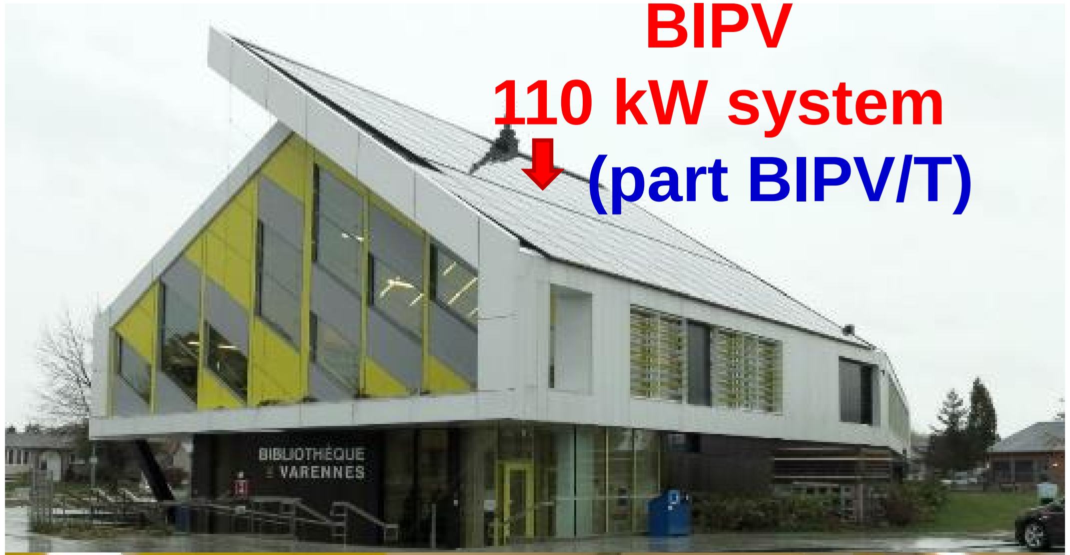
- Natural cross-ventilation
- Exterior fixed solar shading

