Integrated Design Lab

Ventilation Requirements for Residential Buildings in Cold Climates

December 19, 2023

A presentation for NEEA

Jaya Mukhopadhyay

Montana State University
Bozeman, Montana

INTEGRATED idl DESIGN LAB
BOZEMAN
MONTANA STATE UNIVERSITY
SCHOOL OF ARCHITECTURE
offering daylight and energy efficiency analysis to Montana's architects

JAYA MUKHOPADHYAY

Associate Professor

School of Architecture, MSU

Integrated Design Lab

Bozeman MT

Energy Systems Lab

College Station TX

Ph.D.

Department of Architecture, TAMU

Kirksey

Houston TX

KEVIN AMENDE

Associate Professor

Mechanical & Industrial Engineering, MSU

Integrated Design Lab

Bozeman MT

COE Technical Services

Bozeman MT

CURRENT LAB CAPABILITIES

- COMPLIANCE WITH GREEN RATING SYSTEMS
- COMMERCIAL CODE ENHANCEMENT
- DAYLIGHTING & ENERGY MODELING
- BUILDING PERFORMANCE
- O&M OF HIGH-PERFORMANCE BUILDINGS

MSU School of Architecture

- PSYCHROMETRIC TESTING FACILITY
- MEASUREMENT & VERIFICATION

MSU CoE

Example Case Studies

Orange Crush Building

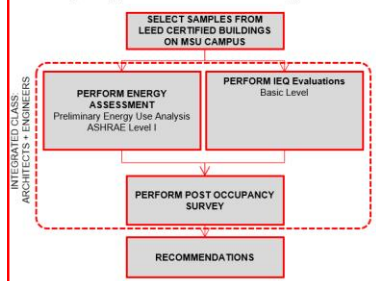
Location: Great Falls MT
Building Type: Renovation
Total Area: 25, 000 ft^2
Architects: CTA Group
Engineers: CTA Group
Certification: LEED Gold
High Performance Systems:
Open loop GSHP, radiant heating & cooling, solar preheated outdoor ventilation air

Jabs Hall, Montana State University

Location: Bozeman, Montana
Building Type: Higher Education
Total Area: 50,830 ft2
Architects: HE Architects
Engineers: Morrison - Maierle, Inc.
Certification: LEED Gold
High Performance Systems:
GSHP, transpired solar collector, enthalpy wheel, radiant floor hydronic system, VAV

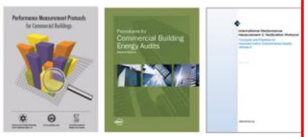
The goal is to evaluate the physical performance LEED-certified Green buildings in terms of energy consumption and the resultant IEQ.

- The performance will be evaluated by measuring energy consumption and IEQ in such buildings.
- The study also aims to compare measured IEQ data to responses from the occupants regarding comfort and ideal working conditions.



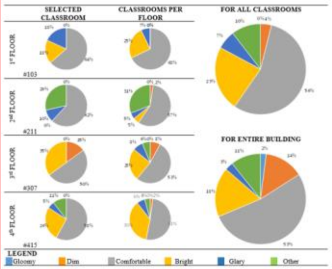
Flowchart for EPA P3 Project

Case Study for Project
Gallatin Hall- LEED Gold Certified

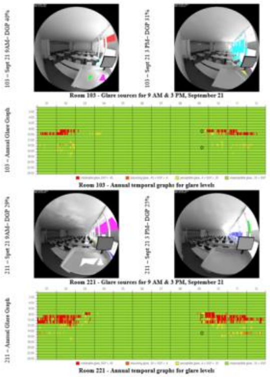


Evaluating Glare in LEED Certified Green Buildings to Inform Criteria for Daylighting Credits

Paper in review, International Journal of Sustainable Environment



Results of P.O.E Survey



Point-in-time Glare Analysis

ACKNOWLEDGEMENT

SPONSOR

Research Expansion Funds Program
Office of Research & Economic Development
Montana State University

STATITSTICAL SUPPORT

Statistical Consulting & Research Services Lab
Montana State University

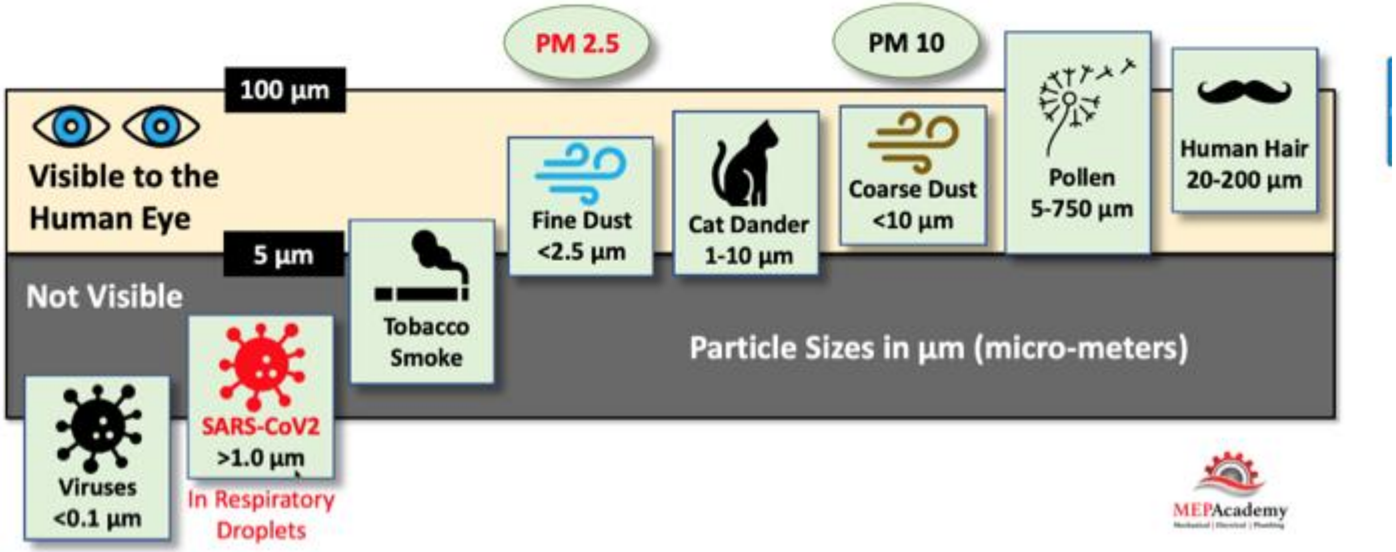
HOST INSTITUTION

Cold Climate Housing Research Center
Fairbanks Alaska

BACKGROUND

- **Residential buildings in cold climates face specific challenges to maintaining IAQ**
- **People spend more time indoors**
- **Trend towards more efficient, airtight homes that trap excess moisture & pollutants indoors**

Ventilation is important BUT can be very energy consumptive



Air Filter Particle Sizes in Micrometers

PROBLEM STATEMENT

This study evaluates the impact of ventilation & filtration measures on IAQ & energy consumption in residential buildings in cold climates

Intent to ensure energy efficient operation, adequate indoor environmental quality in such buildings by incorporating ventilation & air cleaning strategies within environmental control system of the building

A combination of ventilation & air cleaning strategies optimally operated for residential buildings in cold climates will maintain appropriate IAQ without significant increase in energy consumption.

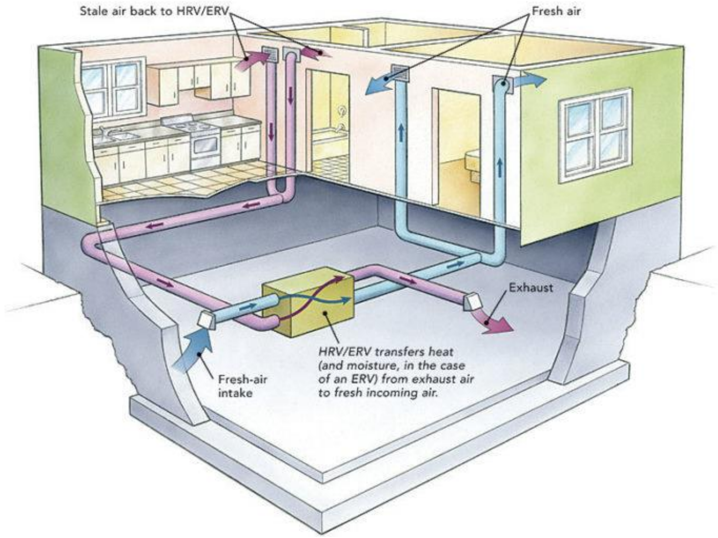


Diagram of a Residential HRV System

RESEARCH QUESTIONS

- **What is the best combination of ventilation & filtration strategies that will reduce energy consumption and maintain adequate indoor air quality?**
- **What is the optimal operation of these strategies?**
- **To what extent can filters as part of mechanical systems or standalone air cleaners reduce exposure to indoor air pollutants?**
- **To what extent air cleaning can enable reduction in outdoor ventilation rates?**

OBJECTIVES

1. **Establish acceptable IAQ in residential buildings.**
2. **Select appropriate environmental control systems (ventilation + air cleaning) for residential buildings located in cold climates that ensure adequate IAQ.**
3. **Establish alternate operation strategies for these environmental control systems that integrate the use of air-cleaning & ventilation systems.**
4. **Evaluate selected combinations of ventilation + air cleaning systems.**

PROCESS

Road map adopted by this research study

INTENT OF RESEARCH STUDY

GOAL

To ensure energy efficient operation, adequate indoor environmental quality and good health of occupants in residential buildings located in cold dry climate by proposing occupant centered and climate sensitive building design.

