PERFORMANCE OF DEMAND CONTROLLED VENTILATION SYSTEMS WITH CENTRAL AND ZONAL CONTROL IN A SINGLE-FAMILY HOUSE

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INTRODUCTION

As national and EU-level energy performance standards become more demanding, residential ventilation systems must be designed not only to ensure adequate indoor air quality (IAQ) but also to minimize energy consumption. In Estonia, Regulation No. 58 establishes the methodology for calculating the energy performance of buildings, which includes detailed procedures for determining heating demand and assessing the efficiency of technical systems. These calculations form the basis for meeting national energy performance requirements and indirectly promote the reduction of heating energy use and the improvement of system efficiency. One of the key technologies to support these goals is demand-controlled ventilation (DCV), which dynamically adjusts airflow rates based on real-time indicators such as CO_2 concentration and occupancy patterns.

DCV has the potential to significantly reduce ventilation-related energy use by supplying air only when and where it is needed, without compromising occupant comfort or air quality. However, the effectiveness of DCV depends heavily on the chosen control strategy and the technical configuration of the ventilation system.

This report investigates DCV implementation in a five-room single-family house through dynamic simulations using IDA-ICE 5.1. Four control strategies are evaluated: constant airflow (CAV), central CO_2 control using a sensor in the exhaust duct, central CO_2 control using the highest reading from individual rooms, and zonal CO_2 control where the building is divided into two zones, each controlled by the highest CO_2 level in the zone. These strategies are analyzed in combination with two heat recovery systems—enthalpy (ERV) and sensible-only (HRV), ERV and HRV are cross-counterflow plate heat exchangers. The goal is to benchmark the energy performance and IAQ outcomes of each strategy under realistic operating conditions, including detailed occupancy profiles and Estonian climate data, and to identify practical, scalable solutions for low-energy residential buildings.

METHODS

A dynamic simulation model of a 160 m² five-room single-family house (Figure 1) was created in IDA-ICE 5.1 using detailed construction documents and input data based on Estonian Regulation No. 58. The building includes three bedrooms, a living room combined with a kitchen, an office, sauna facilities, and various utility spaces. A detailed floor plan is available in Appendix A. Heating is provided by a hydronic underfloor heating system supplied by an air-to-water heat pump. Additional information about the building model is available in Appendix B.

Figure 1. (a) 3D image of the single-family house model. (b) Exterior view of the building.

Ventilation is provided by a central ventilation unit. Supply air is delivered to the living room, kitchen/dining area, sauna lounge, office, and bedrooms, while exhaust air is extracted from the bathroom, toilets, sauna, utility room, entrance, and walk-in wardrobe, following the layout of the floor plan. Table 1 provides an overview of the ventilation airflow rates for each room.

Table 1. Ventilation airflow rates for the modelled building.

Room	Supply Air, l/s	Extract Air, l/s
Living room/Kitchen	14	12
Bedroom 1	15	-
Bedroom 2	10	-
Bedroom 3	10	-
Office	10	-
Sauna Lounge	8	-
Bathroom	-	15
Sauna	10	10
Toilet 1	-	10
Toilet 2	-	10
Utility Room	-	5
Entrance	-	5
Walk-in Closet	-	10
TOTAL	**77**	**77**

SIMULATIONS

Energy and indoor climate simulations were designed to compare the performance of three different heat recovery types within the ventilation unit under four system configurations with different control scenarios. The scenarios are as follows:

1. **Constant airflow** – the ventilation operates at a fixed airflow rate regardless of occupancy or indoor conditions. For constant ventilation, airflow rates are based on design values (see Table 1).
2. **Central control - CO_2 control via exhaust sensor** –fan speed is adjusted based on CO_2 concentration measured in the ventilation unit extract air, with a setpoint of 600 ppm.
3. **Central control - CO_2 control based on highest concentration measured across rooms** – Sensors are installed in the bedrooms, office, and living room/kitchen, with a setpoint of 950 ppm.
4. **Zonal control – CO_2 control using room sensors in a dual-zone configuration.** The house is divided into two ventilation zones, each regulated with dampers based on the highest CO_2 concentration within the respective zone, with a setpoint of 950 ppm.

While supply airflow was dynamically modulated in all demand-controlled scenarios, the exhaust air volume was adjusted to match the supply to maintain balance. Minimum airflow was constrained to 0.1 $l/(s \cdot m^2)$ in accordance with the standard EVS-EN 16798-1:2019. The indoor air temperature was maintained at 21.5 °C, and outdoor climate data was derived from the Estonian Test Reference Year (TRY) for 1990–2020. For demand-controlled ventilation, regulated by CO_2 and RH, the system must meet Category II indoor climate conditions per EVS-EN 16798-1:2019+NA2019, requiring CO_2 levels to stay below 550 ppm above outdoor air in bedrooms and 800 ppm in the living room, with outdoor CO_2 assumed at 400 ppm.

Two different types of heat recovery systems were considered in the simulation: enthalpy recovery plate (ERV) and heat recovery plate (HRV) heat exchangers. Each system was modeled with identical specific fan power (SFP) of 1.2 $kW/(m^3/s)$ to enable fair comparison. An overview of the key parameters for each system is provided in Table 2.

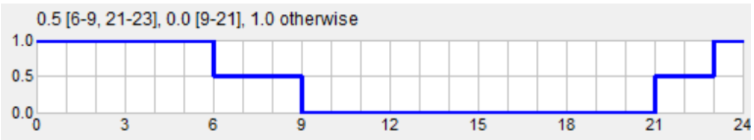
1. The **ERV** has a temperature ratio of 0.8. It uses a pre-heating coil with a setpoint of −6 °C, which activates when the outdoor air temperature drops below this threshold. This is a product specific setup that ensures frost protection and sufficient supply air temperature without post heater and enables both sensible and latent heat recovery.

2. The **HRV** offers higher heat recovery temperature ratio at 0.9. It includes a pre-heating coil with a setpoint of 0 °C for frost protection. Unlike the ERV, the HRV recovers only sensible heat and does not transfer moisture between air streams.

