Montreal Solar Decathlon Electrical teams Progress Report

Edvinas Bigaila, Team representative

E-mail: edvinasbigaila@gmail.com

Tel.: 438-937-3887

Montreal

5/9/2014

Contents

Concept 1: BIPV/T

BIPV/T (Building Integrated Photovoltaic – Thermal) roof is an innovative way of redesigning standard structural building elements in a way that they become an energy generating parts as well as being standard component of the building. Considerable work has been done on architecturally integrating solar components into the built environment. Photovoltaic/thermal (PV/T) systems may be integrated into buildings to form a durable exterior skin while generating electricity and heat. Their cost effectiveness is thus improved in comparison with stand-alone systems that need a separate support structure, particularly when they replace expensive envelope exterior layers, such as stone panel or architectural glazing.

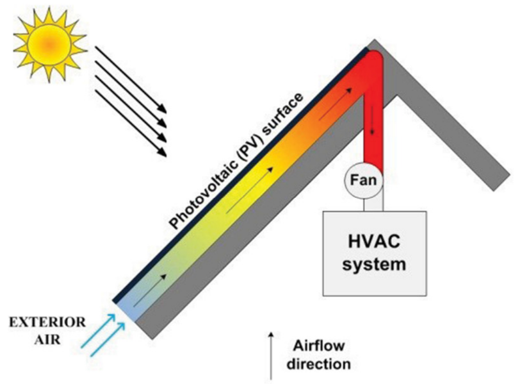


Figure 1: BIPV/T concept.

The design can also be used as a prefabricated modular plug-and-play wall system to save time and money during the installation process. It is possible to use it for retrofits or new building roofs and facades and is easy maintainable. This solution is capable in reducing the overall construction and PV installation costs, since this kind of PV module integration into envelope turns them into an exterior wall layer, as well as an energy generating layer. So in the overall turnout the owner is benefiting because he doesn't need to construct additional support mechanisms for PV modules, as well as benefiting from saving on construction material cost and installation time.

The prototype design

The prototype BIPV/T walls and roofs are designed in Concordia Solar Simulator facility. The PVs are mounted on construction layers creating a gap between the roof or wall surface and PV. This gap serves as a plenum where injected exterior air is used to cool the PVs and then the preheated air can be used for building zone ventilation, input into a heat pump or through air to air or air to water heat exchangers. The PVs are customized for a convenient mounting on the mullions or other custom structural materials, which allows easy access for maintenance. The PVs are mounted like shingles, so increasing the PV cell amount per façade or roof area, optimizing the angle of incidence and acting as an architecturally pleasing façade or roof.

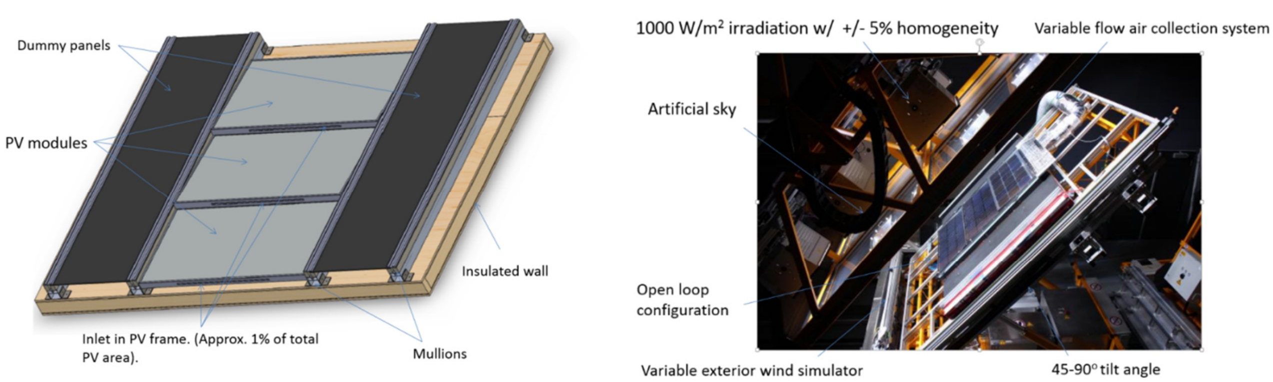


Figure 2: Experimental work.

The inlet design in PVs allows to cool the cells in an optimal manner, since the exterior air stream is distributed directly at the back of the PV module surface. The inlets can be in PV frames on the PVs can be frameless, whichever way can make the PV/T concept easy, effective, cheap and simple with reduced amount of structural and PV/T mounting components.

Experimental setup and preliminary results

Several prototypes have been built already in Concordia Solar Lab. And several prototypes are currently being designed and built as well. Some tests results with a variable speed fan in an open loop configuration, using the environment air as test heat transfer fluid are presented below. The additional details of the testing setup are visible in the picture above on the right. The preliminary prototype tests demonstrated thermal efficiency of 67% with mass flow rate of ~200 $kg/h/m^2$ and 20% @ 50 $kg/h/m^2$. The PV efficiency increases by 1% in a ventilation mode on a low wind condition. The preliminary efficiency dependencies from the mass flow rates are plotted below.

With air as the transfer medium having a much smaller specific heat capacity than water and therefore a much lower heat transfer coefficient between the absorber and the medium, there is a reduced collector efficiency factor (F’) for air heating collectors. The temperature difference between that of the absorber (Tabs) and the mean temperature of the medium (Tm) is much higher for the case of air heating collectors.

The thermal efficiency is calculated as: $n_{thermal}=Q_{air}/I_{incident}$ and $Q_{air}=mC_pdT$, m being the mass flow rate, C_p the specific heat capacity of air and dT the temperature difference between the inlet and the outlet. As T_{in}, the ambient temperature, T_{amb}, is used.