HYPOTHESIS

A combination of ventilation and air cleaning strategies for residential buildings in cold climates will maintain appropriate IAQ without significant increase in energy consumption.

OBJECTIVES

Objectives #1:
Establish acceptable IAQ in residential buildings.
Objective #2:
Select appropriate environmental control systems that ensure adequate IAQ.
Objective #3:
Evaluate selected combination of systems.

LITERATURE REVIEW

Define acceptable IAQ in residential buildings

Research Question:
What is good IAQ in residential buildings?

Approach:
- Review of indoor air pollutants
    - List of indoor air pollutants
    - Assess the conditions under which each pollutant is generated
    - Assess the impact of each pollutant on occupant health
- Assess impact of building characteristics on generation of each pollutant
- Assess strategies to mitigate the presence of each pollutant
- Role of building codes & standards in retaining good IAQ

Select appropriate ventilation & air filtration systems

Research Question:
What is a good ventilation / air infiltration system for code compliant single family residential building that can ensure appropriate IAQ in a cold climate.

Approach:
- Review of ventilation and air filtration systems
    - How they address the shortlisted air pollutants
    - How they perform under given building characteristics & occupant activities

EXPERIMENTAL SETUP

Evaluate the performance of selected ventilation and air filtration strategies

Research Question:
What is a good ventilation / air infiltration system for code compliant single family residential building that can ensure appropriate IAQ in a cold climate for the given conditions.

Approach:
Experimental Setup
- Selection of house(s) that is representative of the housing stock in Alaska / ideal cold climate construction?
- Shortlist for this study citing reasons for selection
    - Indoor air pollutants
    - Ventilation & air filtration systems
- Develop a procedure to measure levels of pollutants on the implementation of the selected systems
    - Set up of systems & operations to be evaluated
    - Experiment set up / measurement plan for IAQ & energy
        - Selection of instruments & sensors
        - Location of instruments
        - Determination of measurement time period
    - Documentation of activities in the house(s)
        - Survey of occupants
        - Daily log of occupant activities

Data Analysis
- Selection of statistical methods to be used for analysis
- Assessment of measured data
    - Trends in outdoor air pollutants
    - Trends in indoor air pollutants
    - Energy consumption
    - Correlations btwn:
        - Different systems
        - Indoor & outdoor
        - Pollutant levels & energy consumption

LITERATURE REVIEW

Literature review summarized

- PM & VOCs are generated by occupant activities - cooking & cleaning
- House characteristics & choice of appliances impact IAQ
- Pollutant levels inside can also be impacted by exterior conditions

- Standards not consistent in the values reported
- No established levels for PM in indoor air

- Whole-house ventilation systems w/ heat recovery preferred in cold climates because of energy savings
- These systems do not perform as intended because of operational and maintenance issues

LITERATURE REVIEW

Literature review summarized (continued…)

- For kitchen, recirculating hoods were less effective than those venting to the outside
- Recirculating systems were preferred in cold climates because of reduced energy use

- An environment characterized by presence of several pollutants cannot be addressed by a single Air purification strategy
- Supplementing ventilation systems with air purification strategies can effectively reduce energy consumption

- Provisions for ventilation and air filtration systems are currently available in the building codes and are relatively straight forward to implement
- This is not the case for inclusion of air-purification systems

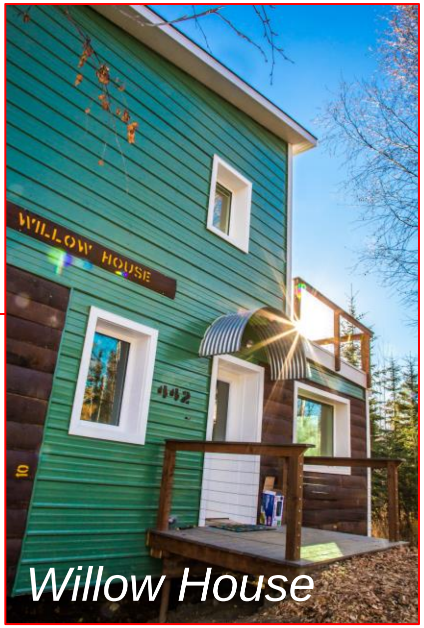
TEST CASE HOUSES

Selection of Test Case Houses

- Two residential buildings located at the UofA Fairbanks Sustainable Village

Variables Measured

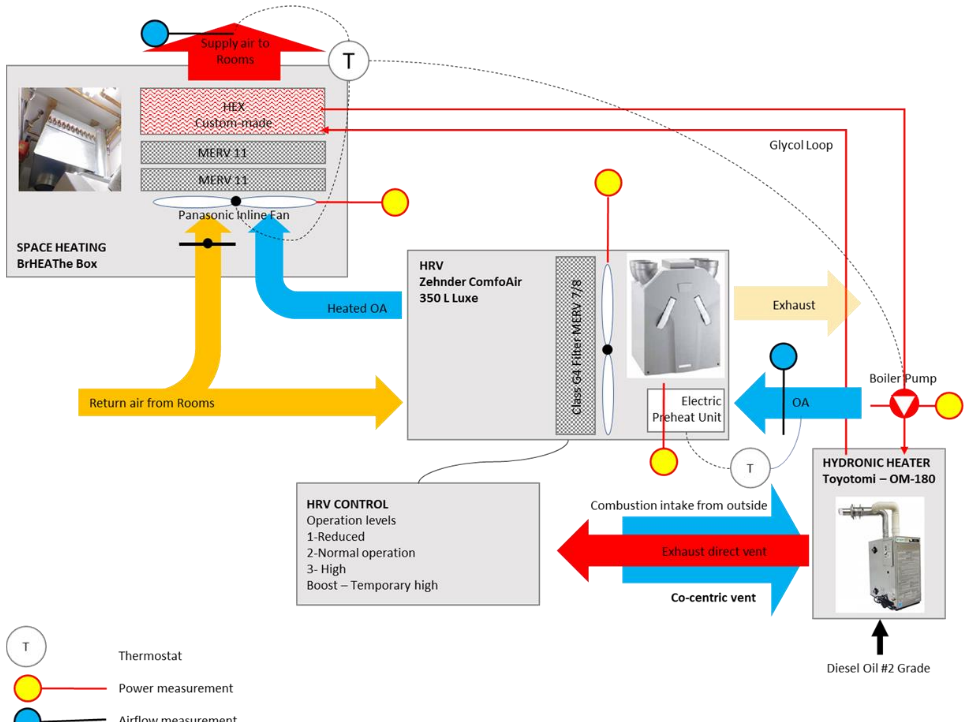
- Particulate matter (PM 1, PM 2.5, PM 10)
- Carbon dioxide (CO2)
- Total Volatile Organic Compounds (TVOCs)
- Energy consumption



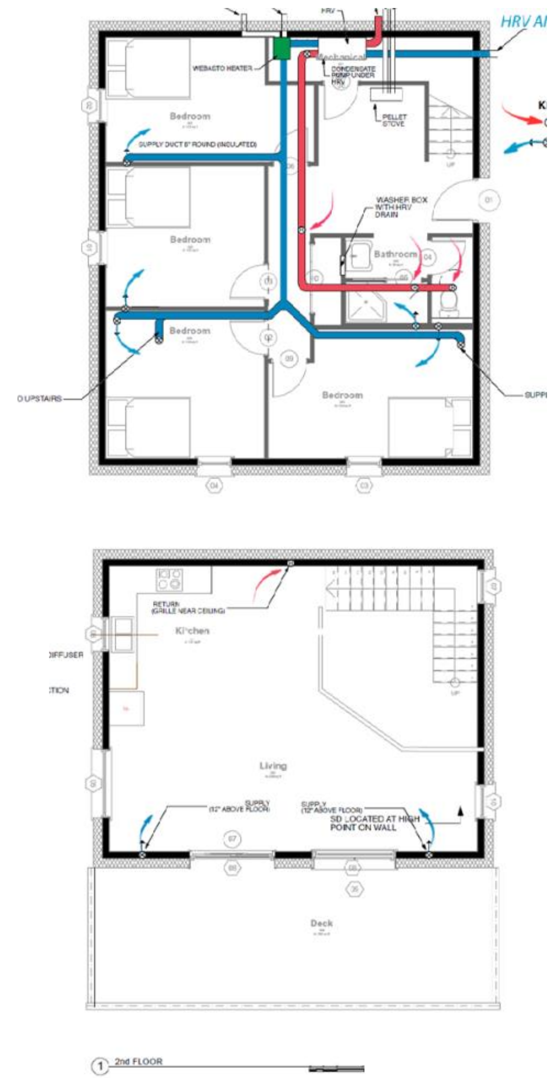
Sustainable Village at UAF | Cold Climate Housing Research Center

Birch House

- Forced air space conditioning system - BREAThe
- HRV systems:
  - Continuous ventilation – Zehnder
  - Intermittent ventilation - Venmar