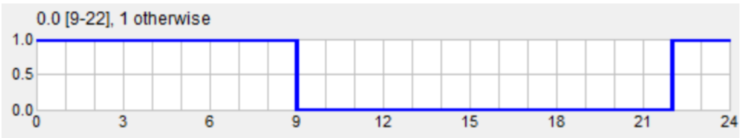
Table 2. Summary of Heat Recovery System Parameters

	ERV	HRV
SFP	1.2 kW/(m³/s)	1.2 kW/(m³/s)
Temperature ratio	0.8	0.9
Heating coil	pre-heater, setpoint -6 °C	pre-heater, setpoint 0 °C

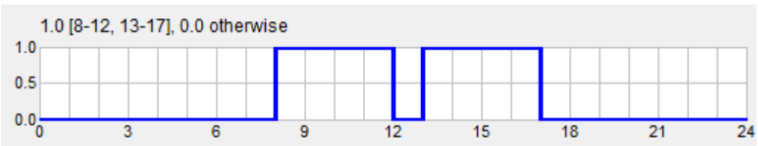
The simulation model incorporates dynamic occupancy profiles based on Estonian Regulation No. 58, which provides standardized assumptions for residential usage patterns. According to these profiles, bedrooms are primarily occupied during night-time hours, while living rooms experience higher occupancy during the day. These time-based presence patterns were used to define internal heat gains and CO_2 generation rates in each room. Internal heat gains from occupants and appliances were estimated following the values specified in the regulation. This methodology allows for the evaluation of different control strategies under realistic residential conditions, enabling a more accurate assessment of indoor climate performance and energy efficiency. The occupancy profiles used in the simulations are illustrated in Figure 2.



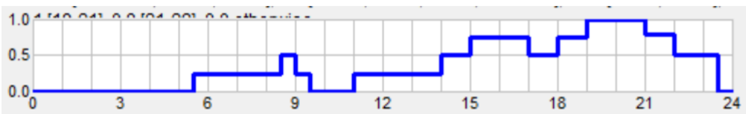
Bedroom 1 – 2 persons



Bedroom 2 and bedroom 3 – 1 person each



Office – 1 person



Living room / Kitchen – 4 persons

Figure 2. Occupancy profiles in different zones

Zonal supply air control was implemented to enhance ventilation efficiency in a single-family house with an extract ductwork without dampers/controls. The building was divided into two functional supply zones served by supply air ductwork branches with dampers based on occupancy patterns: a daytime zone including the living room, kitchen, office, sauna and sauna lounge, and a night time zone covering all the bedrooms. Each zone (except sauna and sauna lounge) was equipped with CO_2 sensors, and ventilation supply airflow rate was regulated based on the highest concentration measured within the zone. Although exhaust air was continuously extracted from fixed locations (e.g., bathrooms, utility room, toilets), its volume was modulated in parallel with the supply airflow, maintaining a balanced air exchange rate at all times. This dual-zone supply air control strategy allowed for more precise matching of ventilation to actual demand, without altering the simplicity of the extract ductwork layout. The two ventilation zones are illustrated in Figure 3. Zone 1 (blue) includes the bedrooms, while Zone 2 (orange) comprises the living room and kitchen, office, sauna lounge, and sauna.

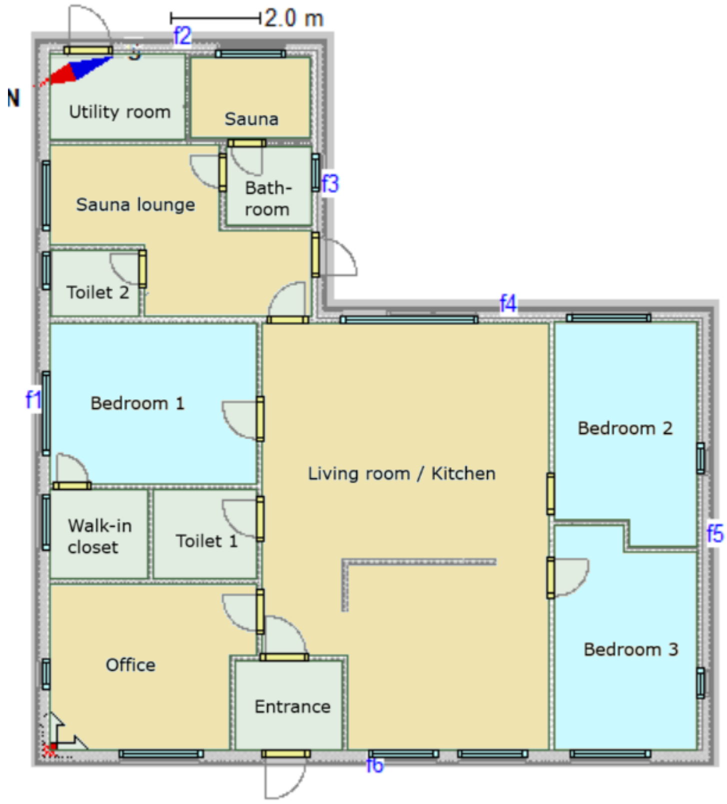


Figure 3. Zonal division of the single-family house for demand-controlled ventilation simulations.

RESULTS

Figure 4 illustrates the annual energy use (in kWh/m²·yr) associated with four different ventilation control strategies in a single-family house. The energy use is broken down into three components: space heating (heat produced by heat pump), supply air heating (electric pre or post heater), and fan electricity. The constant ventilation strategy results in the highest total energy use, primarily due to higher fan electricity use and heating demand. Introducing CO_2-based control on the exhaust side (setpoint 600 ppm) reduces total energy use slightly by lowering fan operation during periods of low occupancy. Considerable improvement is seen when CO_2 sensors are placed in individual rooms with a higher setpoint (950 ppm), allowing for more demand-driven airflow reduction. The most energy-efficient solution is the zonal ventilation strategy, where the system is divided into two zones. Two zones were divided according to the previously shown room layout (Figure 3). Airflow to the bedrooms is individually regulated based on the highest CO_2 concentration detected in any of the bedrooms. This approach allows the system to reduce airflow to unoccupied bedrooms during the day while ensuring adequate ventilation at night, without unnecessarily ventilating the living room. As a result, the system maintains good indoor air quality while minimizing energy consumption.