The effect of mass flow rate on the temperatures of the absorber and air at the outlet of the collector, the mean air temperature and the net useful thermal power, are summed up on the following graph.

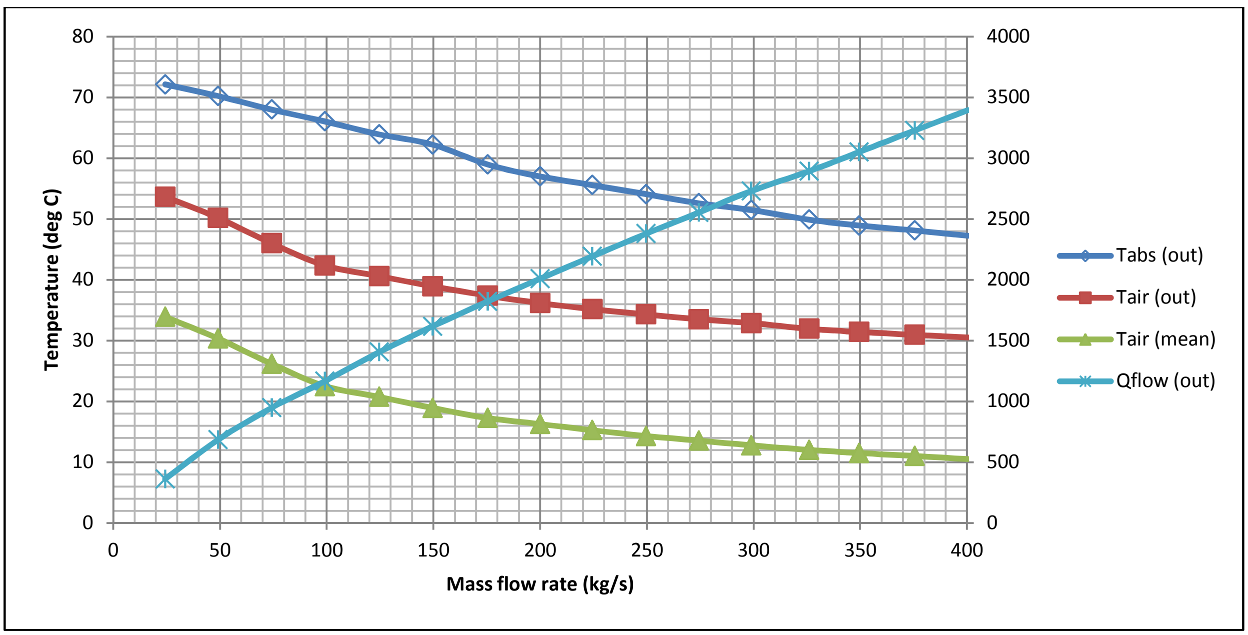


Figure 3: Temperature distributions in PV/T air collector @ test conditions.

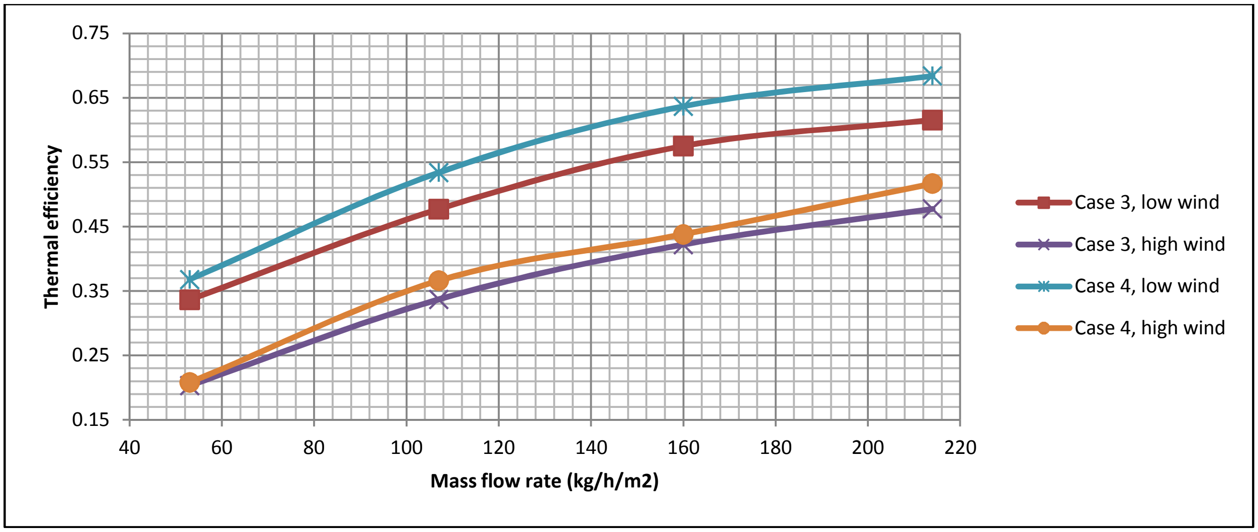


Figure 4: Thermal efficiency in relation to mass flow rate for cases 3 and 4 for low and high wind conditions.