Base-case system layout for Birch House with Zehnder HRV

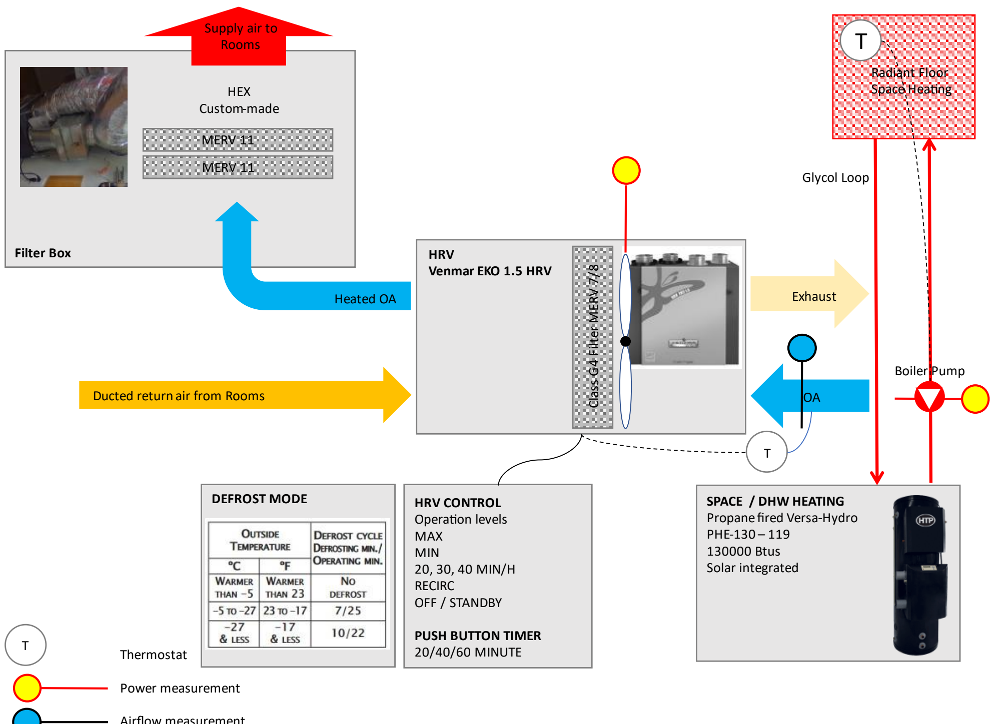


Floor plans

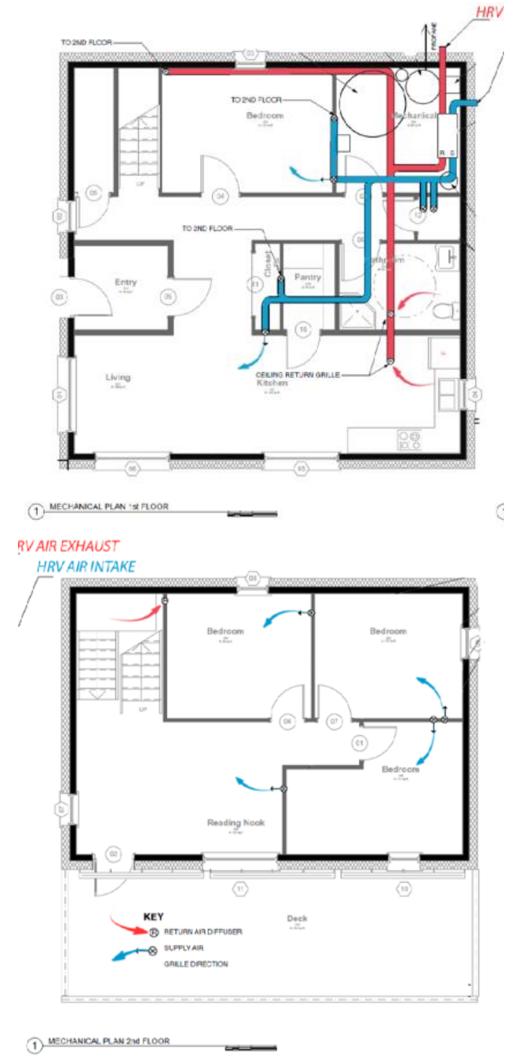
TEST CASE HOUSES

Willow House

- Hydronic space conditioning system
- HRV systems:
  - Intermittent ventilation - Venmar



Base-case system layout for Birch House with Zehnder HRV



Floor plans

STRATEGIES

Filtration / Air-purification Strategies

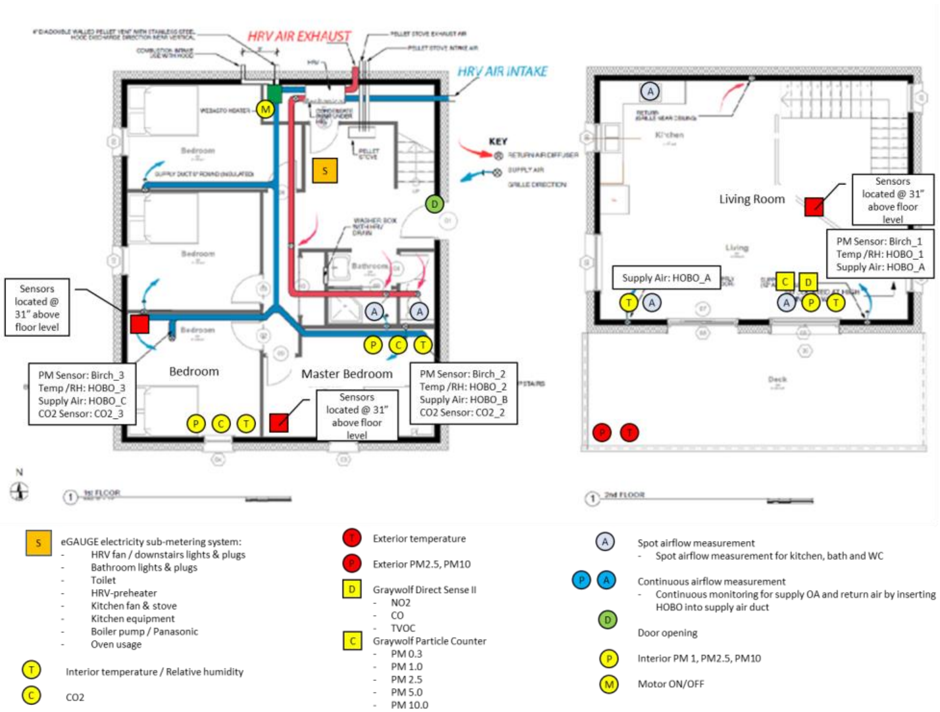
- **High-performance air filters for space heating system:**
  - MERV 13
  - Activated carbon filter

- **High-performance air filters for HRV systems:**
  - MERV 13 – for Zehnder ComfoAir 350 Luxe

- **Stand-alone air-purification systems:**
  - Blue Air 211 + carbon activated filter
  - Blue Air 411 + carbon activated filter

EXPERIMENTAL SETUP

Instrumentation Plan



Instrumentation plan for IAQ in the Birch House

List of Measured Variables & Instruments

Loc.	Variables	Instruments / Procedures	Units	Time interval
Exterior	OA Conditions			
	Outside Air Temperature	Onset HOBO MX2301A	F	10 minutes
	Exterior Pollutants			
	PM2.5, PM10	Purple Air PA-II-FLEX	ug/m3	10 minutes
Interior	Interior Pollutants			
	PM2.5, PM10	GrayWolf DirectSense Purple Air PA-I-LED	ug/m3	10 minutes
	NO2	GrayWolf DirectSense		10 minutes
	CO	GrayWolf DirectSense		10 minutes
	CO2	Onset HOBO MX1102A		10 minutes
	Ambient Conditions			
	Temperature	Onset HOBO UX100-003	F	10 minutes
	Relative Humidity		%	10 minutes
	Energy Usage			
	Bathroom	eGauge Core EG4015	kWh	10 minutes
	Toilet		kWh	10 minutes
	HRV Preheat + fan		kWh	10 minutes
	Kitchen fan + stove		kWh	10 minutes
	Kitchen equipment		kWh	10 minutes
	Boiler pump + Panasonic		kWh	10 minutes
	Oven usage		kWh	10 minutes
	HRV usage in Willow House	Onset HOBO UX120-018	kWh	10 minutes
	Motor On/Off			
	Panasonic fan	HOBO U9-004	On/Off	
	HRV fan	HOBO U9-004	On/Off	
	Kitchen fan	HOBO U9-004	On/Off	
	Airflow			
	Bathroom / toilet exhaust fan	VelociCalc TSI 9565-P	ft/s, CFM	Point-in-time
	Kitchen recirculating fan	VelociCalc TSI 9565-P		Point-in-time
	HVAC supply air	Motor On/Off		
	HRV supply air to rooms	VelociCalc TSI 9565-P	ft/s, CFM	Point in time
	Outside air supply to HRV	TEC DG-1000		One hour time
	Schedules			
	Door opening & closing	Onset UX90-001		

RESULTS & DISCUSSION

Particulate Matter (PM)