Compared to constant ventilation, the zonal control strategy resulted in:

- 17% lower space heating energy (from 54.9 to 45.4 kWh/m²·yr)
- 46% lower supply air heating (from 6.9 to 3.7 kWh/m²·yr)
- 64% lower fan electricity consumption (from 9.5 to 3.4 kWh/m²·yr)

Compared to central control with room CO_2 sensors, the zonal strategy achieved:

- 13% lower space heating energy (from 52.2 to 45.4 kWh/m²·yr)
- 31% lower supply air heating (from 5.4 to 3.7 kWh/m²·yr)
- 48% lower fan electricity consumption (from 6.6 to 3.4 kWh/m²·yr)

Considering that heat pump operates with seasonal performance factor (SPF) of 2.9, total electricity saving in space heating, supply air heating and fan electricity results:

- 35% for zonal control strategy compared to constant ventilation
- 24% for zonal control strategy compared to central control with room sensors

These findings highlight the critical role of control logic in demand-controlled ventilation systems. While the type of heat recovery unit contributes to baseline efficiency, the choice of control strategy has a more pronounced effect on overall energy consumption. Implementing zonal supply control does not require additional ductwork for extract air, making it a practical and scalable solution for residential buildings with balanced ventilation systems. By aligning airflow more closely with real-time occupancy patterns, this approach enables energy savings without compromising indoor air quality. As residential buildings move toward stricter energy performance standards, the integration of intelligent, zone-based ventilation control offers a promising pathway for achieving both regulatory compliance and operational efficiency.

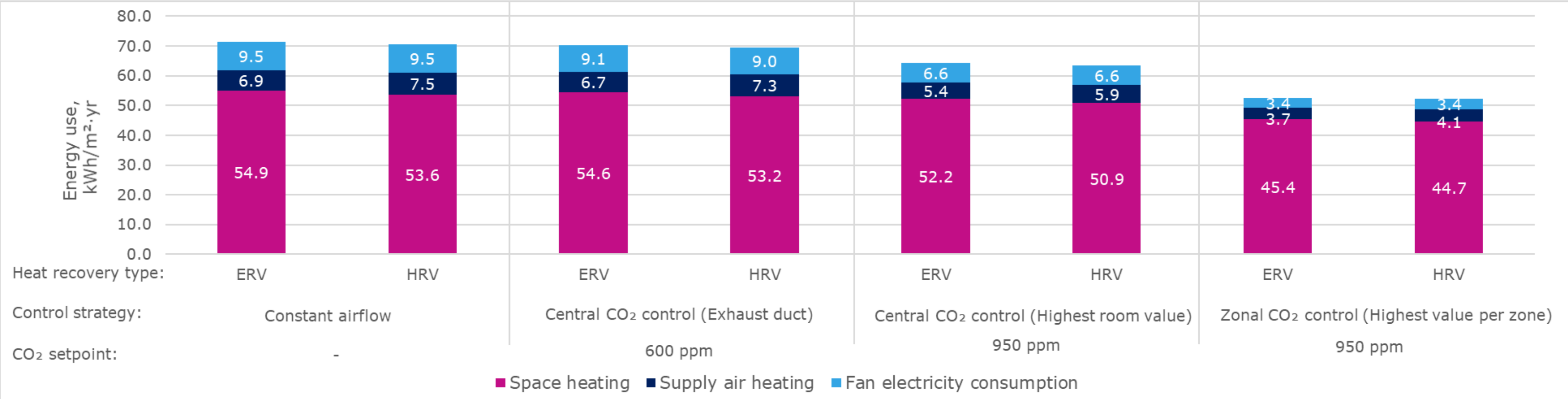


Figure 4. Comparison of annual energy use by ventilation control strategy (kWh/m²).

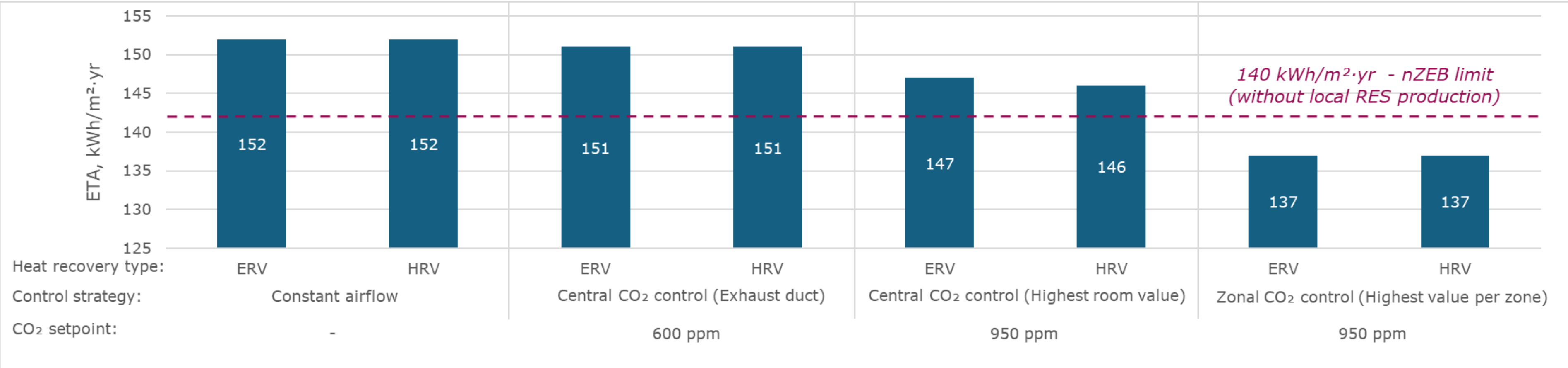


Figure 5. Energy Performance Indicator (ETA, kWh/(m²·a)) under different ventilation control strategies and heat recovery unit types.

Figure 5 presents the calculated energy performance primary energy indicator (ETA, kWh/(m²·a)) for a residential building under different ventilation control strategies and heat recovery types. The results show that the choice of control strategy significantly impacts the building's primary energy use. The constant airflow strategy yields the highest ETA values across both recovery types, peaking at 152 kWh/(m²·a). Introducing CO_2-based demand control with a setpoint of 600 ppm in the exhaust duct reduces ETA marginally. Further energy savings are achieved with room-based control (950 ppm), but the most significant improvement occurs with the zonal supply-based maximum CO_2 strategy. This strategy lowers the ETA to as little as 137 kWh/(m²·a) with ERV, demonstrating the effectiveness of tailored, demand-driven ventilation in minimizing energy use while maintaining indoor air quality. These findings highlight the importance of combining efficient heat recovery systems with smart control strategies to meet stringent energy performance requirements in residential buildings. According to the Estonian minimum energy performance requirements for nearly zero-energy buildings (nZEB), the energy performance indicator must not exceed 140 kWh/(m²·a) for detached houses with a heated area between 120–220 m² when local renewable electricity production is not considered. As indicated by the dashed magenta line in Figure 5, only the most efficient combinations successfully meet this threshold.