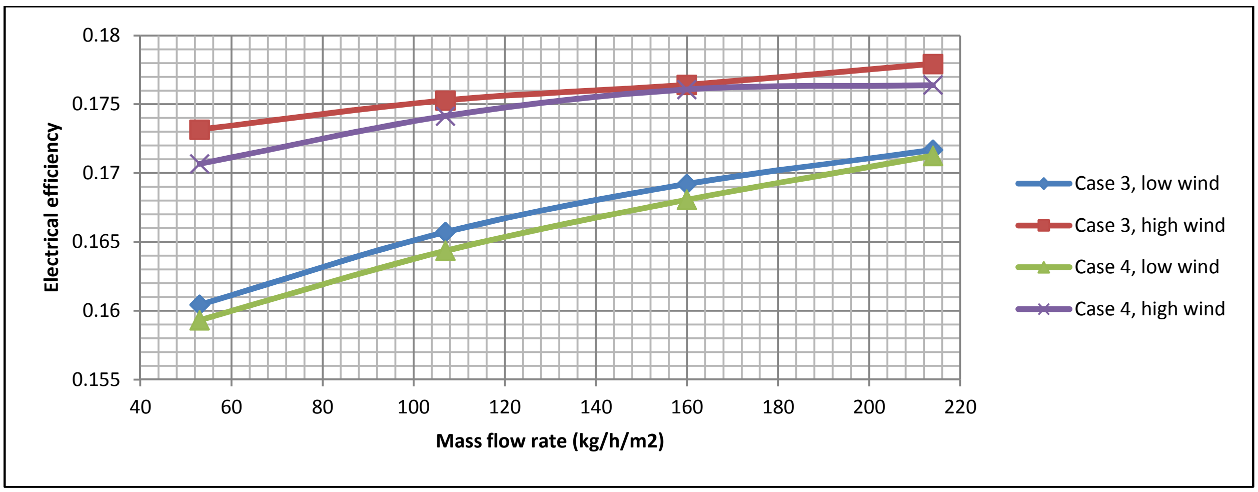


Figure 5: Electrical efficiency in relation to mass flow rate for cases 3 and 4 for low and high wind conditions.

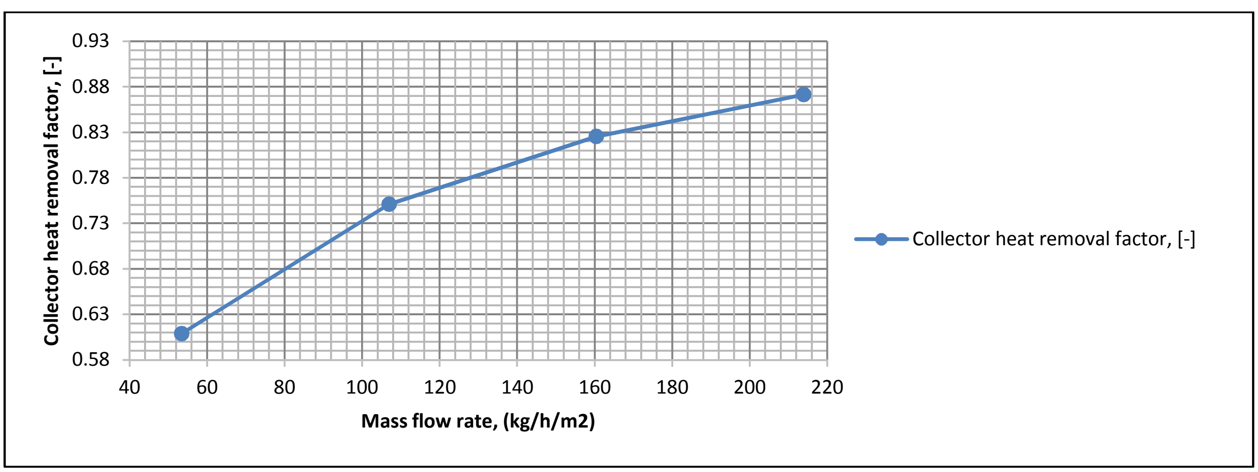


Figure 6: Collector heat removal factor dependency from mass flow rate for case 1 with low wind conditions.

Mathematical modeling

Thermal model

A lumped parameter model is created for the air source BIPV/T. The model uses upwind discretization scheme with control volumes. This allows different CHTCs to be applied for different locations along the channel in the direction of the flow. This is particularly important for our purposes because we interested in studying the effects of different local CHTCs. The model is 2D and is shown in pic below. The radiative heat transfer is not linearized. Simplification is made, conduction and radiation are assumed to be confined to each control volume. Self-shading problem must be addressed when designing this collector. Optimal distance between PV modules must be chosen to avoid module cell shading during summer months, when sun is high, when the installation is installed in high latitudes. Also, the effect of frames on the heat transfer coefficient must be addressed, because it will create turbulence and friction in the area close to the end of the PV module. This effect will be studied experimentally.

Equation nr.	Equations solved for each control volume	Energy balance on point:
1	$\frac{T_{pv}-T_{bpv}}{R_{pv}}+\varepsilon_1\,\sigma\left(T_{pv}^4-T_{sky}^4\right)+\left(T_{pv}-T_o\right)h_o-0.96K\tau\alpha_b(\theta)(\tau\alpha)_n I_T+P_{elect}=0$	T_{pv}
2	$\frac{T_{bpv}-T_{pv}}{R_{pv}}+\frac{\sigma F_{bpv,insu}(T_{bpv}^4-T_{insu}^4)}{\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}-1}+(T_{bpv}-T_b)h_{ct}=0$	T_{bpv}
3	$\left(T_b-T_{bpv}\right)h_{ct}+(T_b-T_{insu})h_{cb}-(Tout-Tinlet)(MFR\cdot\, A\cdot\frac{cp_{air}}{ACS})=0$	T_b
4	$\frac{\sigma F_{bpv,insu}(T_{insu}^4-T_{bpv}^4)}{\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}-1}+(T_{insu}-T_b)h_{cb}+\frac{T_{insu}-T_{room}}{R_{insu}+\frac{1}{h_{ci}}}=0$	T_{insu}
5	$-T_b+\frac{1}{\Delta x}\int_0^{\Delta x}\left(\frac{h_{ct}T_{bpv}+h_{cb}T_{insu}}{h_{ct}+h_{cb}}+(T_{inlet}-\frac{h_{ct}T_{bpv}+h_{cb}T_{insu}}{h_{ct}+h_{cb}}e^{\frac{-W_{pv}(h_{ct}+h_{cb})}{\dot{m}c_p}x}\right)dx=0$	T_{out}
6	$P_{elect}=(\eta_{stc}+\beta_{mp}(T_{pv}-25^oC))I_T$	P_{elect}
	Unknowns: Tpv, Tbpv, Tb, Tinsu, qrec, Tout, Pelect	