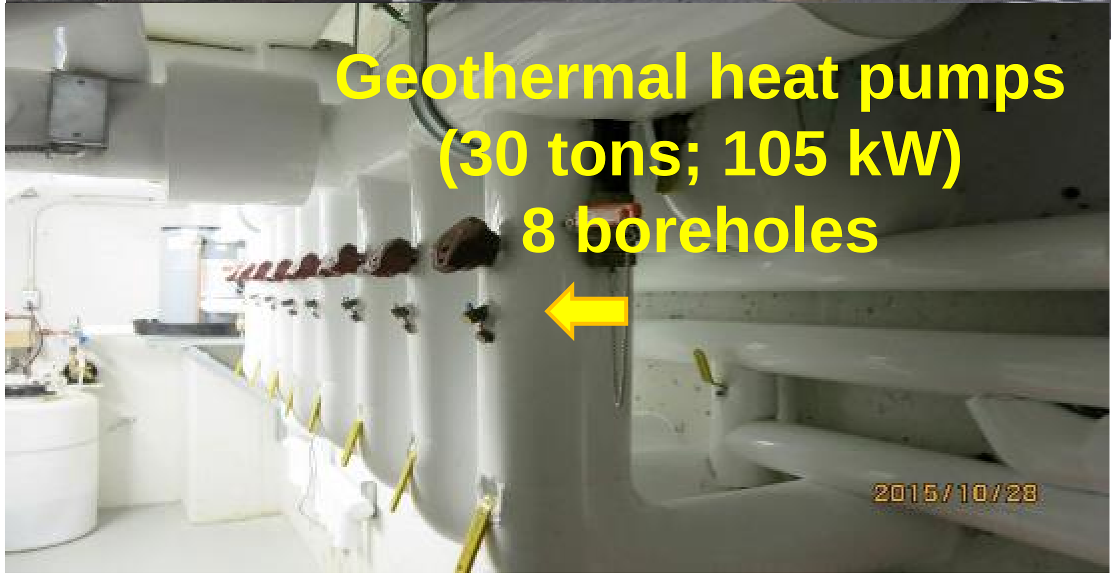
Window to wall ratios

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

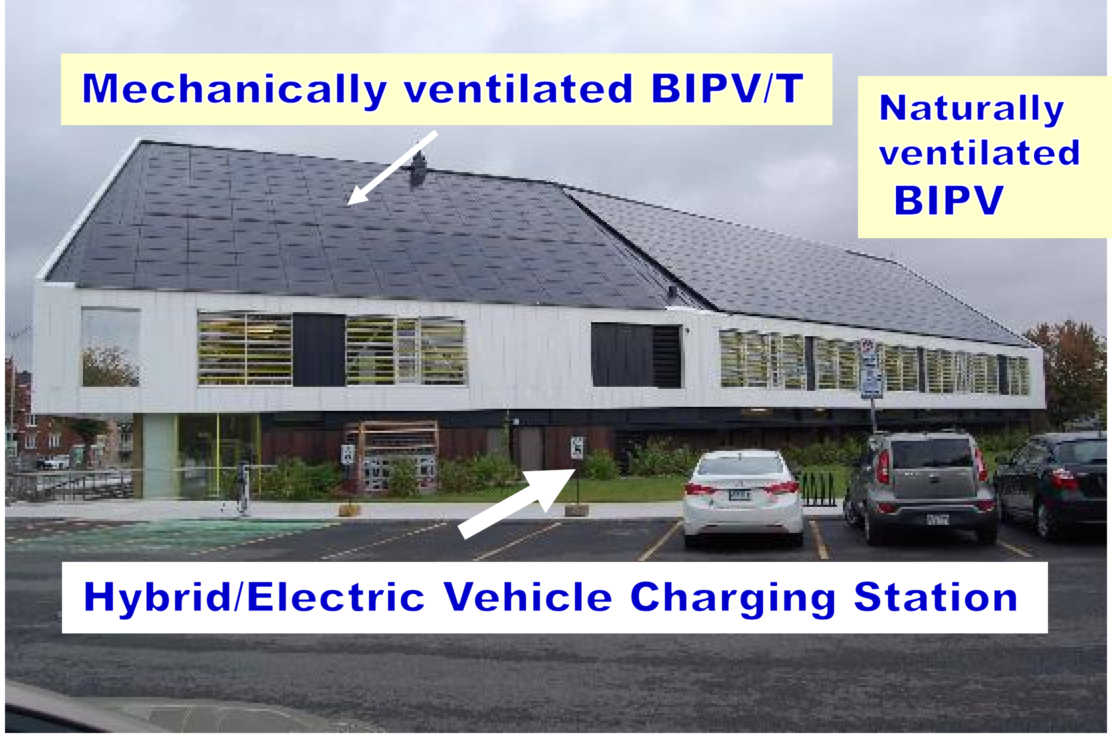
Building has become **a living lab**: photo from class visit