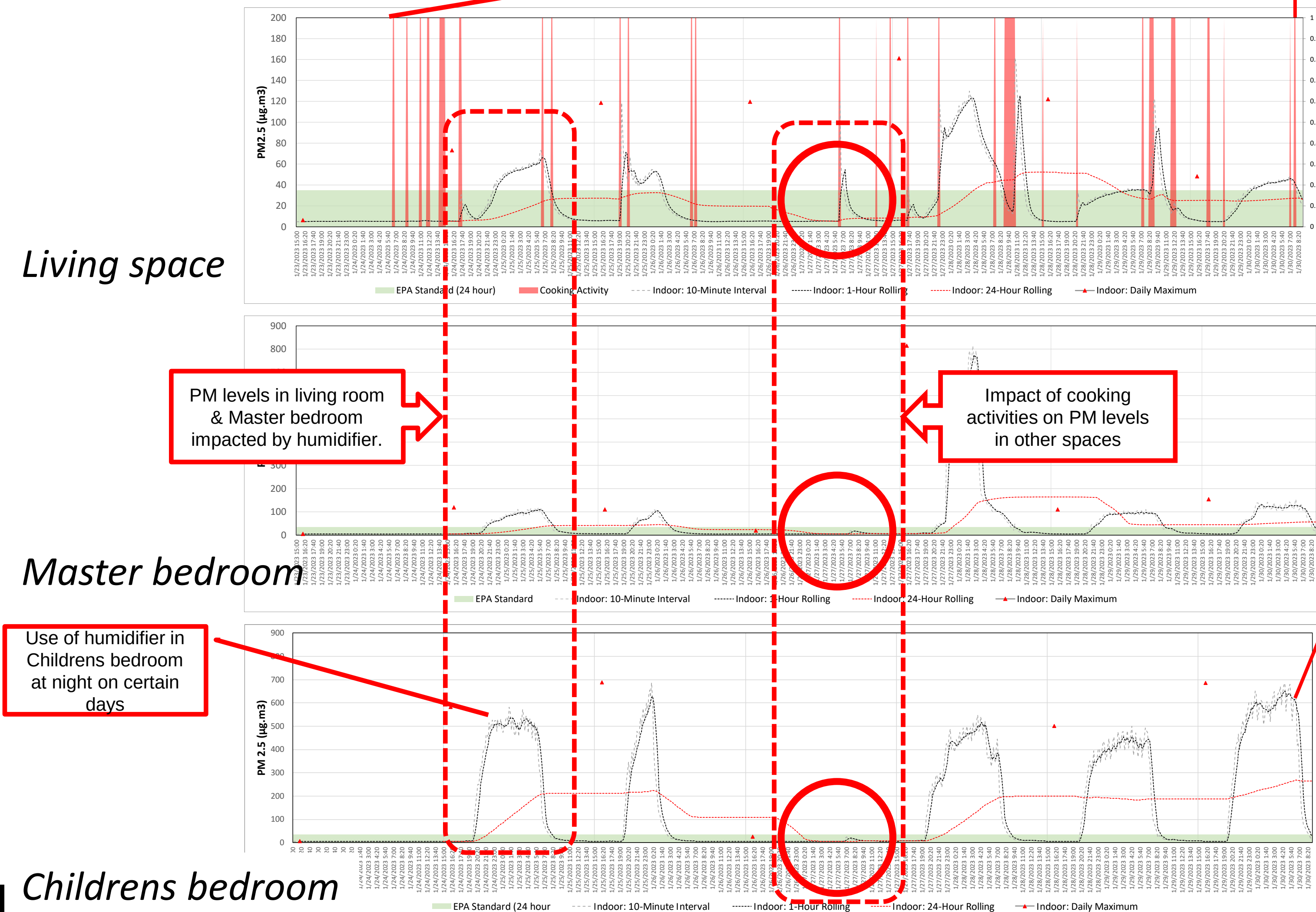
- **Dependence of indoor PM on outdoor PM concentrations**
  - Pearson test for indoor PM & outdoor PM - weak / not significant
    - Indoor PM concentrations independent of outdoor PM concentrations indicating tight envelope
    - Air filters installed in HRVs & mechanical system were functioning according to intent of design
  - ARIMA models – reduced models for most cases
    - Cooking & occupancy play a greater role in indoor PM trends than outdoor PM concentration

- **Dependence of indoor PM on outdoor air temperature**
  - Pearsons test for indoor PM & OAT – weak / insignificant
    - Temperature inversions & resultant increase in outdoor PM concentration levels do not have an impact for most part on the corresponding indoor PM concentration levels
  - ARIMA models – reduced models for most cases
    - Cooking & occupancy play a greater role in indoor PM trends than OAT
    - Extremely OAT impacts PM levels – attributed to HRV operation

Cooking activities superimposed on PM trends.

Particulate Matter (PM)

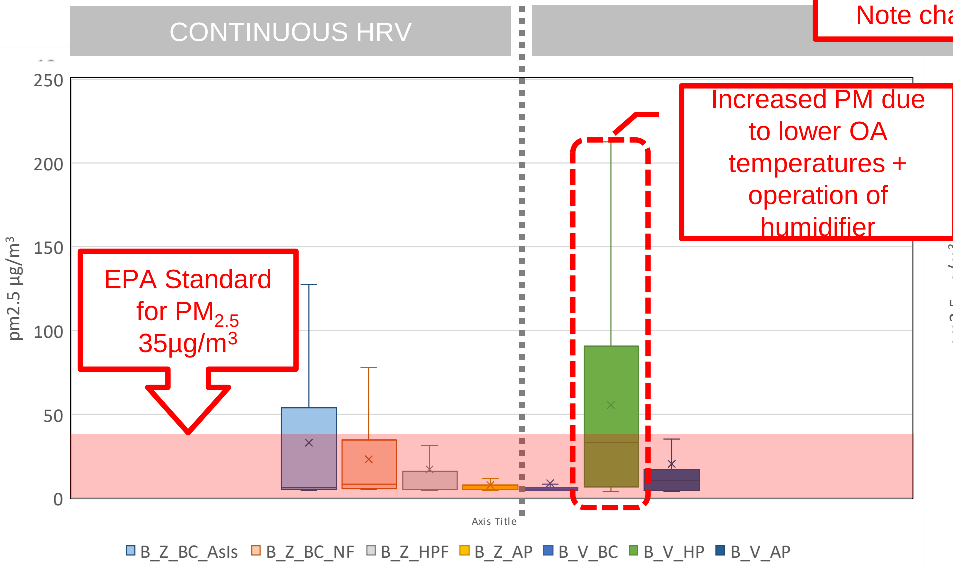
- **Dependence of indoor PM on spatial configurations & activities – Birch House**



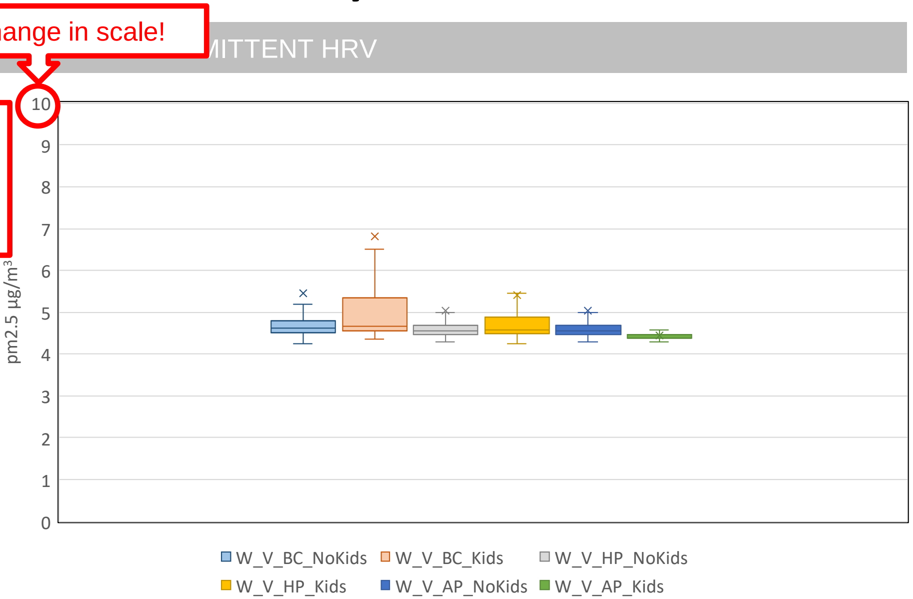
RESULTS & DISCUSSION

Particulate Matter (PM)