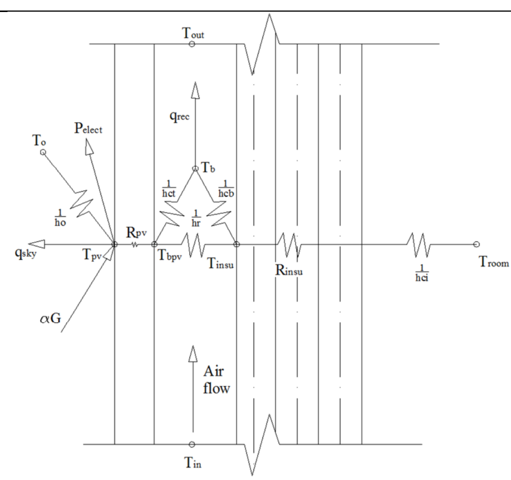


Figure 7: Thermal model of a BIPV/T.

PV cell and array modeling

Module Operating Temperature (Thermal model)

For thermal performance temperature data from the standard NOCT (Nominal Operating Cell Temperature) measurements used to compute the module temperature *Tc* at each timestep. The NOCT temperature (*Tc,NOCT*) is the operating temperature of the module with a wind speed of 1 m/s, no electrical load, and a certain specified insolation and ambient temperature [Beckman and Duffie, 1991]. The values for insolation *GT,NOCT* and ambient temperature *Ta,NOCT* are usually 800 W/m2 and 20º C. Model uses the NOCT data to determine the ratio of the module transmittance-reflectance product to the module loss coefficient:

$$\frac{\tau\alpha}{U_L} = \frac{\left(T_{c,NOCT} - T_{a,NOCT}\right)}{G_{T,NOCT}}$$

Assuming that this ratio is constant, the module temperature at any timestep is:

$$T_c = T_a + \frac{\left(1 - \eta_c / \tau\alpha\right)}{\left(G_T \tau\alpha / U_L\right)}$$

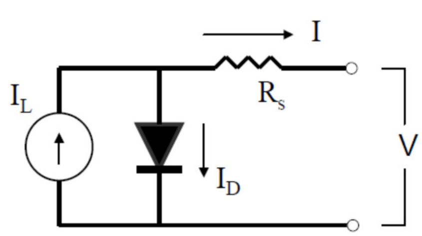
η_c is the convesion efficiency of the module, which varies with ambient conditions. *Tc,NOCT*, *Ta,NOCT*, and *GT,NOCT* are set in PARAMETERS 12, 13, and 14 respectively. $\tau\alpha$ may be either a constant or the a value calculated from an incidence angle correlation, or measured experimentally.

Mathematical description (4-parameter model)

The four-parameter equivalent circuit model was developed largely by Townsend [1989] and also detailed by Duffie and Beckman [1991]. The model was first incorporated into a TRNSYS component by Eckstein [1990], and much of the code in Type 94 comes from Eckstein's work. Type 94 employs this model for crystalline PV modules. **This model is used whenever TRNSYS PARAMETER 19 (the module's short-circuit IV slope) is set to zero or a positive value.** The four parameter model assumes that the slope of the IV curve is zero at the short-circuit condition:

$$\left(\frac{dI}{dV}\right)_{v=0} = 0$$

This is a reasonable approximation for crystalline modules. The "four parameters" in the model are *IL,ref*, *Io,ref,* γ, and *Rs.* These are empirical values that cannot be determined directly through physical measurement. Type 94 calculates these values from manufactures' catalog data; these calculations are discussed in the following. The four-parameter equivalent circuit is shown below.



The IV characteristics of a PV change with both insolation and temperature. The PV model employs these environmental conditions along with the four module constants *IL,ref*, *Io,ref*, γ , and *Rs* to generate an IV curve at each timestep. The current-voltage equation of circuit shown in Figure above is as follows:

$$I = I_L - I_o\left[\exp\left(\frac{q}{\gamma k T_c}\left(V + IR_s\right)\right) - 1\right] \quad [1]$$

Rs and γ are constants. The photocurrent *IL* depends linearly on incident radiation:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}} \quad [2]$$

The reference insolation *Gref* is given by PV cell manufacturer. It is nearly always defined as 1000 W/m2. The diode reverse saturation current *Io* is a temperature dependent quantity:

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 \quad [3]$$

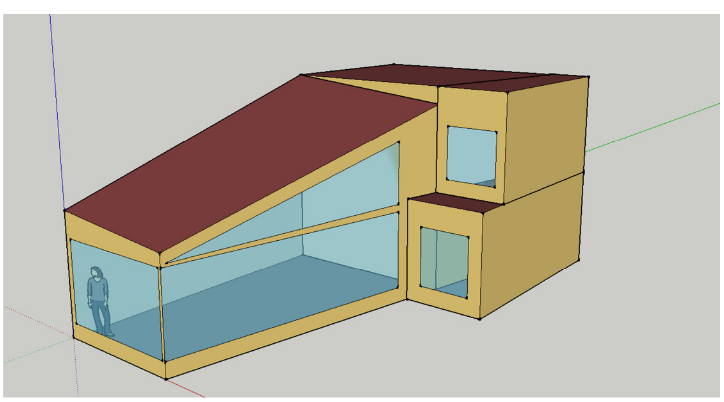
Eq 1 gives the current implicity as a function of voltage. Once *Io* and *IL* are found from Eq 2 and Eq 3, Newton's method is employed to calculate the PV current. In addition, an iterative search routine finds the current (*Imp*) and voltage (*Vmp*) at the point of maximum power along the IV curve.