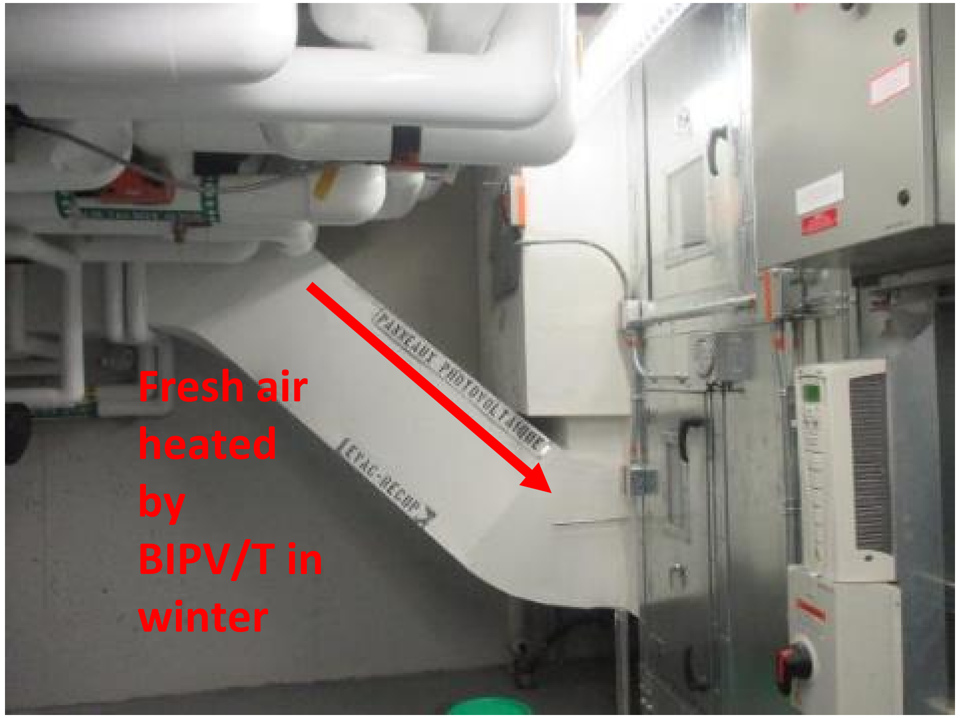
Varennes Library – key features





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

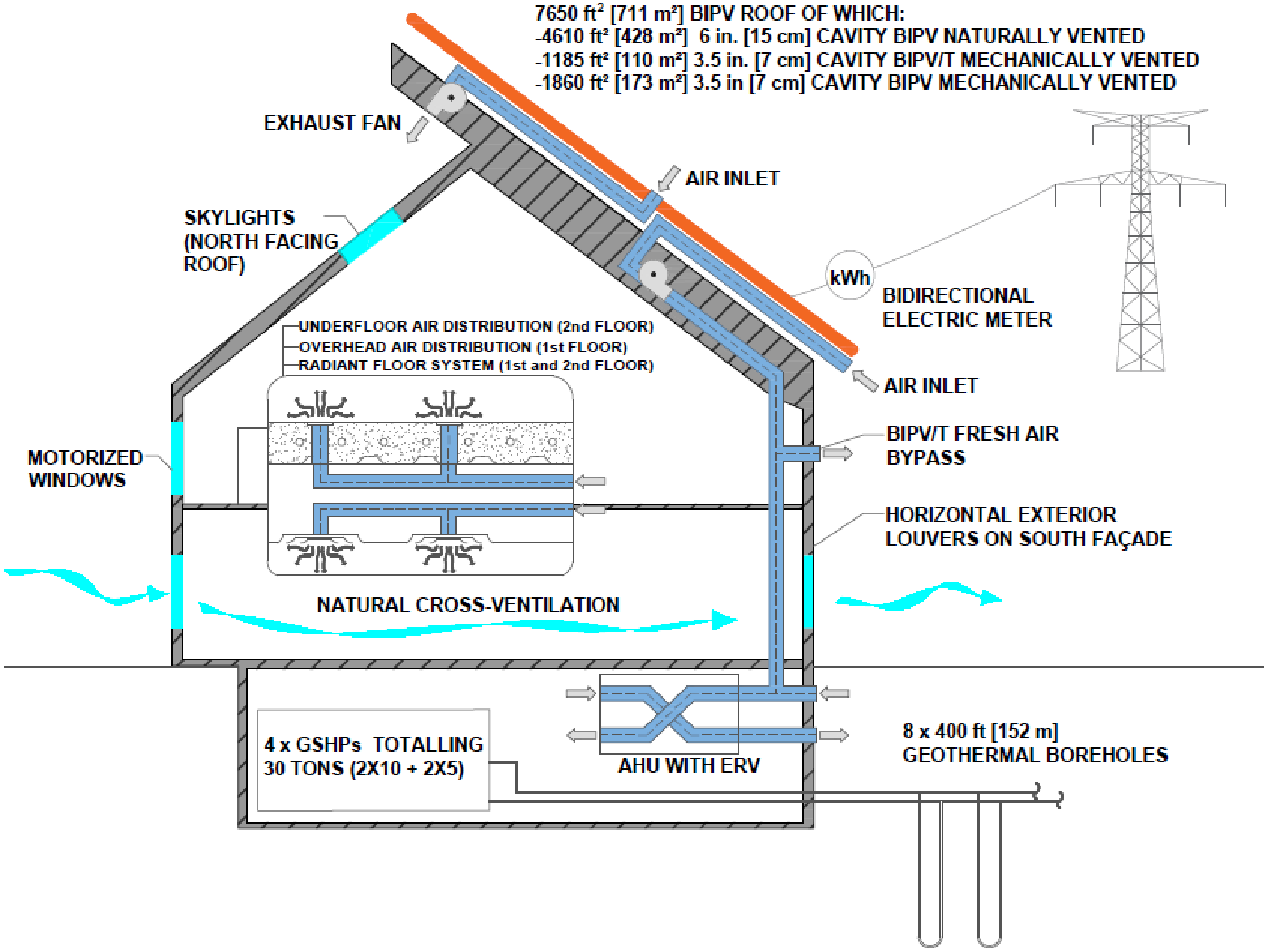




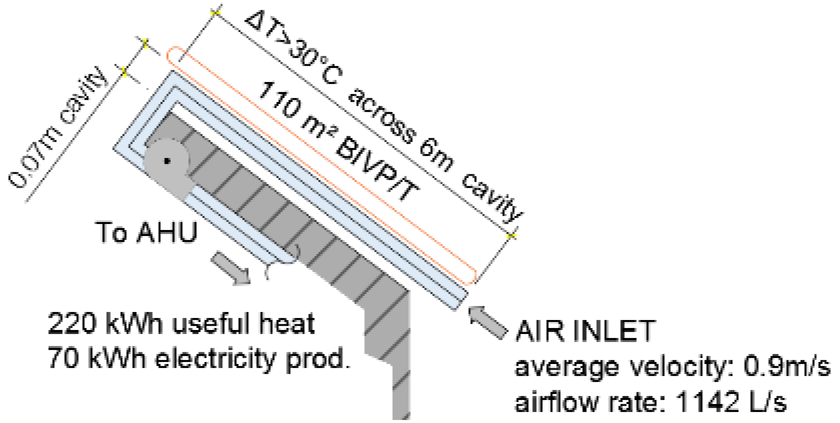
110 kWe BIPV (part BIPV/T)
Heat recovered on part of the array to supplement fresh air heating