- **Comparing performance between different HVAC & HRV systems**



For Birch House



For Willow House

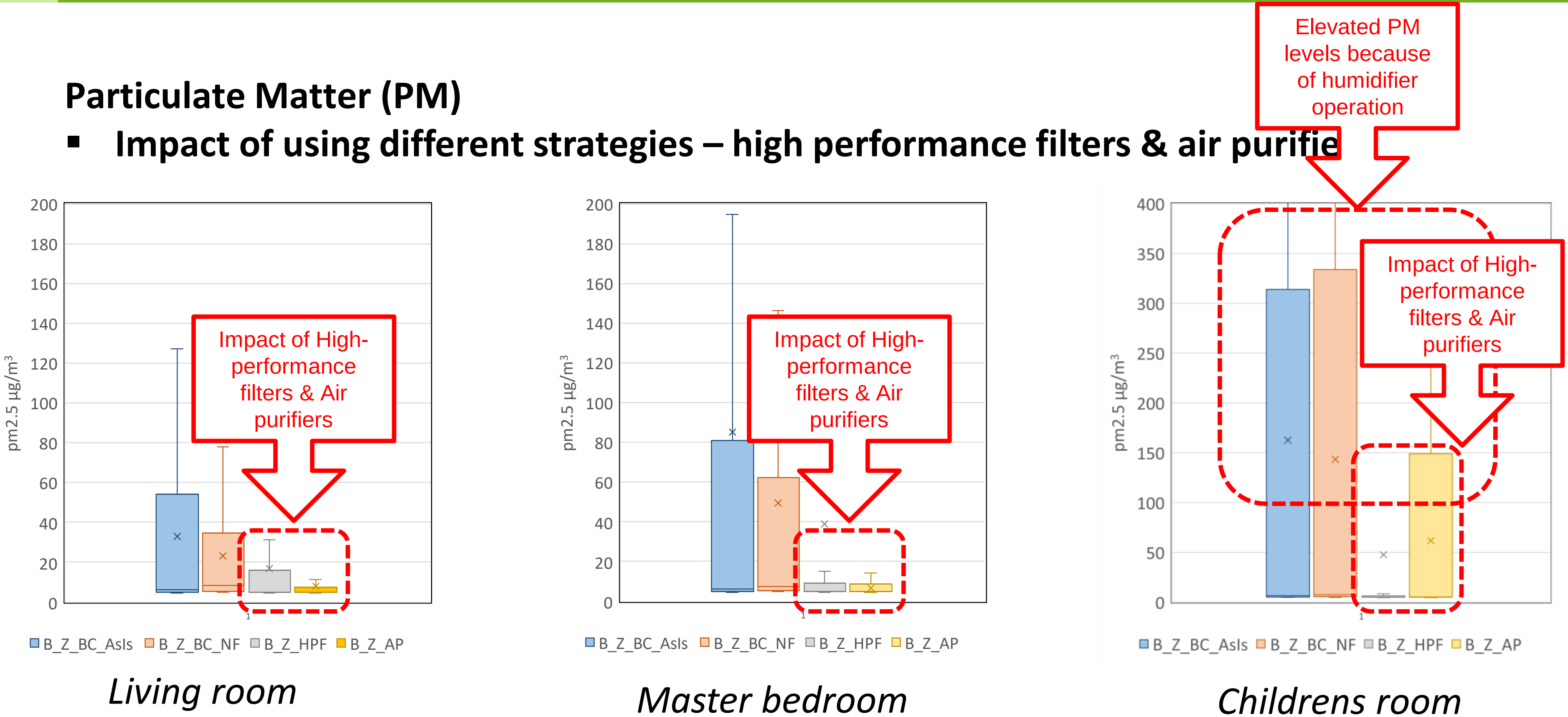
Legend:
B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers
B_V_BC: Birch house/Venmar/ Basecase
B_V_HP: Birch house/Venmar/ High performance filters
B_V_AP: Birch house/Venmar/ Air purifier

W_V_BC_NoKids: Willow/Venmar/Basecase w/o kids
W_V_BC_Kids: Willow/Venmar/Basecase w/ kids
W_V_HP_ NoKids: Willow/Venmar/High performance filters w/o kids
W_V_HP_ Kids: Willow/Venmar/High performance filters w/ kids
W_V_AP_NoKids: Willow/Venmar/Air purifiers w/o kids
W_V_AP_Kids: Willow/Venmar/Air purifiers w/ kids

Box plots for PM2.5 levels from Zehnder & Venmar HRV operation in Living Space in Birch House & Venmar HRV operation in the Willow House

Particulate Matter (PM)

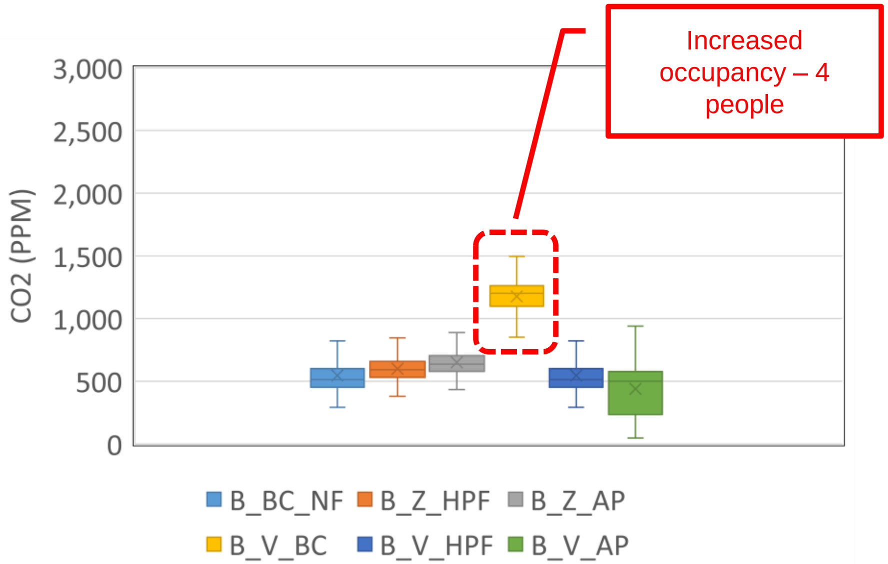
- **Impact of using different strategies – high performance filters & air purifie**



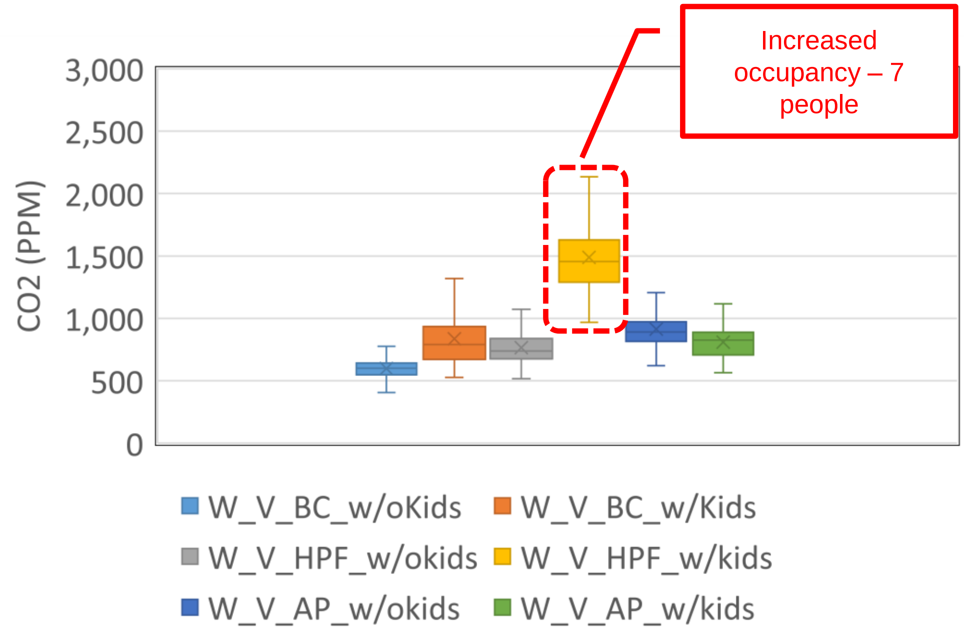
Legend:
B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers

Bar charts for Zehnder HRV operation in Birch House for Living room, Master bedroom & Children's bedroom.