Multi array modeling

The electrical calculations discussed for the four-parameter and five-parameter PV models deal only with a single module. Type 94 may be used to simulate arrays with any number of modules. TRNSYS PARAMETERS 10 and 11 define the number of modules in series (NS) and modules in parallel (NP) for the entire array. The total number of modules in the array is the product of NS and NP. When simulating a single module only, both NS and NP are set to 1. The single-module values for all currents and voltages discussed here above are multiplied by NP or NS to find values for the entire array. This approach neglects module mismatch losses.

Electrical installation design considerations

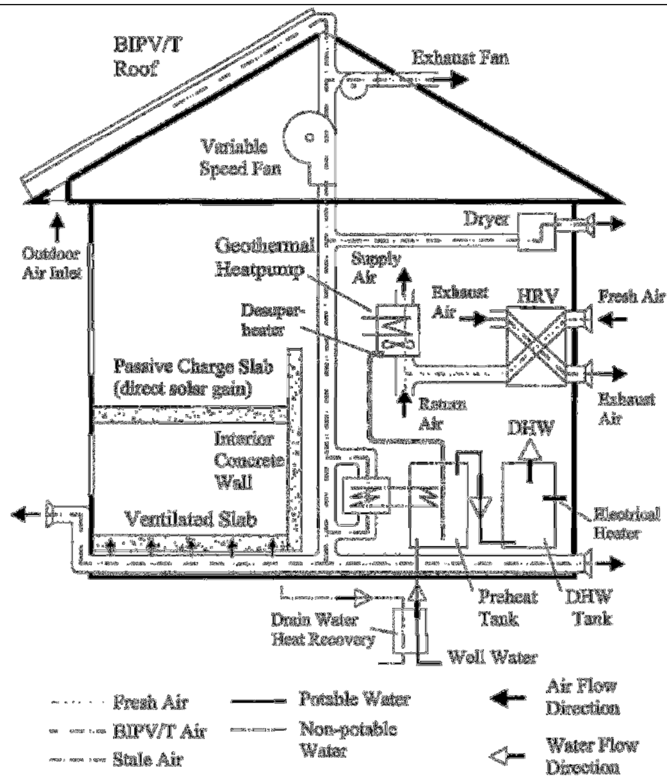
Based on the existing Solar Decathlon house location and architectural design of the house, all systems will be modeled using both Energy Plus and TRNSYS. The geometry is done with Sketchup including all shading effects from existing obstacles. The preliminary energy models with Sketchup and TRNSYS are presented below.



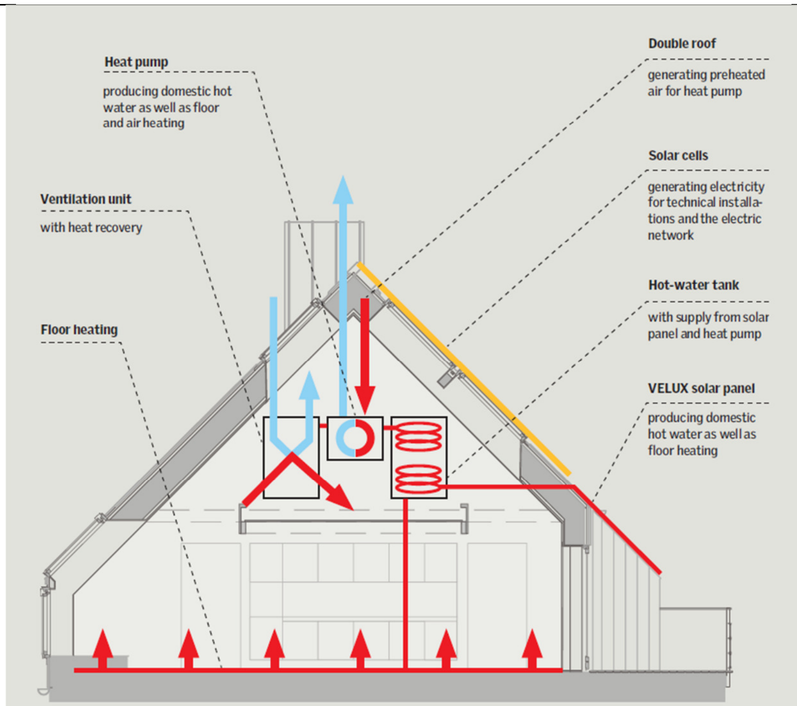
Integration into HVAC system considerations

Integrating PV/T roof into HVAC system is the most important part to make the system feasible solution. This will require to dedicate some time in modeling and probably testing several options to get the maximum of the proposed system. The benefit basically is additional heat that can be gathered all year round and used for DHW and space heating as well, if integrated well. Some examples from endless solutions, are demonstrated here:

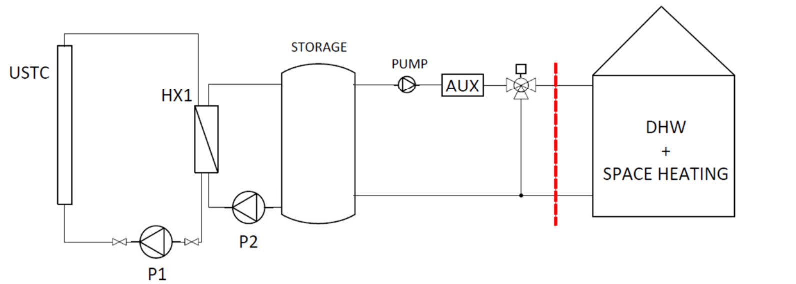
- Ecoterra house example – PV/T is connected to preheat water tank through air to water heat exchanger. The preheated water is used during heating season for both space and DHW and during cooling season for only DHW. The innovation would be, if we could manage to integrate Solar Water and Air heaters into one system.