In the ETA calculation, an air-to-water heat pump with a seasonal performance factor (SPF) of 2.9 was used, as defined in Table 10 of Estonian Regulation No. 58. Space heating is primarily provided by hydronic underfloor heating on slab, with a distribution efficiency of 0.85 according to Table 9. The heating energy mix consists of 92% from the heat pump and 8% from direct electric heating.

Figure 6 presents the distribution of time spent within various indoor CO_2 concentration ranges under four ventilation control strategies across exhaust duct, bedrooms, and living room. According to EVS-EN 16798-1:2019+NA:2019, Category II indoor climate requirements specify that CO_2 levels should not exceed 950 ppm in bedrooms and 1,200 ppm in living rooms, assuming an outdoor concentration of 400 ppm. The results show that demand-controlled ventilation strategies—particularly those based on room-specific and zonal CO_2 measurements—successfully maintain CO_2 levels within the required thresholds for the majority of the time. While constant airflow ensures basic ventilation, it lacks responsiveness to occupancy, leading to unnecessary overventilation. The exhaust CO_2 control strategy offers modest improvement, but it is the central CO_2 control (highest room value) and zonal CO_2 control (highest per zone) strategies that provide the best performance. These approaches significantly increase the time spent below 780 ppm, particularly in bedrooms, while minimizing the time spent in higher concentration ranges. Overall, DCV proves to be an effective method for maintaining acceptable indoor air quality while allowing for energy-efficient operation, especially when minimum airflow is limited to 0.1 l/(s·m²) and maximum flow rates are governed by system design values.

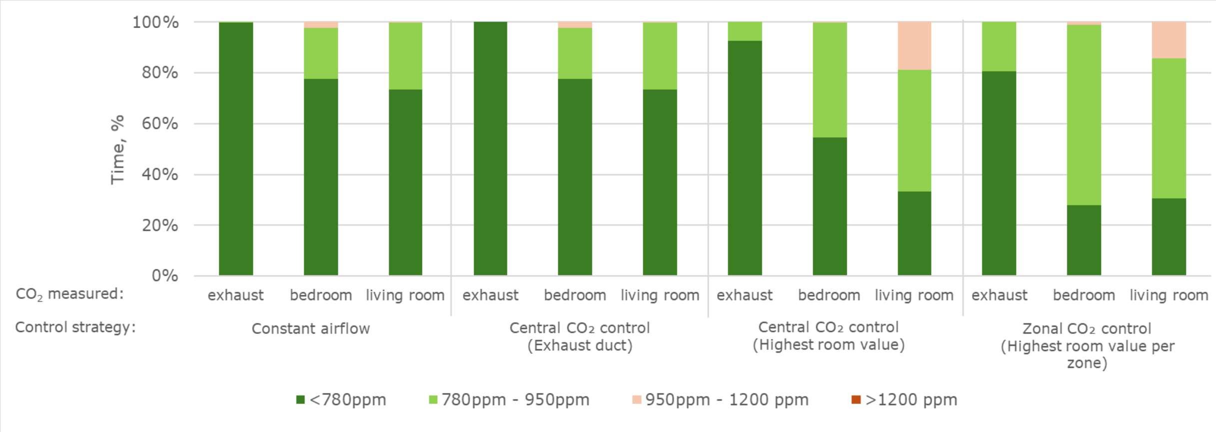


Figure 6. Distribution of time spent within different indoor CO_2 concentration ranges across four ventilation control strategies.

The central exhaust duct CO_2 control strategy exhibits clear limitations due to its reliance on a single measurement point that reflects the average of extracted air from all rooms. In this case, a setpoint of 600 ppm was necessary to maintain acceptable indoor air quality, significantly lower than typical room-specific thresholds. This low value compensates for the system's inability to identify localized air quality issues. However, such a setpoint is not universally applicable and must be tailored to each building based on layout, occupancy, and system design. If set too high, the system may respond too late, resulting in poor air quality despite operating as intended. Compared to room-based or zonal strategies, exhaust duct control is less effective in ensuring consistent IAQ and offers limited potential for energy-efficient, demand-based ventilation.

Figures 7 and 8 present annual CO_2 concentration duration curves for four ventilation control strategies in a living room and bedroom, respectively. In Figure 7, the living room results are compared against the Category II limit of 1200 ppm, while in Figure 8, the bedroom data is evaluated against the Category II limit of 950 ppm. All strategies maintain CO_2 concentrations within the respective Category II limits over the course of the year, with variations in the curve shape reflecting differences in control logic and ventilation responsiveness. The duration curves for constant airflow (CAV) and central CO_2 control based on exhaust duct measurements appear very similar. This is because the CO_2-based control strategy relies on a single sensor located in the central exhaust duct, which reflects the average CO_2 concentration of extracted air from all rooms. Since this signal does not detect elevated concentrations in individual rooms—especially in the bedroom during night-time—the control system often maintains a relatively constant airflow to ensure overall air quality, resulting in performance that closely resembles constant ventilation. The limited responsiveness to localized occupancy-driven CO_2 peaks means that the system behaves similarly to a fixed ventilation rate throughout the year.