Performance in Gaseous Pollutants - CO_2 levels



a) Birch House



b) Willow House

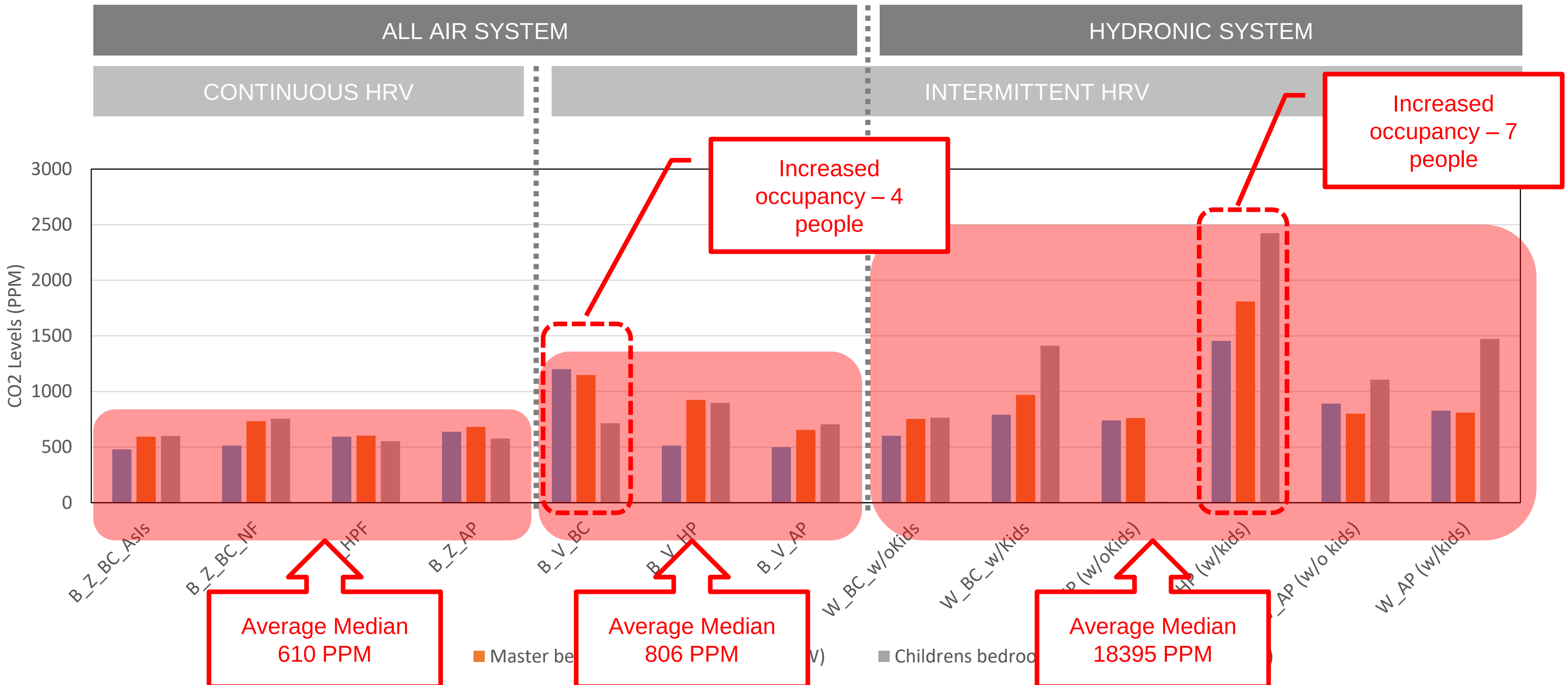
Legend:
B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers
B_V_BC: Birch house/Venmar/ Basecase
B_V_HP: Birch house/Venmar/ High performance filters
B_V_AP: Birch house/Venmar/ Air purifier

W_V_BC_NoKids: Willow/Venmar/Basecase w/o kids
W_V_BC_Kids: Willow/Venmar/Basecase w/ kids
W_V_HP_ NoKids: Willow/Venmar/High performance filters w/o kids
W_V_HP_ Kids: Willow/Venmar/High performance filters w/ kids
W_V_AP_NoKids: Willow/Venmar/Air purifiers w/o kids
W_V_AP_Kids: Willow/Venmar/Air purifiers w/ kids

Box plots reporting CO_2 levels for all cases in Living room space of Birch House and Willow House

RESULTS & DISCUSSION

Performance in Gaseous Pollutants - CO2 levels



Legend:

B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers
B_V_BC: Birch house/Venmar/ Basecase
B_V_HP: Birch house/Venmar/ High performance filters
B_V_AP: Birch house/Venmar/ Air purifier

W_V_BC_NoKids: Willow/Venmar/Basecase w/o kids
W_V_BC_Kids: Willow/Venmar/Basecase w/ kids
W_V_HP_ NoKids: Willow/Venmar/High performance filters w/o kids
W_V_HP_ Kids: Willow/Venmar/High performance filters w/ kids
W_V_AP_NoKids: Willow/Venmar/Air purifiers w/o kids
W_V_AP_Kids: Willow/Venmar/Air purifiers w/ kids

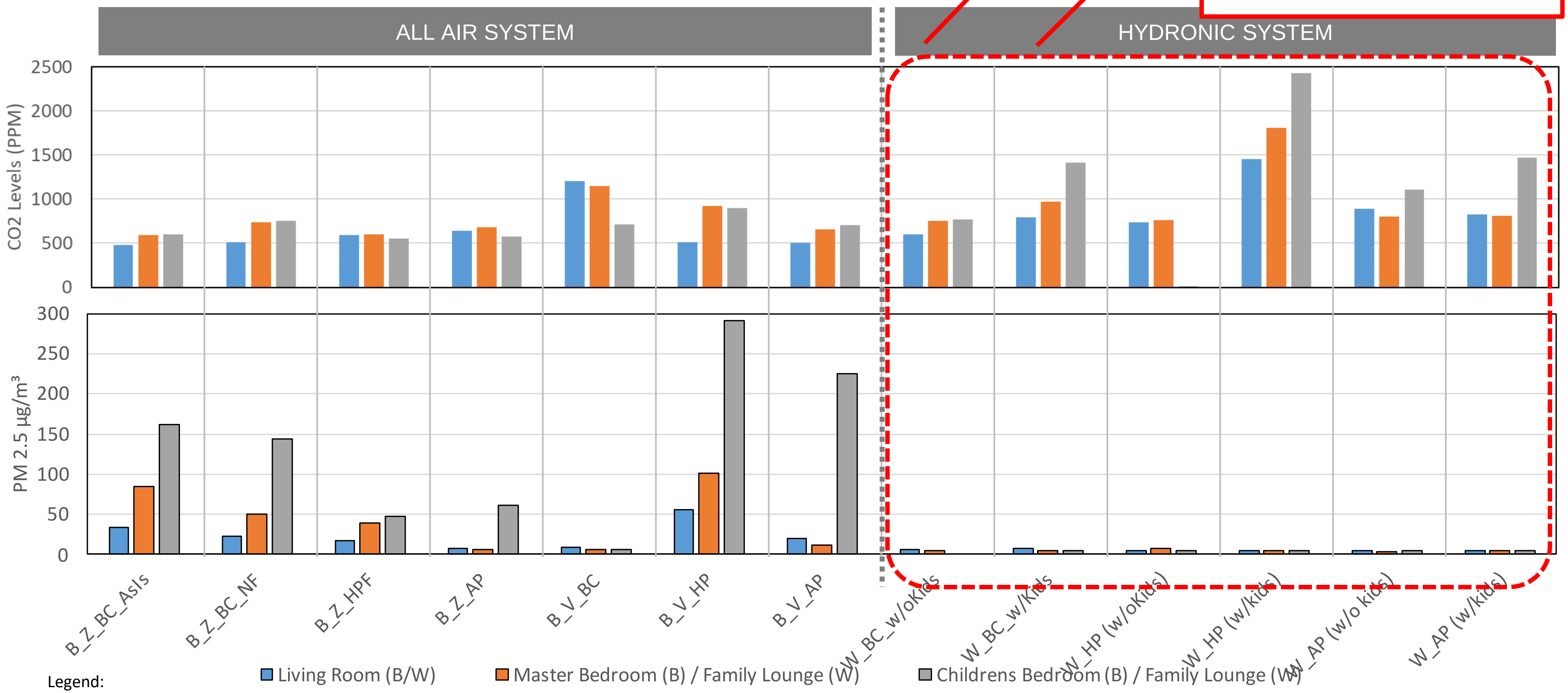
Median CO2 levels for all spaces in Birch house and Willow house

RESULTS & DISCUSSION

High CO2 levels does not correspond wi/ high PM levels

Complaints of stuffiness & odors from occupant log

Performance in Gaseous Pollutants - CO_2 levels



Legend:

B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers
B_V_BC: Birch house/Venmar/ Basecase
B_V_HP: Birch house/Venmar/ High performance filters
B_V_AP: Birch house/Venmar/ Air purifier

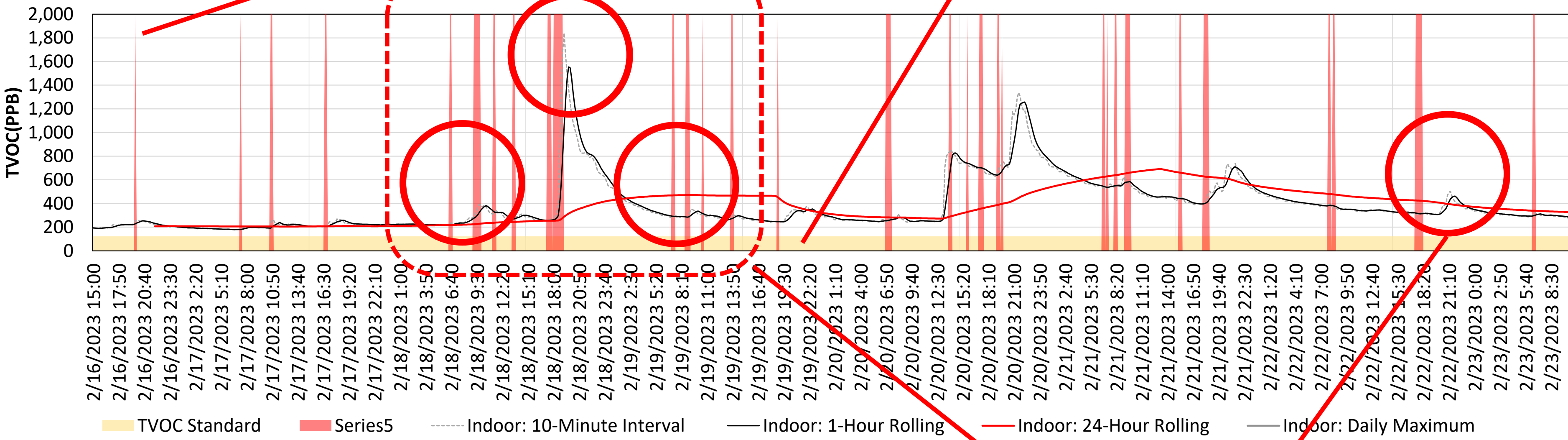
W_V_BC_NoKids: Willow/Venmar/Basecase w/o kids
W_V_BC_Kids: Willow/Venmar/Basecase w/ kids
W_V_HP_ NoKids: Willow/Venmar/High performance filters w/o kids
W_V_HP_ Kids: Willow/Venmar/High performance filters w/ kids
W_V_AP_NoKids: Willow/Venmar/Air purifiers w/o kids
W_V_AP_Kids: Willow/Venmar/Air purifiers w/ kids