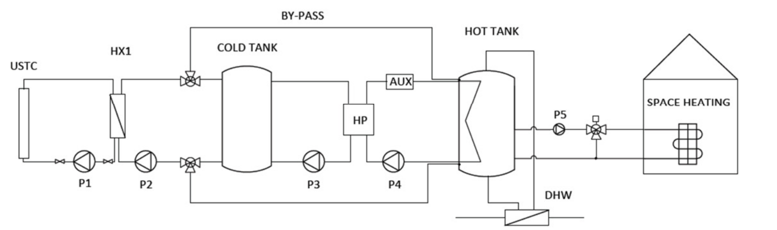
- Soltag example – integration of PV/T air through a Heat Pump with a ventilation unit and water tank. Depending from the HP, probably cooling might be possible.



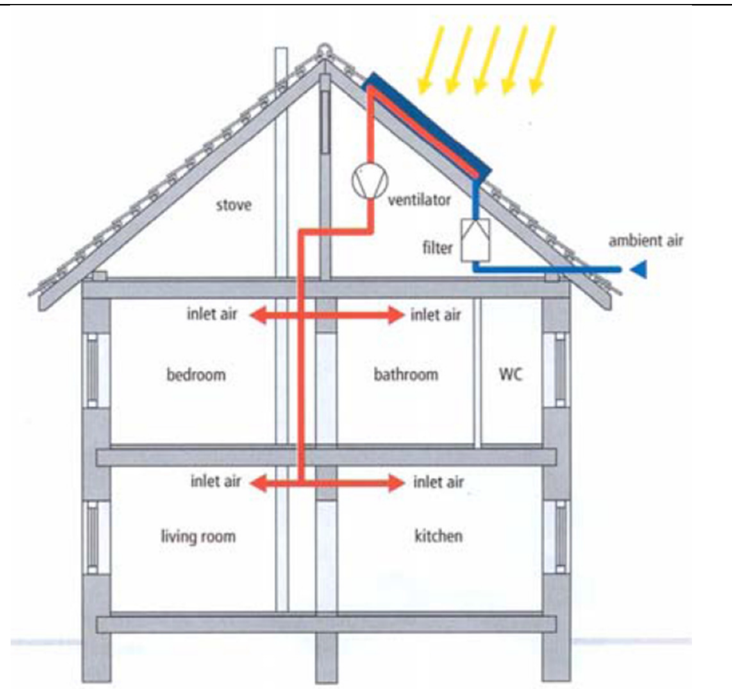
- USTC stands for unglazed solar air heater. In here the system is basically the same as above, just without all the additional components.



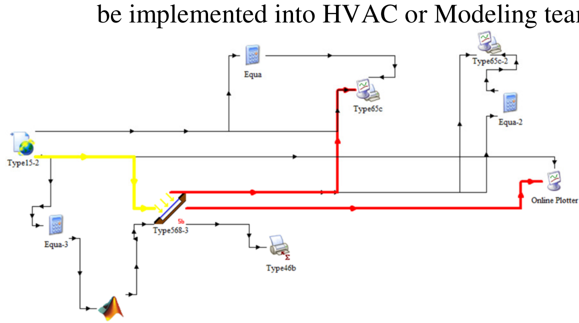
- A system with water to water heat pump with a by-pass when water temperature is higher than applied minimum temperature setpoint (45 degC).

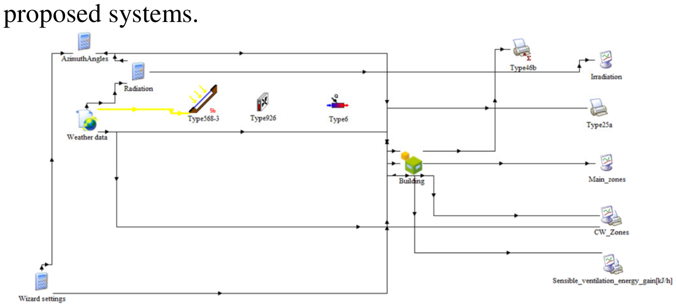


- Simplest way to integrate the system would be to do a single pass system, to use the solar preheated air as fresh air intake. Exhaust air leaves the building through leakage or air flaps. It is the cheapest. Other solar air heating systems you can see in the presentation I attached. **(FOR ME – ADDRESS – 0004LEC11AIR.PDF)**



- Currently the PV/T models are being developed with TRNSYS/Matlab tools for PV/T air system, that can be implemented into HVAC or Modeling team proposed systems.