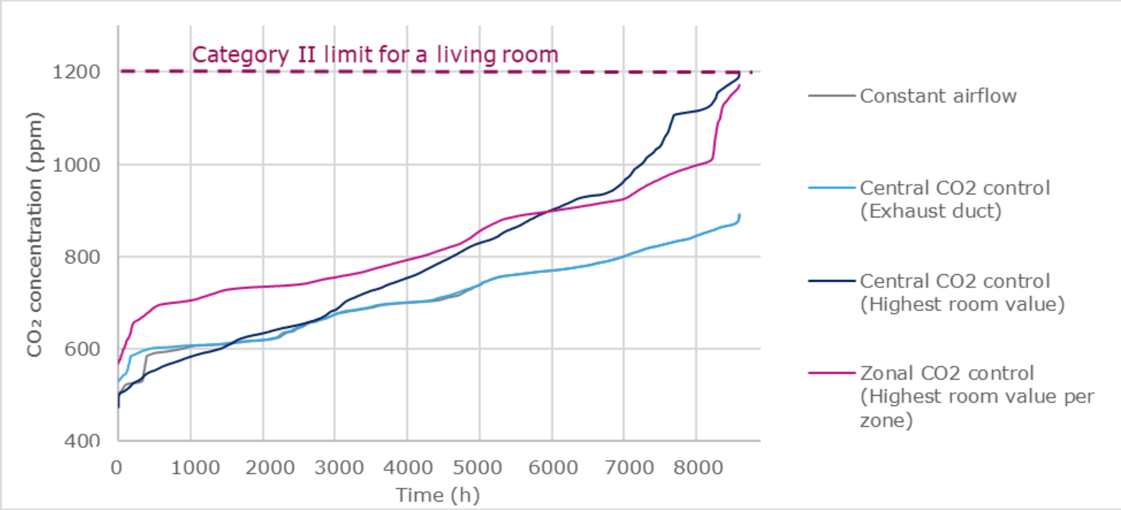


Figure 7. Annual CO_2 duration curves comparing ventilation control methods in a living room

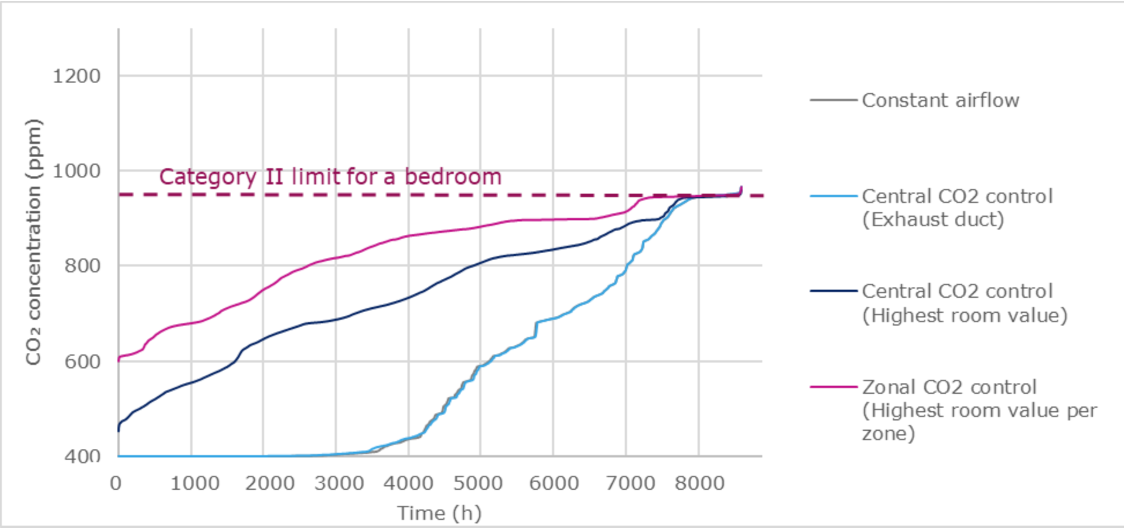


Figure 8. Annual CO_2 duration curves comparing ventilation control methods in bedroom 1

Figure 9 presents the annual supply airflow rate duration curves for four ventilation control strategies. The constant airflow strategy maintains a fixed ventilation rate of approximately 77 l/s throughout the year. In contrast, the demand controlled strategies adjust airflow based on indoor CO_2 concentrations, resulting in significant variations over time. The central CO_2 control based on exhaust duct measurements operates near the maximum flow rate most of the time due to its low setpoint and limited spatial resolution. The room-based and zonal control strategies achieve lower average airflow rates by more precisely responding to occupancy patterns. Notably, the zonal strategy maintains the lowest airflow for much of the year, reflecting its ability to reduce ventilation in unoccupied zones without compromising air quality.

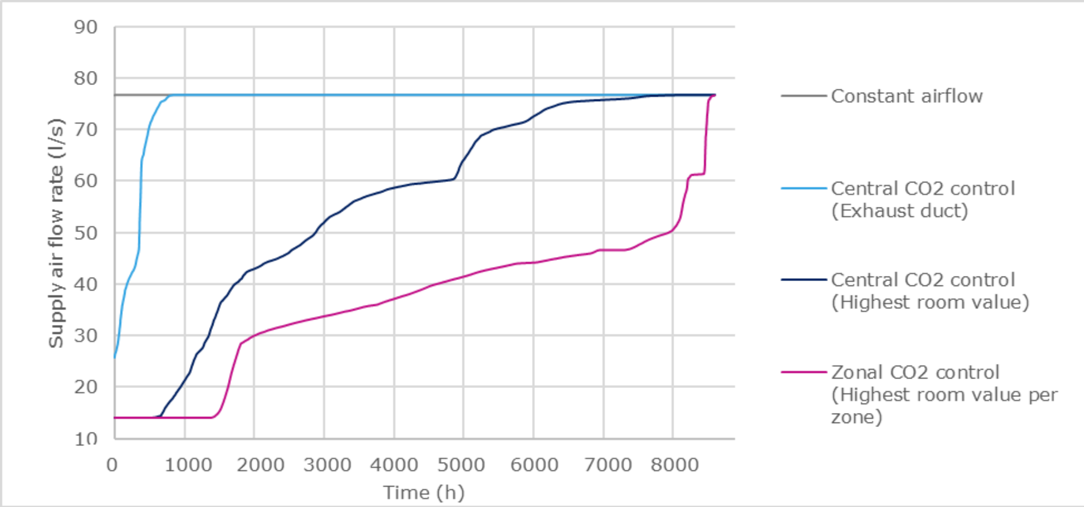


Figure 9. Annual supply airflow rate duration curves for different ventilation control strategies

CONCLUSION

This study benchmarked the implementation of demand-controlled ventilation (DCV) in a single-family house using dynamic simulations that accounted for realistic occupancy profiles, Estonian climate conditions, and regulatory indoor climate standards. Four control strategies—constant airflow, central CO_2 control via exhaust duct, room-based central CO_2 control, and zonal CO_2 control—were compared across two types of heat recovery systems.