Comparing CO2 (top) & PM (bottom) levels for Birch & Willow Houses

Performance in Gaseous Pollutants - TVOC levels

Superimposition of cooking activities

Recommended TVOC level - USGBC



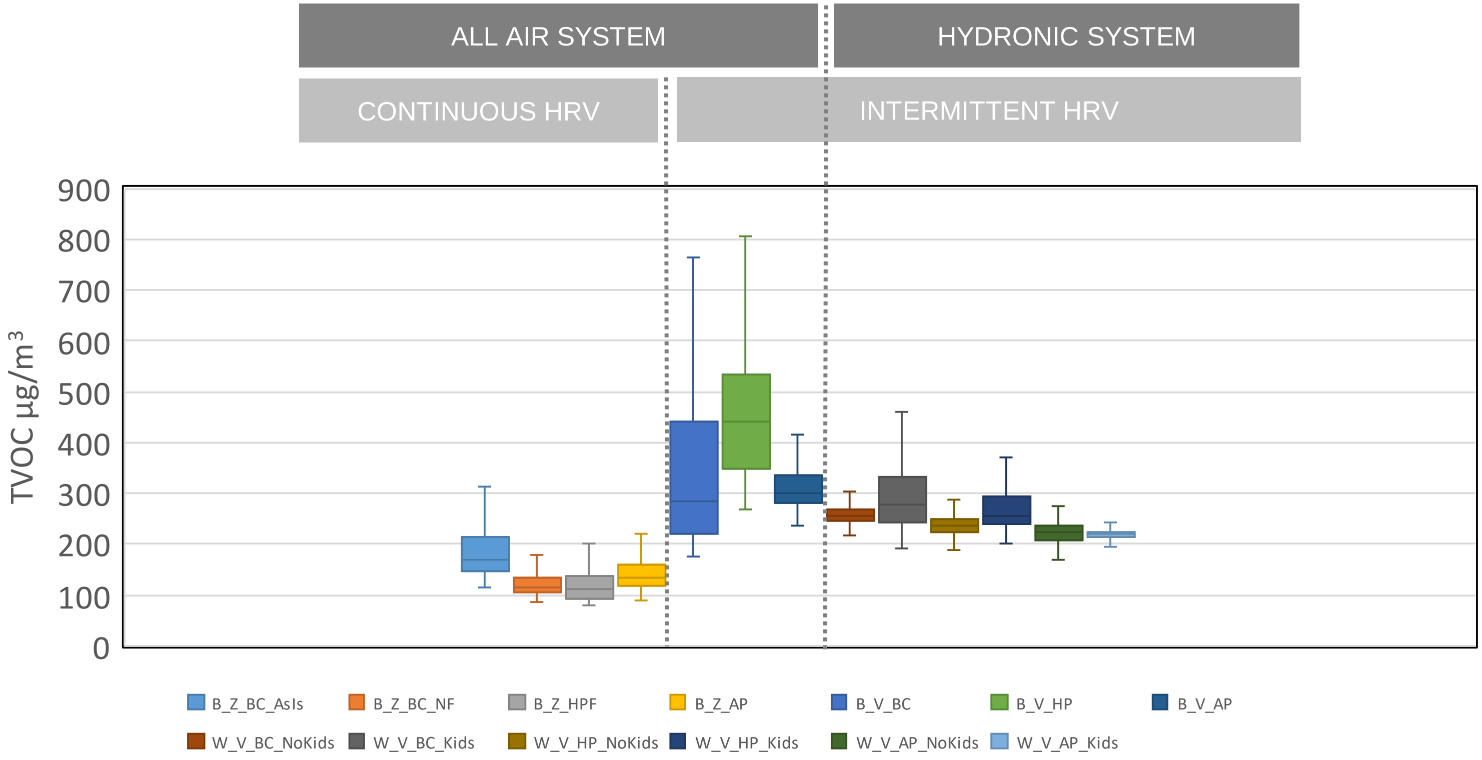
Birch House base case w/ Venmar

TVOC levels independent of cooking activities

TVOC levels dependent on different cooking activities

RESULTS & DISCUSSION

Performance in Gaseous Pollutants - TVOC levels



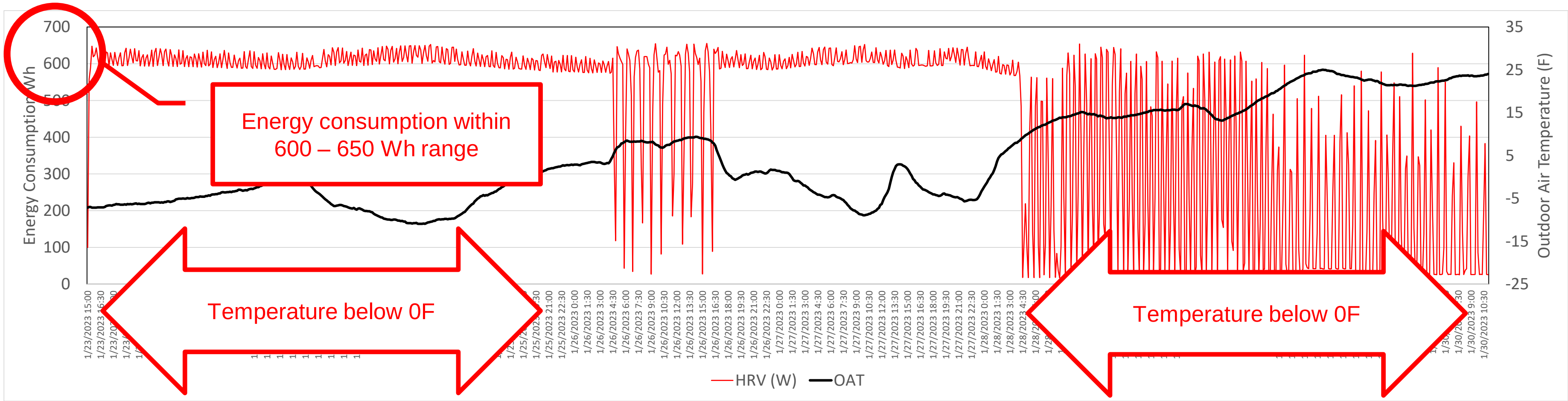
Legend:

B_Z_BC_AsIs: Birch house/Zehnder/Basecase w/ as-is filters
B_Z_BC_NF: Birch house/Zehnder/ Basecase w/ new filters
B_Z_HPF: Birch house/Zehnder/ High performance filters
B_Z_AP: Birch house/Zehnder/ Air purifiers
B_V_BC: Birch house/Venmar/ Basecase
B_V_HP: Birch house/Venmar/ High performance filters
B_V_AP: Birch house/Venmar/ Air purifier

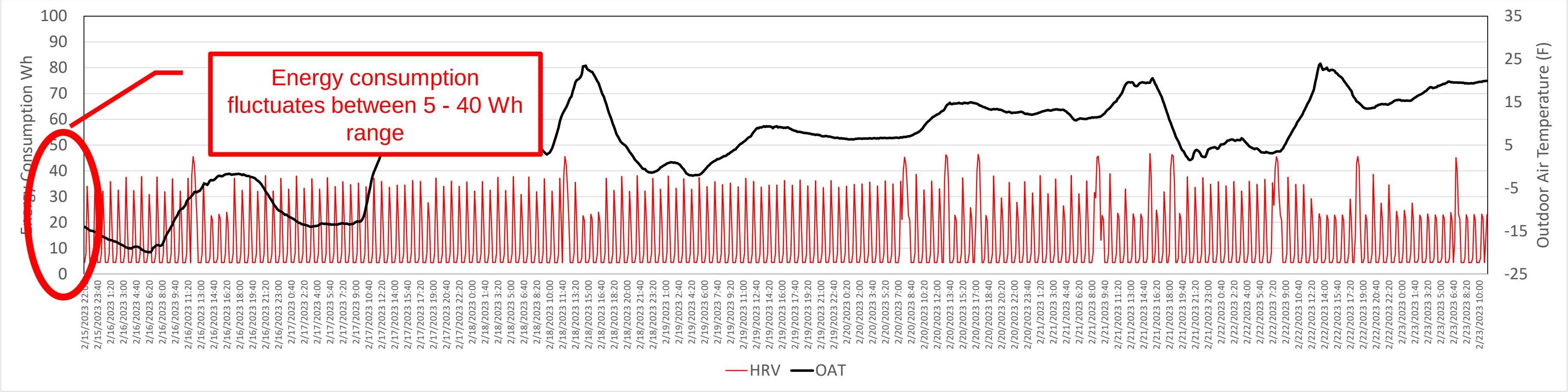
W_V_BC_NoKids: Willow/Venmar/Basecase w/o kids
W_V_BC_Kids: Willow/Venmar/Basecase w/ kids
W_V_HP_ NoKids: Willow/Venmar/High performance filters w/o kids
W_V_HP_ Kids: Willow/Venmar/High performance filters w/ kids
W_V_AP_NoKids: Willow/Venmar/Air purifiers w/o kids
W_V_AP_Kids: Willow/Venmar/Air purifiers w/ kids