38° slope, oriented South to South-East


Skylights
Vegetation Screen (Growing)
Smaller triple glazed windows on North Side
BIBLIOTHEQUE
Fixed solar shading on South side
Geothermal Wells (8)

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

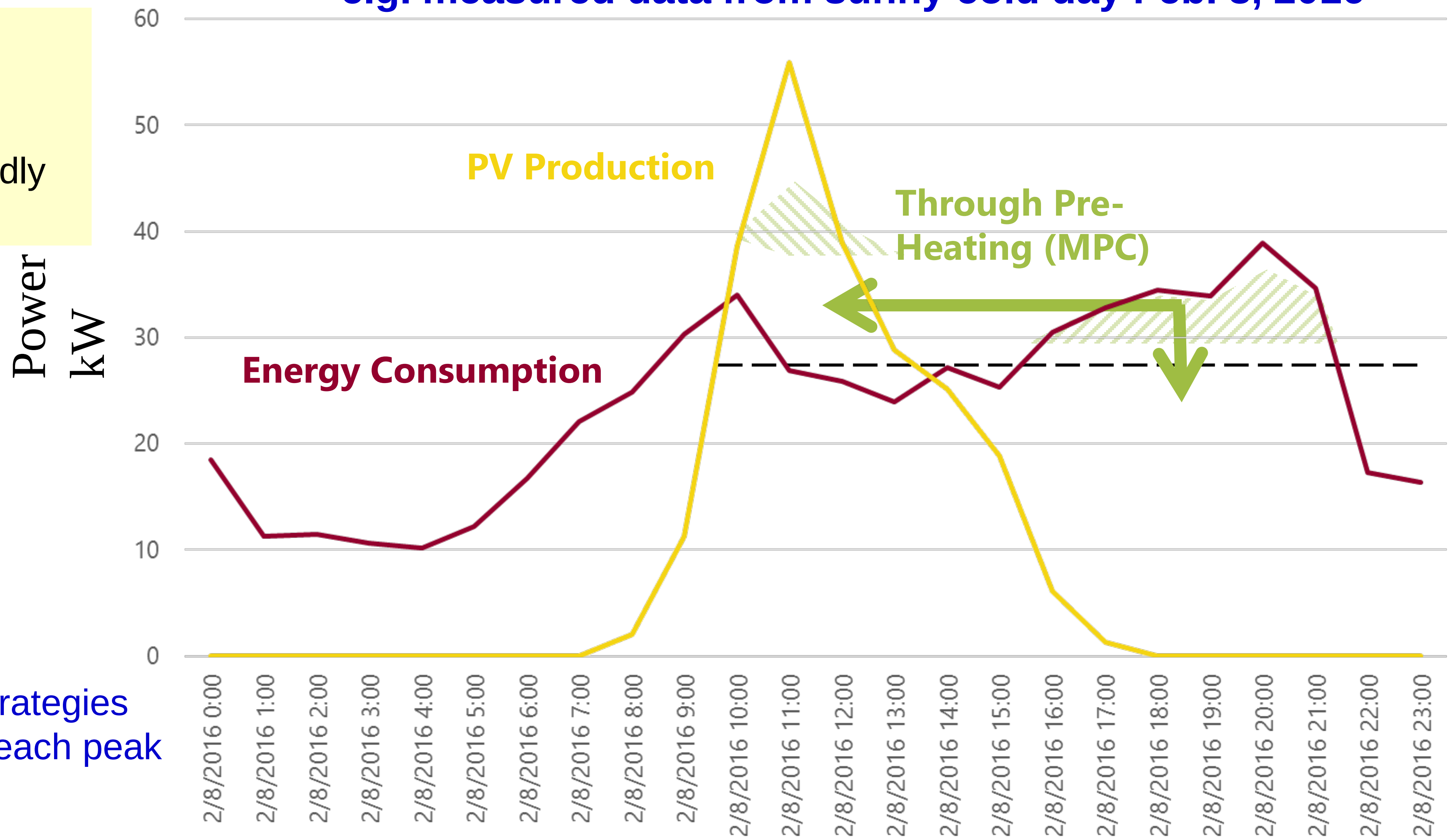
Production and Consumption Mismatch:

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?



Different strategies
To reduce each peak

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

Quantify & Harness energy flexibility

Technologies providing energy flexibility

The combination of different technologies such as: **building-integrated photovoltaics (BIPV), geothermal heat pumps, hydronic radiant slab for thermal storage (and later battery storage)** can offer many strategies of flexibility to reduce peak load and electricity consumption over a certain period of time.

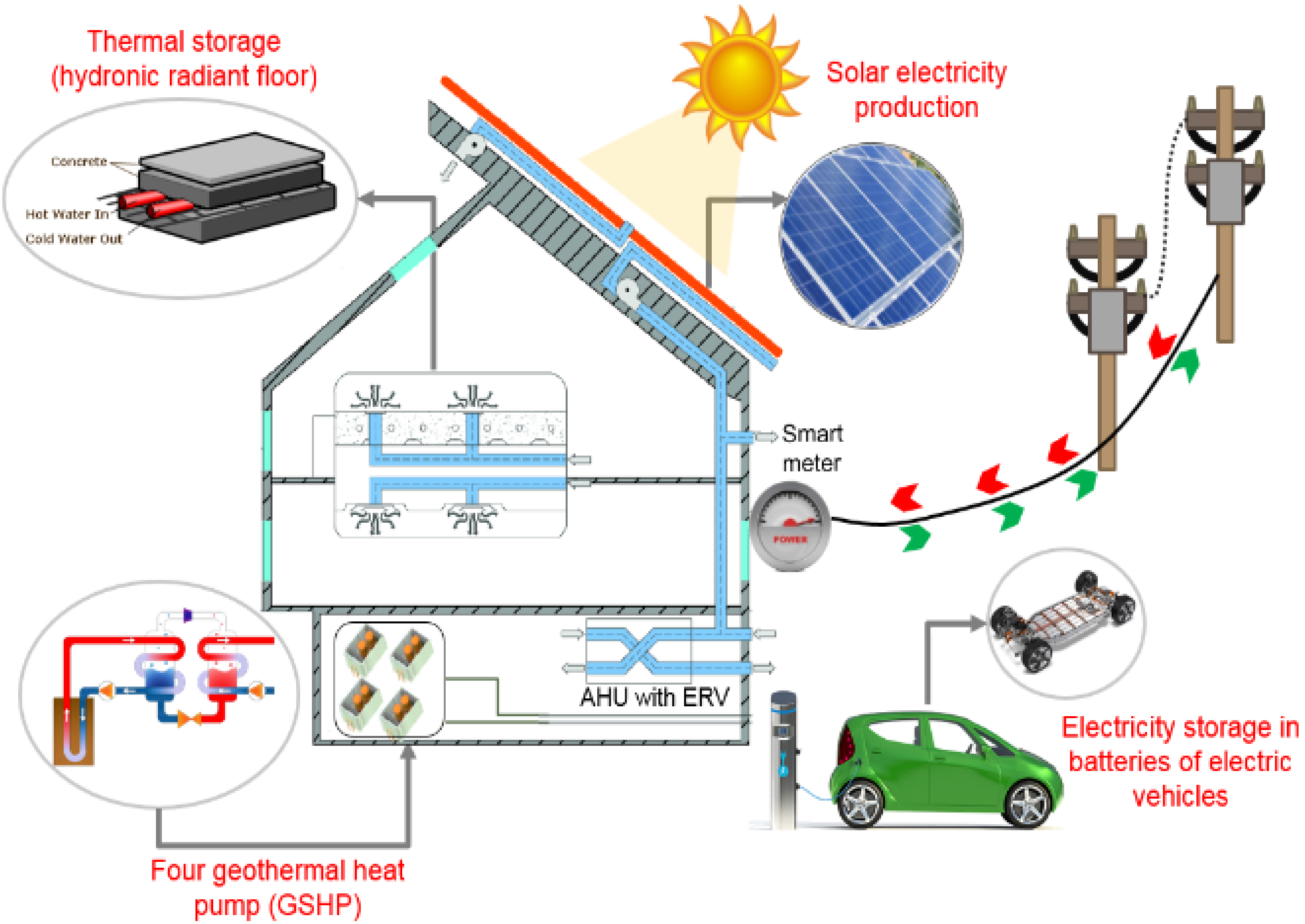
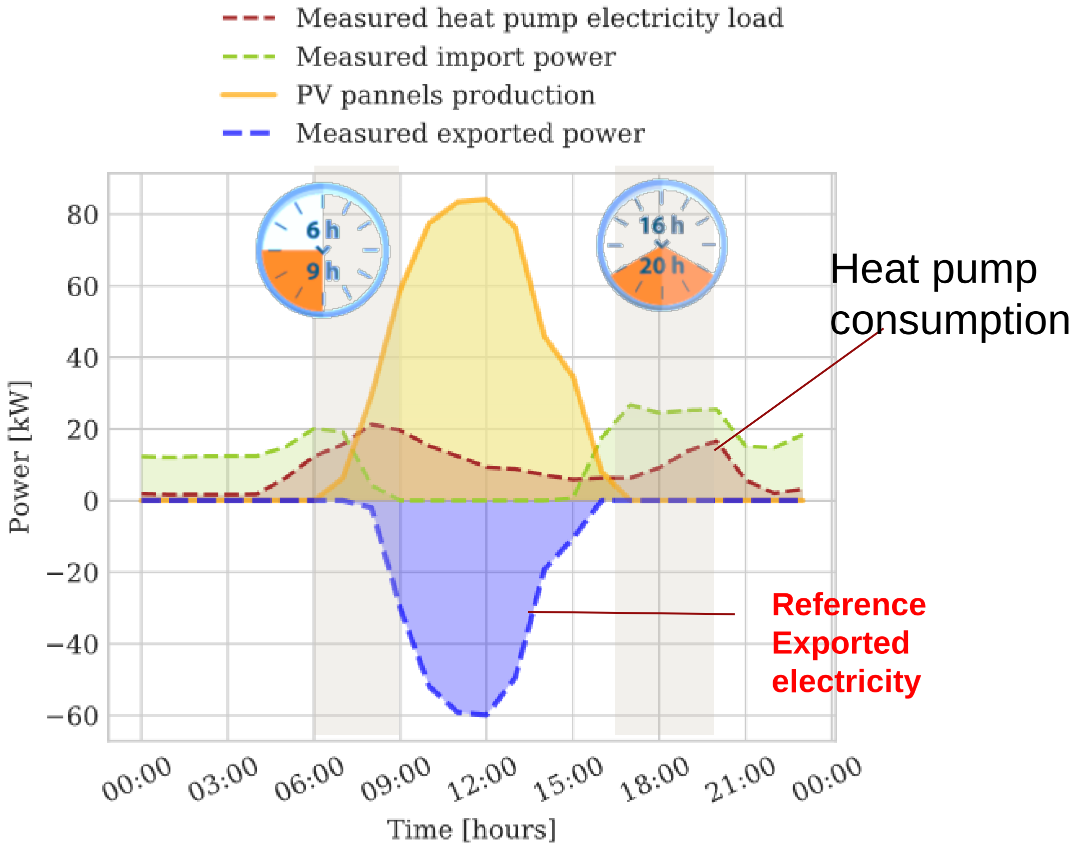
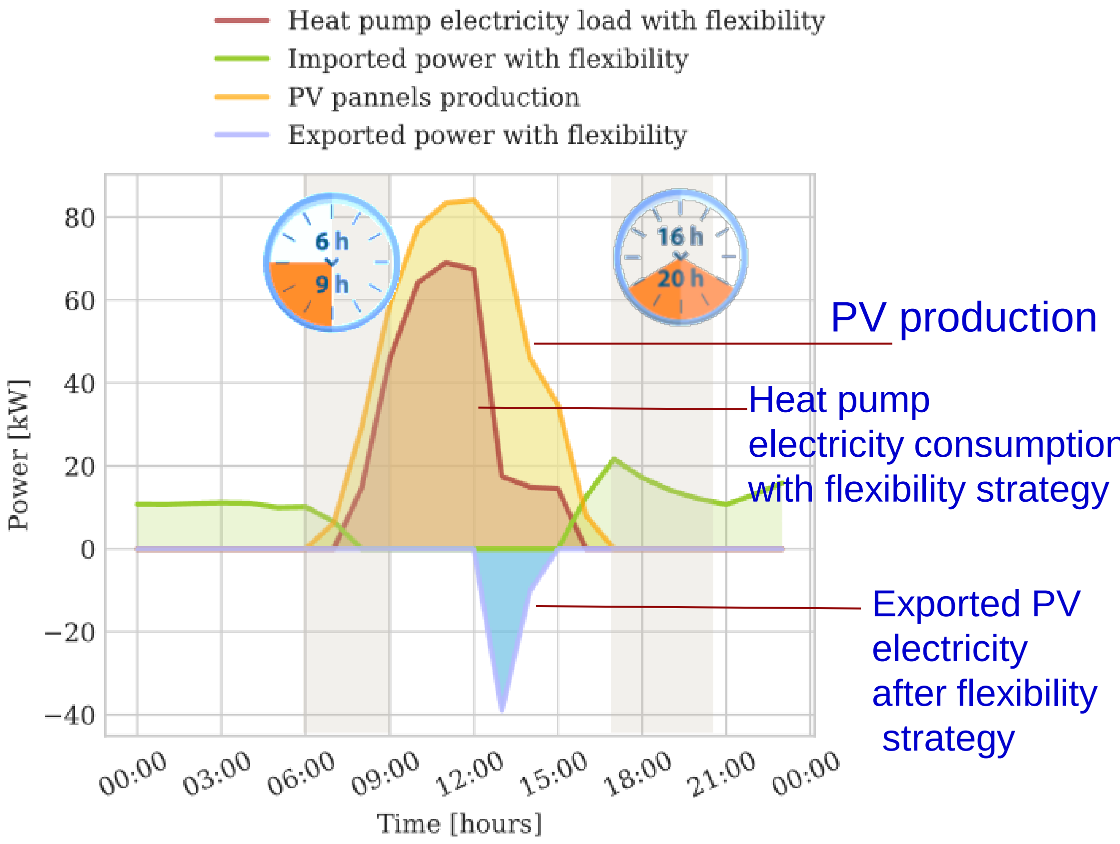