The results show that zonal CO_2 control was the most energy-efficient strategy. Compared to constant airflow, zonal control reduced:

- Space heating energy by 17% (from 54.9 to 45.4 kWh/m²·yr)
- Supply air heating energy by 46% (from 6.9 to 3.7 kWh/m²·yr)
- Fan electricity use by 64% (from 9.5 to 3.4 kWh/m²·yr)

In total electricity for space and supply air heating and fans by 35%.

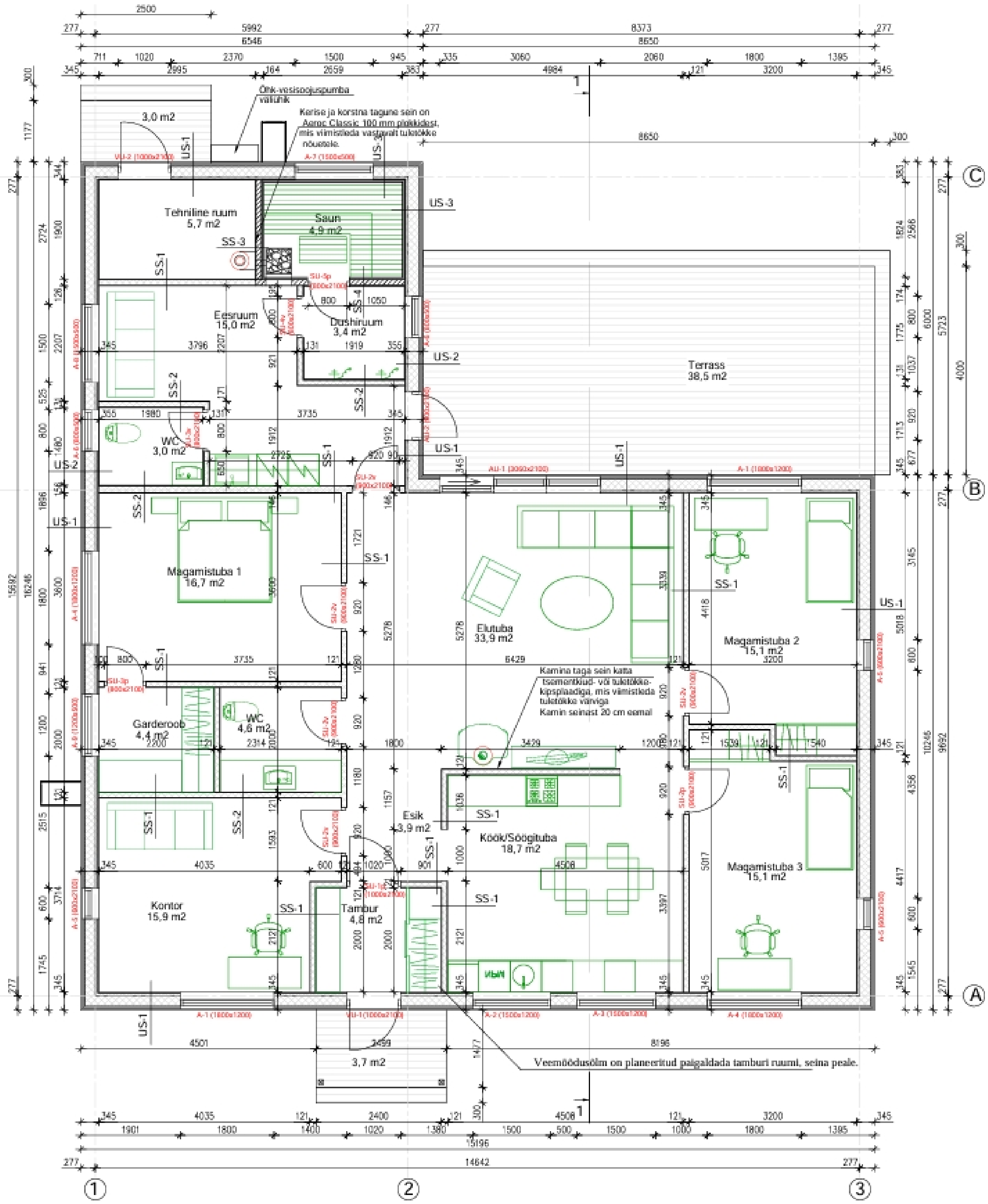
All control strategies maintained indoor CO_2 concentrations within Category II limits. CO_2 duration curves indicated that the exhaust duct CO_2 control strategy performed similarly to CAV due to its reliance on an averaged exhaust signal, which limits responsiveness to elevated CO_2 levels in individual rooms. This resulted in relatively uniform airflow similar to a constant-rate system. Controlling ventilation based on CO_2 measurements in the central exhaust duct is not recommended, as it lacks the spatial resolution to detect elevated concentrations in individual rooms and may fail to respond adequately to localized occupancy. To compensate for this limitation, a considerably lower CO_2 setpoint—such as 600 ppm in this case—may be required to ensure adequate ventilation. However, the appropriate setpoint is not universal and must be individually determined based on the building's layout, occupancy patterns, and ventilation system configuration.

In contrast, room-based and zonal control strategies adjusted ventilation dynamically based on real-time CO_2 levels in specific rooms or zones, enabling more precise airflow delivery aligned with occupancy patterns.

The combination of zonal control and an efficient enthalpy recovery ventilator (ERV) system resulted in a low energy performance indicator (ETA) of 137 kWh/(m²·a), successfully meeting Estonia's nZEB target of 140 kWh/(m²·a). These results demonstrate the potential of smart demand-controlled ventilation with ERV systems as a practical, scalable approach to enhance both energy efficiency and indoor environmental quality in residential buildings.