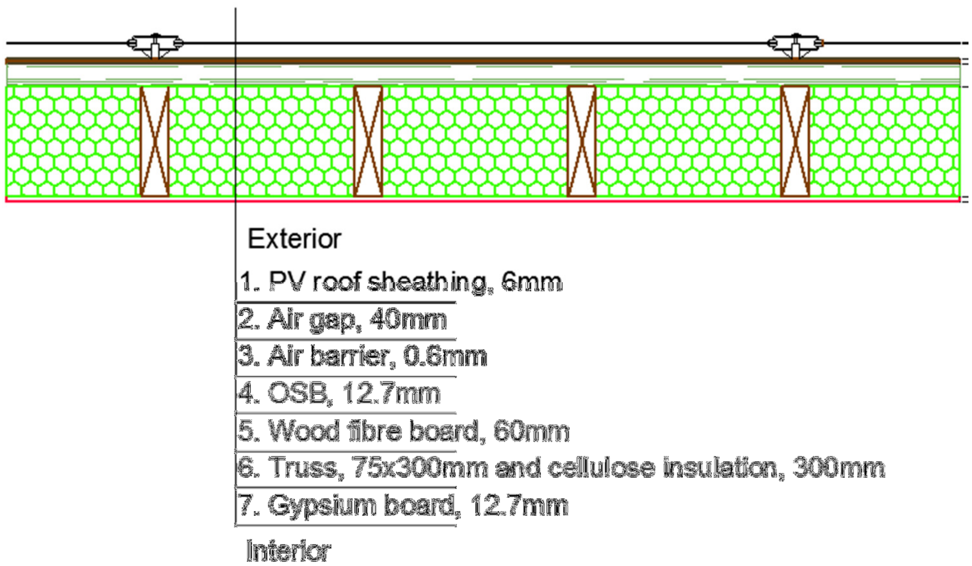




Integration into roof construction design considerations

For the HOLCIM award this roof configuration was already proposed. These tasks will be solved with Envelope team and Structural team. Basically the tasks are:

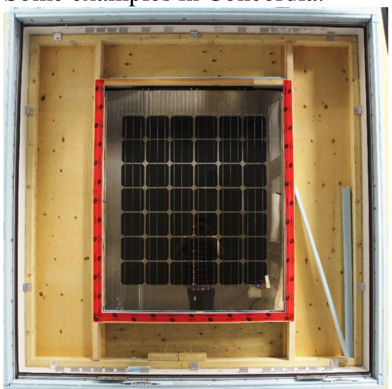
- Make the roof water tight;
- Create as less obstacles for the air flow while attaching the PV sheathing;
- Make the roof easy constructable and deconstructable, so we could assemble it in a day or two on site (some kind of plug and play solution). Hardest task will be to connect the roof parts together, since the roof is quite large in the current design.

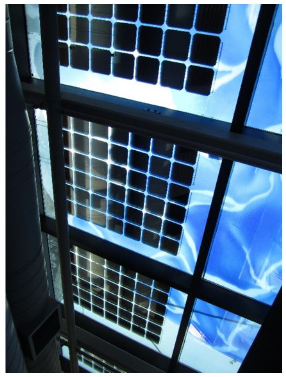


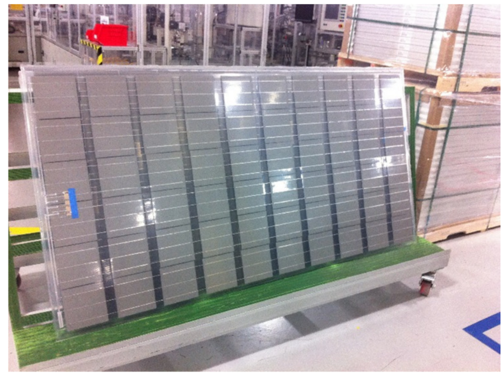
Concept 2: Semi-transparent Photovoltaic Windows

A possibility to add Semi Transparent PV windows is possible, since a large window area exists on the South façade, which would actually help to reduce the cooling loads in the heating season, since it would act as a shading device as well as electricity generating element. Some otions exist in the market even in Canada.

Some examples in Concordia:



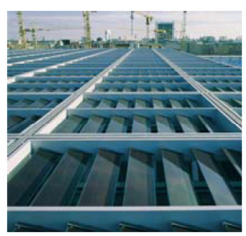




Some examples outside of Concordia:

Canopy

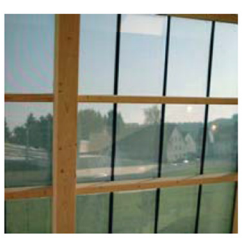
Insulated roof glazing



Louvers

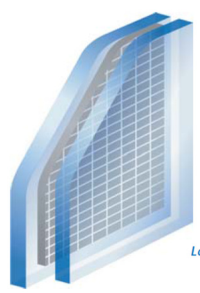
Double glazing

Opaque cladding

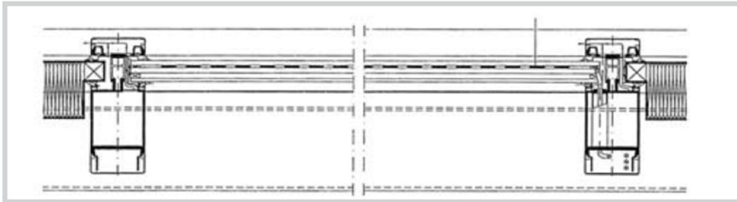


Insulated facade

Integrated roof panels

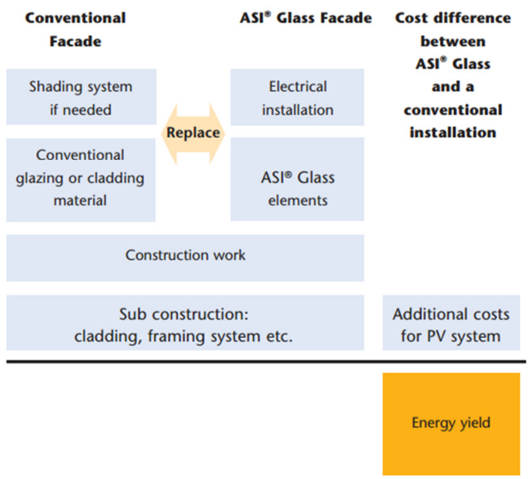


Laminate



Cables are within the framing system

Simplified cost breakdown comparing with conventional unit can be expressed as mentioned in a presentation below. Although still, not any glazing unit can be remanufactured with PV cells, since different companies have different manufacturing techniques and not all can easily add a PV addition to an IGU manufacturing step into their lines. So, this is a nice cost breakdown for marketing strategies. ;)



