Modelling and Design of Smart Net-zero Energy Solar Buildings

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Major international trends in high performance buildings

- Adoption by ASHRAE and developed countries of net-zero energy/zero carbon as a long term goal (e.g., ASHRAE Vision 2020);
- 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;
- Steps to efficiently integrate new energy technologies such as controlled shading devices and solar systems, thermal and electrical storage;
- Energy flexibility in building used to optimize performance and interaction with smart grids; predictive control.
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

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

Smart Solar Building concept – towards resilience
Residential energy use in Canada

Fact: The annual solar energy incident on a roof of a typical house far exceeds its total energy consumption.

Source: NRCan

A net-zero energy house produces from on-site renewables as much energy as it consumes in a year.
Optimization of buildings for solar collection

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

Optimize surfaces Ar and façade Aw simultaneously
Smart Net-Zero Energy Solar 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 Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) builds on the previous NSERC Solar Buildings Research Network (SBRN) – now under renewal - Smart solar buildings and communities
Electricity demand and generation in solar house with BIPV typical profile for NZEB on cold clear day

**Ontario** has a summer (due to cooling) peak demand
27 GWe

**Quebec** has a winter peak demand
38 GWe on Jan. 24, 2011 7:30 am with
To = -33 C in Montreal

Peak heating demand can be reduced through predictive control

NZEBs need to be designed to ensure a predictable impact on the grid and to reduce and shift peak demand
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!
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
BIPV/thermal – integration in EcoTerra

- **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
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 the electrical efficiency of PV is a function of temperature (increases with lower temperatures of PV).
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/T roof construction in a home builder factory as one system – a major Canadian innovation under the NSERC Solar Buildings Research Network (2005 – 2010)

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
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
Assembly of House Modules (in about 5 hours)

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

*Quality of installation is enhanced*
Resilience: Note snow melting from BIPV/T roof integration.

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

Athienitis house, Domus award finalist
Integration – BIPV/T (1.9 kWₑ)
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 m² 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.
PV panels are same width as the curtain wall; spandrel sections could accommodate more PV

Just 288 sq.m. was covered
Imagine possible generation with 3000 sq.m. BIPV/T

Shades could be automatically controlled

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

**Occupant behavior:**

- Note shade positions
- IoT with smart sensors can facilitate automation of shades
Development of BIPV/T systems
Solar Simulator - Environmental Chamber (SSEC)

Accurate model development for innovative systems that was not possible with outdoor testing

BIPV/T prototype tested in vertical position;

BIPV/T: Peak efficiencies (thermal + electric) of 55% +

Concordia solar simulator testing BIPV/T system Roof system

2-storey high environmental chamber with solar simulator
New Varennes Municipal Library (2016) – Solar NZEB

Official opening:
May 16, 2016

2017 sq.m. NZEB

South elevation – before final

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 – Canada’s first institutional solar NZEB

- 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 guided the energy design of the building

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

Officially opened May 2016
Varennes Library: living lab

At a Glance
- Net Floor Area: 2100 m²
- 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
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 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)

For such systems to become low-cost and routine, prefabricated roof sections must be built in a factory (similar to curtain wall systems) and assembled by crane.
BIPV/T System (winter clear day performance)

- BIPV/T fan activated for outlet air temperature >25°C
- Rated electrical efficiency: 15.9% STC
- Combined efficiency: ~60% (thermal and elec.)
Production and Consumption Mismatch
Clear cold day, Feb. 8 2016 - how do we make NZEBs grid friendly

Model Predictive Control (MPC) is being developed to reduce peaks due to heating demand and optimally export electricity to the grid; 6 hours to 1 day prediction horizon
Solar Decathlon China 2018 – our team  

TeamMTL

House

Two-story row house
Automated off-site prefabrication
Total heated space: 200 m²

HVAC
BIPV/T and BIPV
Water-to-water heat pump
Two thermal storage tanks
Energy Recovery Ventilator (ERV)

Modeling
TRNSYS (13 thermal zones)
Energy System for TeamMTL Solar Decathlon

Energy flows between house and grid can be optimized based on grid state and price signal

Based on house load/generation flexibility
BIPV/T, BIPV design and Solar Decathlon China 2018

TeamMTL
Concordia-McGill

Grid interaction Strategies for Energy flexibility
Collaboration with Hydro Quebec

Awards in Architecture Engineering Innovation …

BIPV/T roof
Modular design
Developed at Concordia (CZEBS)
In Solar Simulator lab
Semi Transparent Photovoltaic (STPV) Window development

- Turn Building Envelope to Solar Power Plant
- Offset Electric Lighting Loads by Daylight Transmission
- Reduce Heat Losses in Winter & Heat Gains in Summer
- Integrated with Structural, Functional & Aesthetic Properties
- Reduce GHG Emissions in the Lifecycle Building Performance
Towards smart netzero solar buildings and communities

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<th>FUTURE SMART NET-ZERO SOLAR BUILDINGS</th>
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<td>Optimized for passive design and integration of active solar systems</td>
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<td>Small systems optimally controlled; integrated with solar, CHP; Communities: seasonal storage and district energy; smart microgrid, EVs</td>
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<td>Solar systems</td>
<td>No systematic integration – an after thought</td>
<td>Fully integrated: daylighting, solar thermal, PV, hybrid solar, geothermal systems, biofuels</td>
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<td>Predictive control to optimize comfort and energy/cost performance; online demand prediction; grid-friendly.</td>
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<td>Operating strategies not optimized with design.</td>
<td>Integrated design that considers optimized operation; optimize form and basic features in early design</td>
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