APPENDICES

APPENDIX A – FLOOR PLAN



APPENDIX B – INPUT DATA REPORT

EQUA SIMULATION TECHNOLOGY GROUP		Input data Report	
Project		**Building**	
Energy performance of buildings, Estonia. -q50 for detached house 4.0 m3/[h m2(envelope)] -Building height app. 6 meters -The EP regulation based part of standard equipment load(which has none heat gain) is modeled in "Extra energy and losses" (for detached house). -Window airing with special control macro can be turned on in this building template(detached house) window (see detailed description for using the macro by opening the control macro "EST WindowOpenCtrlForH21C27"). By default window airing is not used in this building template. -No electric sauna stoves		Model floor area	340.7 m2
Customer		Model volume	642.6 m3
Created by	Karl-Villem Võsa	Model ground area	174.2 m2
Location	Estonia (EST 2025)	Model envelope area	597.1 m2
Climate file	[Default]	Window/Envelope	4.2 %
Case	DCV - Single-family house	Average U-value	1.178 W/(m2 K)
Simulated	28/06/2025 10:30:35	Envelope area per Volume	0.9292 m2/m3

Fixed infiltration airflow rate			**7.108 l/s**	
Building envelope	**Area [m2]**	**U [W/(m2 K)]**	**U*A [W/K]**	**% of total**
Walls above ground	**186.33**	**0.14**	**25.60**	**3.64**
VS1	186.33	0.14	25.60	3.64
Walls below ground	**0.00**	**0.00**	**0.00**	**0.00**
Roof	**205.14**	**2.93**	**600.85**	**85.42**
K1	205.14	2.93	600.90	85.43
Floor towards ground	**174.19**	**0.11**	**18.48**	**2.63**
PP-1	174.19	0.11	18.48	2.63
Floor towards amb. air	**0.00**	**0.00**	**0.00**	**0.00**
Windows	**25.35**	**0.85**	**21.55**	**3.06**
SGG Planitherm One	25.35	0.85	21.55	3.06
Doors	**6.09**	**1.01**	**6.13**	**0.87**
EST External door(2019), heated space	6.09	1.01	6.13	0.87
Thermal bridges			**30.78**	**4.38**
Total	**597.09**	**1.18**	**703.39**	**100.00**

Thermal bridges	**Area or Length**	**Avg. Heat conductivity**	**Total [W/K]**
External wall / internal slab	118.07 m	0.055 W/(m K)	6.494
External wall / internal wall	70.34 m	0.000 W/(m K)	0.000
External wall / external wall	13.12 m	0.050 W/(m K)	0.656
External windows perimeter	77.92 m	0.030 W/(m K)	2.338
External doors perimeter	18.40 m	0.030 W/(m K)	0.552
Roof / external walls	62.97 m	0.110 W/(m K)	6.926
External slab / external walls	58.20 m	0.240 W/(m K)	13.967
Balcony floor / external walls	0.00 m	0.000 W/(K m)	0.000
External floor towards amb. air / internal wall	0.00 m	0.000 W/(K m)	0.000
Roof / Internal walls	22.63 m	0.000 W/(m K)	0.000
External walls, inner corner	2.62 m	-0.060 W/(m K)	-0.157
Roof / external walls, inner corner	3.67 m	0.000 W/(m K)	0.000
External slab / external walls, inner corner	0.00 m	0.000 W/(K m)	0.000
Total envelope (incl. roof and ground)	597.09 m^2	0.000 W/(m^2 K)	0.000
Extra losses	-	-	0.000
Sum	-	-	**30.775**

Windows	Area [m2]	U Glass [W/(m2 K)]	U Frame [W/(m2 K)]	U Total [W/(m2 K)]	U*A [W/K]	Shading factor g
NNE	5.17	0.58	1.92	0.85	4.40	0.43
ESE	9.34	0.58	1.92	0.85	7.94	0.43
SSW	2.92	0.58	1.92	0.85	2.48	0.43
WNW	7.92	0.58	1.92	0.85	6.74	0.43
Total	25.35	0.58	1.92	0.85	21.55	0.43

Air handling unit	Pressure head supply/exhaust [Pa/Pa]	Fan efficiency supply/exhaust [-/-]	System SFP [kW/(m^3/s)]	Heat exchanger temp. ratio/min exhaust temp. [-/C]
airobot - ERV	720.00/720.00	0.60/0.60	1.20/1.20	0.80/-10.00
airobot - HRV	720.00/720.00	0.60/0.60	1.20/1.20	0.90/-10.00

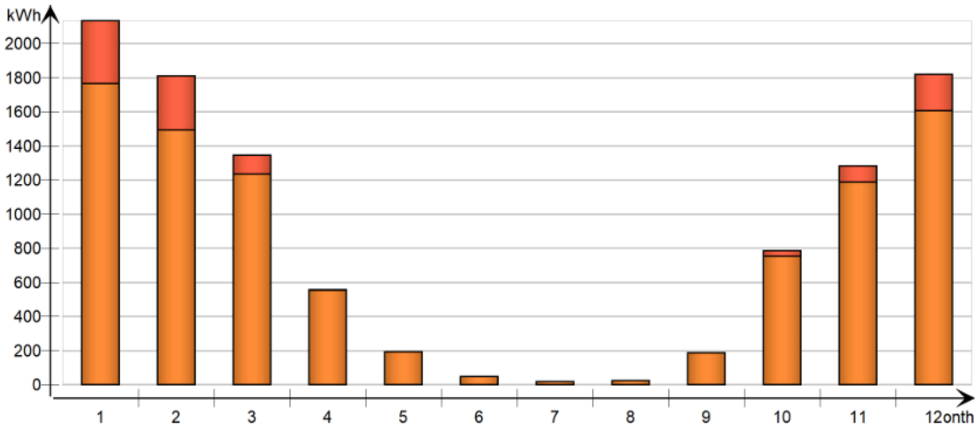
DHW use	L/m² floor area and year	Total, [l/s]
	0.000	0.000

APPENDIX C – SYSTEM ENERGY – CONSTANT AIRFLOW

Used energy

kWh (sensible and latent)