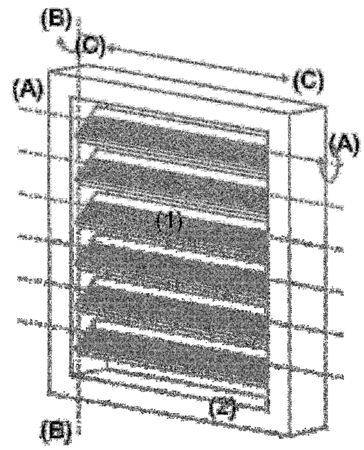
The solutions for adding an IGU with PV or (STPV) could be either:

- Use what exists in the market (Internat Energy, ONYX, ect.);
- Or cooperate with IGU manufacturing companies and integrate PVs into their windows (Unicel, where Concordia has already a close relationship or any other available IGU company with manufacturing capabilities.).

Regarding the modeling of the prototypes, in Concordia university we have a PhD student which has dedicated his thesis to designing and modeling STPV windows. Model includes both thermal, electrical and daylighting aspects of both window and the zones the window is in. So I think there should be no problem with mathematical modeling.

Concept 3: Building Integrated Photovoltaic elements: Overhangs and other shading devices

The most interesting solution that is currently under consideration is exterior venetian blinds with attached PV modules on it. The blind angle can change based on the sun, so it would be both tracking PV system and an advanced shading/daylighting device. And also it is a very architecturally pleasing feature. This system could also be integrated in a IGU (Insulated Glazing Unit), so in that case it would be a window with movable venetian blinds with PV in-between glass panes. This solution is not off the shelf product, so we might have to actually manufacture it, which might include some additional interested investors. The picture below is from Darmstadt Solar Decathlon 2007 team.

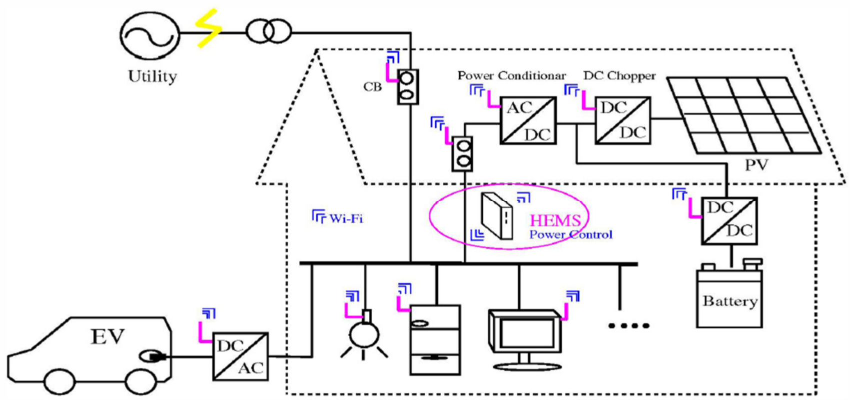


Concept 4: Other innovative solutions for electrical installation for residential house application

Electrical car integration

Electric car can be integrated into the building as an electrical energy storage device. The main goal is to develope a system that can help to both charge and discharge car battery in both direction (PV or Grid to Car Battery and the other way around). Currently it is not really possible to inject the electricity from car batteries back to house easily. Some considerations will be put to study the potential of integrating this kind of system into the Montreal City Smart Net Zero house concept.

The scheme below shows possible configuration for car charging mode. If addressing the car battery discharge towards house issue, it could also be an innovative solution in the house design. It could not be applied for the Solar Decathlon house as a whole, but could be used in the house system description and energy simulation part. And also it could be used to attract possible investors.



House electrical peak load shifting

House electrical peak load during the heating season is an important issue in Quebec in particular. The electrical team with energy modeling and control team can propose smart house operation modes to reduce the peak demand during winter, as well as load shifting during the high electricity rate times and etc. The options can be investigated:

- Electric car battery charging and discharging strategies;
- Predictive control for building heating and cooling modes, light operation, exterior shading device operation, and etc.

PV load matching with grid or community

This task is more of a community scale design exercise. But it could be interesting to do at least a theoretical study of how these problems could be overcome in Montreal case in general. As we know there is no incentive for PV electricity in Quebec, so the electricity production with PV is only good, if the consumer decides to use it. It is less economic more technical study in general. So a technical PV electricity management study can be done for:

- Community scale in Montreal;
- For a house connected to the grid;
- For a grid tied community.

Concept 5: Advanced lighting design

Advanced lighting means energy efficient and comfortable house lighting strategies and design. Ideally this should be done with architectural, interior design and control teams. The idea is to pick most efficient lighting system and design it to be both energy efficient and comfortable. The work will include:

- Propose best daylighting strategies;
- Research of the most efficient lighting systems;
- Propose optimal lighting strategies and smart system, which includes occupancy and lighting sensors research and installation solution proposal, adaptive house lighting scheduling, dimmable lighting, etc.

Problem 1: Electrical wiring and etc.

This task will be done by a team of people, who are currently studying the local electrical wiring standards to comply with local and international codes, Solar Decathlon requirements...

Problem 2: Sensors

This task is still not defined, but should be both control and electrical teams concern in order to achieve desired Smart Net Zero house status. Smart and correct design of sensors and control system of the house can help in reducing the building energy demand by more than 50%. This is necessary to achieve the future requirements of the house, which are not only a comfortable shelter from outdoor environment, but also an environmentally, socially and economically acceptable mean of living of future generations of the Earth.

Possible industry partners

Canadian Solar, Centennial, Internat Energy, Unicel, FATH-Solar, Concordia and SNEBRN.