Illustration of different energy technologies that can be used to enhance flexibility in the operation of the Varennes library

VARENNES LIBRARY ENERGY FLEXIBILITY MODELLING WITH MEASURED DATA





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

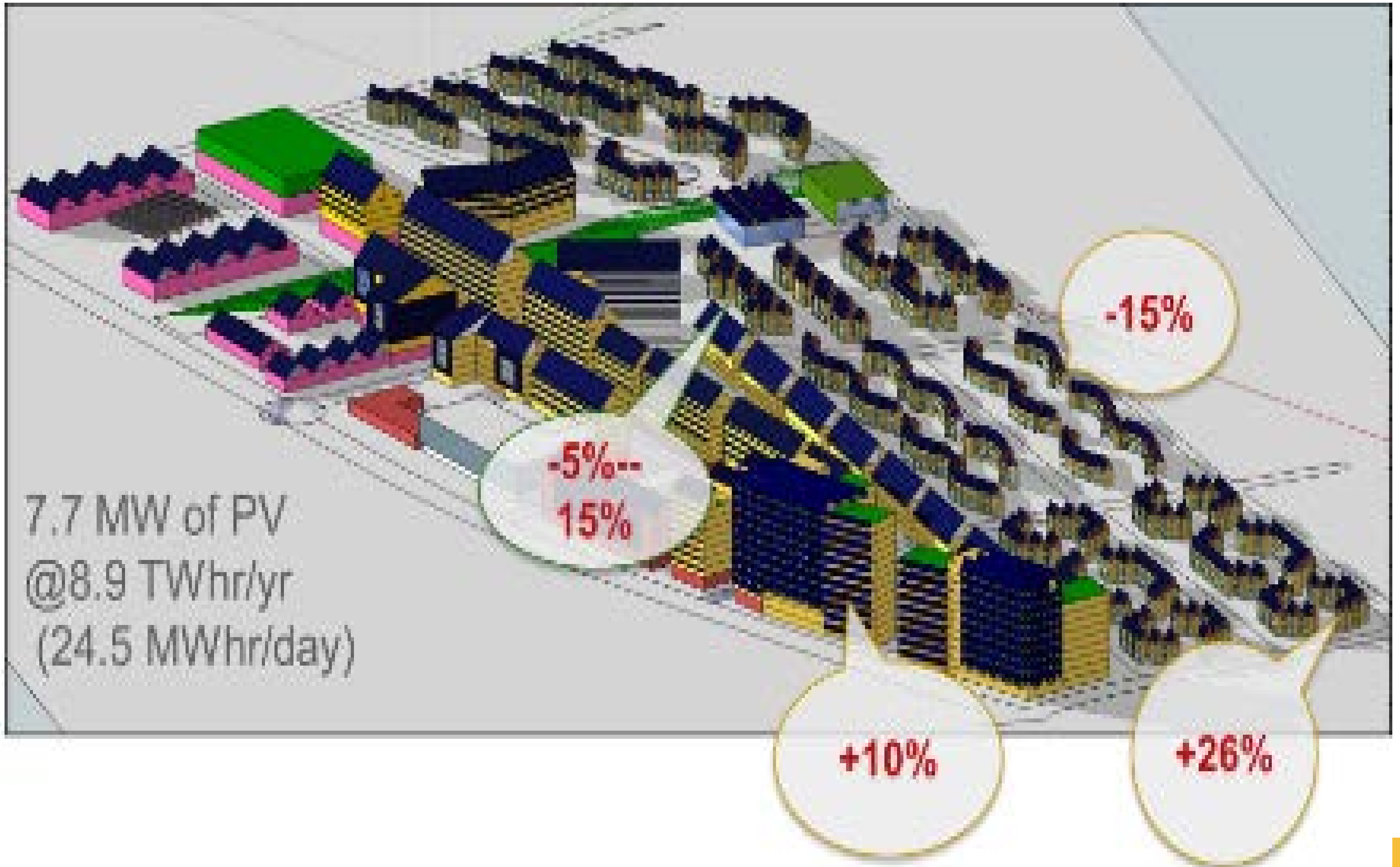
Energy flexibility quantification and use: sunny cold day on February 2, 2018