Box plots presenting TVOC levels for Birch & Willow Houses

Trends in Energy Consumption



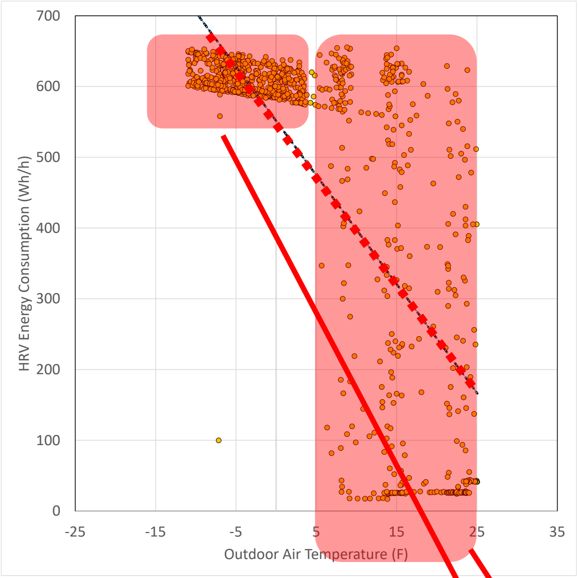
Birch House Base case w/ Zehnder



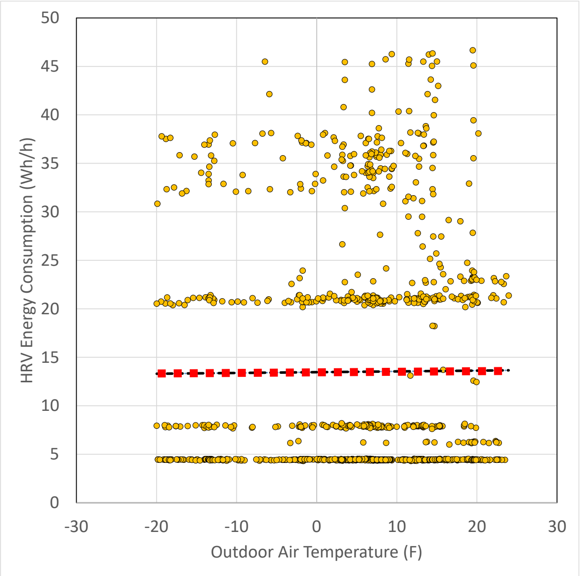
Birch House base case w/ Venmar

RESULTS & DISCUSSION

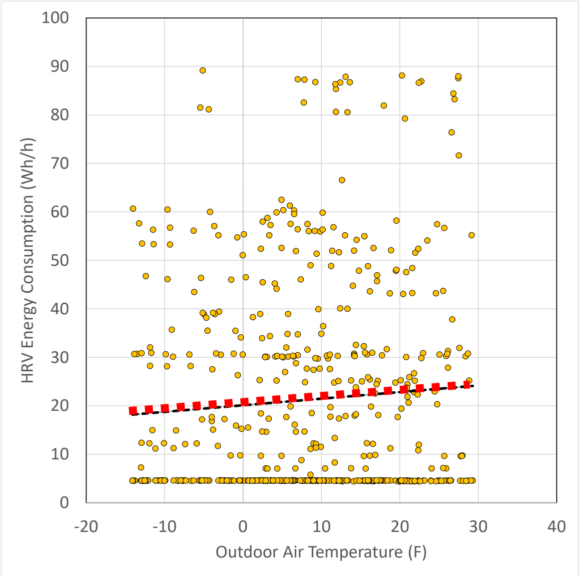
Trends in Energy Consumption



Birch House base case w/ Zehnder



Birch House base case w/ Venmar



Willow House base case (w/kids) w/ Venmar

Pre-heater activated below 23F & a pulsed mode of operation is observed to prevent defrost.

Pre-heater operates in continuous mode below 5F & system goes into unbalanced mode of operation where the supply air gradually decreased while exhaust air rate is kept the same.

CONCLUSIONS & RECOMMENDATIONS

Particulate Matter

- **When considering spatial layout & activities**
  - Indoor PM levels independent of corresponding outdoor PM concentration levels.
  - Open configuration of Living room & proximity of exhaust vents to the cooking area in the room contributed towards maintaining the PM levels for most part within acceptable limits.
  - Location of return air ducts in common spaces such as the corridor & shutting bedroom doors contributed to higher PM levels in these spaces.

- **Recommendations:**
  - Airtight construction in residential buildings (0.5 ACH_{50})
  - Installing two sets of air filters on outdoor air intakes with > 13 MERV ratings
  - Recirculating kitchen vent hood assisted with a boost mode of the HRV system
  - Air vents within or on top of bedroom doors to reduce the buildup of PM concentrations in these rooms, when the doors are closed

CONCLUSIONS & RECOMMENDATIONS

Particulate Matter

- **When comparing the performance of all-air & hydronic systems**
  - Volume of air circulated in an All-air system contributes to the recirculation of PM generated from cooking activities, dust particles & pet dander
  - Higher humidity levels (RH > X%) associated with the operation of radiant floor system resulted in lower PM levels – i.e., aggregation & settling of PM

- **Recommendations:**
  - Hydronic systems for reduced PM concentrations in residential buildings

CONCLUSIONS & RECOMMENDATIONS

Particulate Matter

- **When comparing the performance of continuous & intermittent ventilation systems**
  - Indoor PM levels elevated at extremely low OATs.
  - Higher humidity levels are associated w/ intermittent ventilation system operation lowering resultant PM levels – i.e., aggregation & settling of PM
  - Operation of continuous ventilation system (i.e., Zehnder) more energy consumptive than intermittent ventilation system (i.e., Venmar).
  - No substantial difference was observed in the resultant PM concentrations from both systems

- **Recommendation:**
  - Use of intermittent HRV systems in cold / extremely cold climates

CONCLUSIONS & RECOMMENDATIONS

Particulate Matter

- **When considering different strategies of high-performance filters & air-purifiers**
  - High performance filters & air purifiers have a significant impact on resultant PM concentrations in the living room & bedrooms.
  - Air-purifiers contribute towards reduction in PM levels, however the configuration of the space in which these air-purifiers are located & extent of PM generating activities have an impact on the performance of these systems.

- **Recommendations:**
  - Selection of high-performance measures after assessing pollutant generating activities, HRV type & spatial configuration of the building

CONCLUSIONS & RECOMMENDATIONS

Particulate Matter

- **When considering energy performance**
  - Comparing energy performance of continuous & intermittent HRV systems:
    - energy consumption from continuous HRV system far exceeded that of the intermittent HRV system.
    - the capabilities of both systems to handle elevated PM levels was comparable.
  - Comparing the performance of different filters resulted in insignificant impact on energy consumption.

- **Recommendation:**
  - Use of intermittent HRV systems in extreme cold climates.
  - Use of high-performance filters.
  - Use of ECMs in fan components of HVAC systems.

CONCLUSIONS & RECOMMENDATIONS

Carbon Dioxide

- Positive correlation between ventilation rates and CO_2 levels - higher ventilation rates corresponding to implementation of all-air BREATHe system.
- CO_2 & PM, TVOC levels not related.
- CO_2 levels consistently higher in Willow House that in Birch House, coincided with complaints of stuffiness & odors from occupants of the Willow House.
- **Recommendation:**
  - Prescribed ventilation rates to be considered during certain times of day, during night / unoccupied periods these levels may go below prescribed limits without detrimentally impacting IAQ.

Total Volatile Organic Compounds (TVOCs)

- Comparing the performance of different filters resulted in insignificant impact on resultant TVOC levels in both the homes.
- **Recommendation:**
  - Further research exploring implementation of different configurations of activated carbon filters in residential air filters.

FUTURE WORK

- To expand the evaluation of strategies for maintaining IAQ during summer - when wildfires cause enormous degradation of outdoor air quality in dry regions of US
- To examine the impact of ERV systems on resultant IAQ in residential buildings
- To examine different configurations of air-purifiers
- To incorporate strategies such as HEPA filters & UV irradiation in the assessment on resultant IAQ in residential buildings
- To explore options for mitigating TVOC levels in indoor spaces including use of different configurations of activated carbon filters
- To evaluate impact state-of-the-art technologies such as the use of low-cost particle monitors & occupancy sensors along with HRV systems to optimize provision of outdoor air in interior spaces on resultant IAQ in residential buildings

Questions

Jaya Mukhopadhyay
jaya.mukhopadhyay@montana.edu