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

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

Smart solar community design and simulation: 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
- How do we achieve optimal density and solar energy utilization?



Challenges in the Design of the Built Environment

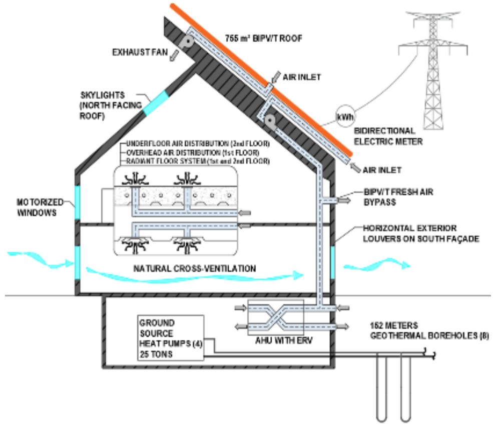
- Canada's goal of **reducing GHG emissions by 80% by 2050** needs a multifaceted and comprehensive approach adapted to different regional contexts and energy mixes. **Resilience** can help develop **practical integrated solution pathways**.
- Many pathways to achieve this goal are being debated in different contexts and from different perspectives. Technology development/adoption trajectories needed.
- Many high performance building metrics but lack of broad consensus: net-zero energy, nearly net-zero, net-zero ready, zero carbon, carbon neutral.
- **But → agreement on Resilient Ultra-low Energy Built Environment with Deep Integration of Renewables until 2050 –** Canadian Academy of Engineering Roadmap initiated (2019-2022):

  https://www.cae-acg.ca/projects/resilient-infrastructure-project/

Some Research Questions, Barriers, Lessons Learned

- What are the **key barriers to deep integration of renewables and energy efficiency** in new building/community design?
- What are the **systemic barriers** to deep integration of building **thermal design and structural design**, particularly early stages?
- What are the **systemic barriers to deep integration of engineering and architectural design**, particularly related to integration into building envelopes of active energy harvesting via renewable energy technologies?

- How to **define energy resilience**, and how can solar/renewable energy utilization and energy storage be integrated into building and community design and operation?
- At what rate upgrade building codes/standards? For example, there are no standards for BIPV etc. Low-e windows took about 30 years!



Towards smart resilient solar buildings & communities: Challenges

BUILDING SYSTEMS	CURRENT BUILDINGS	FUTURE SMART SOLAR BUILDINGS AND COMMUNITIES
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 and grid interaction	Building automation systems not used effectively	Predictive and adaptive controls to optimize comfort and energy/cost performance; online demand prediction; **grid-friendly; energy flexible buildings; resilience**
Integration with design	Operating strategies not optimized with design	**Integrated design for resilience that considers optimized operation; optimize form and basic features in early design**