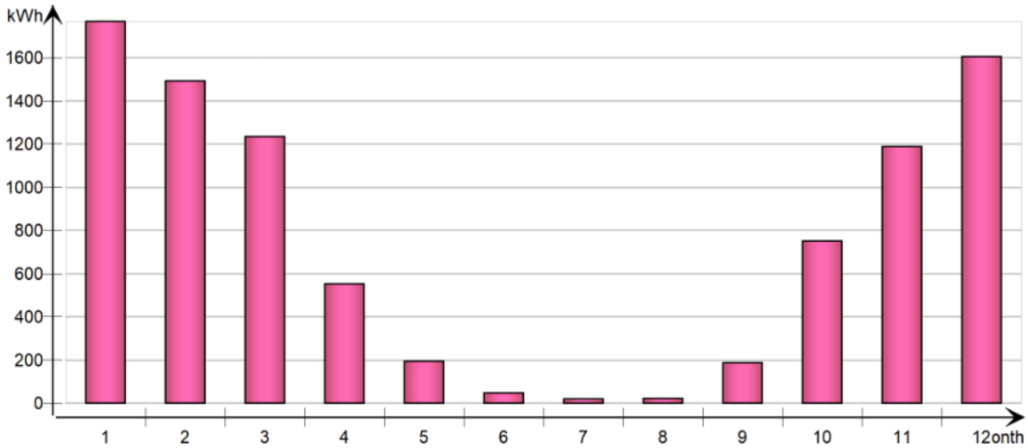
Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	1767.0	0.0	366.8	0.0	0.0
2	1493.0	0.0	316.8	0.0	0.0
3	1235.0	0.0	110.6	0.0	0.0
4	553.3	0.0	4.2	0.0	0.0
5	193.7	0.0	0.2	0.0	0.0
6	47.1	0.0	0.0	0.0	0.0
7	19.1	0.0	0.0	0.0	0.0
8	22.5	0.0	0.0	0.0	0.0
9	185.4	0.0	0.7	0.0	0.0
10	751.3	0.0	32.5	0.0	0.0
11	1189.0	0.0	94.0	0.0	0.0
12	1606.0	0.0	212.3	0.0	0.0
Total	9062.4	0.0	1138.1	0.0	0.0



Zone heating by source

kWh (sensible and latent)

Month	From central plant	From other devices
1	0.0	1767.0
2	0.0	1493.0
3	0.0	1235.0
4	0.0	553.3
5	0.0	193.7
6	0.0	47.1
7	0.0	19.1
8	0.0	22.5
9	0.0	185.4
10	0.0	751.3
11	0.0	1189.0
12	0.0	1606.0
Total	0.0	9062.4

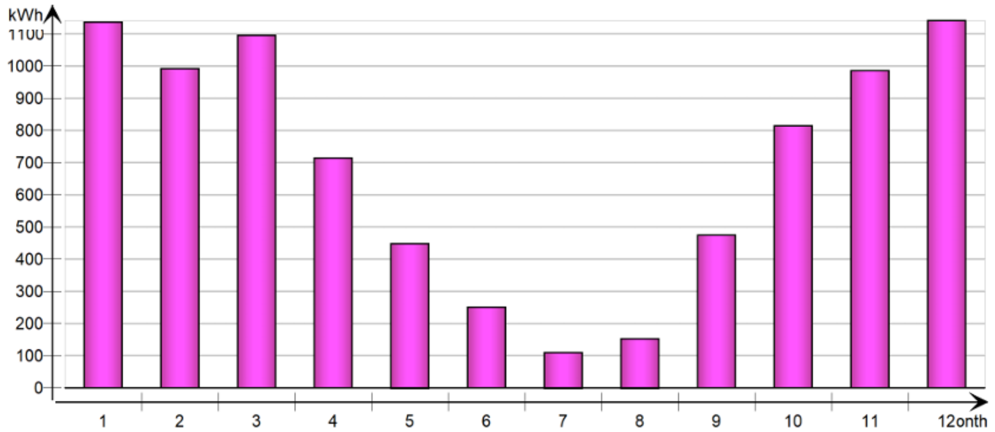


Utilized free energy

kWh (sensible and latent)

Month	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat*	Ambient cold*
1	1137.0	0.0	0.0	0.0					
2	991.8	0.0	0.0	0.0					
3	1095.0	0.0	0.0	0.0					
4	713.6	-0.0	0.0	0.0					
5	448.3	-0.3	0.0	0.0					
6	250.6	-0.1	0.0	0.0					
7	109.6	-0.7	0.0	0.0					
8	152.1	-0.9	0.0	0.0					
9	474.9	-0.0	0.0	0.0					
10	813.6	0.0	0.0	0.0					
11	985.6	0.0	0.0	0.0					
12	1141.0	0.0	0.0	0.0					
Total	8313.1	-2.0	0.0	0.0					

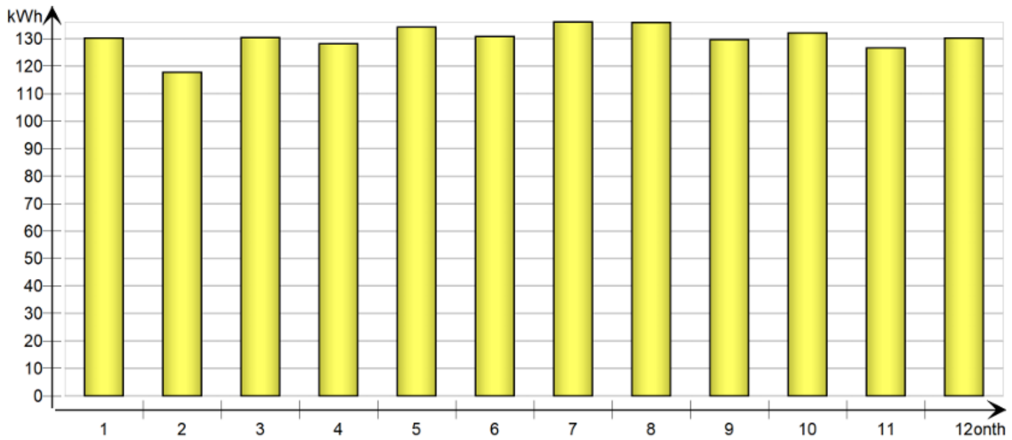
*ambient air may contain a small portion of waste heat from the fan



Auxiliary energy

kWh (sensible and latent)

Month	Humidification	Fans	Pumps
1		130.2	0.0
2		117.8	0.0
3		130.5	0.0
4		128.2	0.0
5		134.2	0.0
6		130.9	0.0
7		136.1	0.0
8		135.9	0.0
9		129.6	0.0
10		132.1	0.0
11		126.7	0.0
12		130.2	0.0
Total		1562.4	0.0



Distribution Losses

kWh

Month	Domestic hot water circuit	Heating	Cooling*	Air ducts*
1	42.1			0.0
2	38.0			0.0
3	42.1			0.0
4	40.7			0.0
5	42.1			0.0
6	40.7			0.0
7	42.1			0.0
8	42.1			0.0
9	40.7			0.0
10	42.1			0.0
11	40.7			0.0
12	42.1			0.0
Total	**495.3**	**0.0**	**0.0**	**0.0**

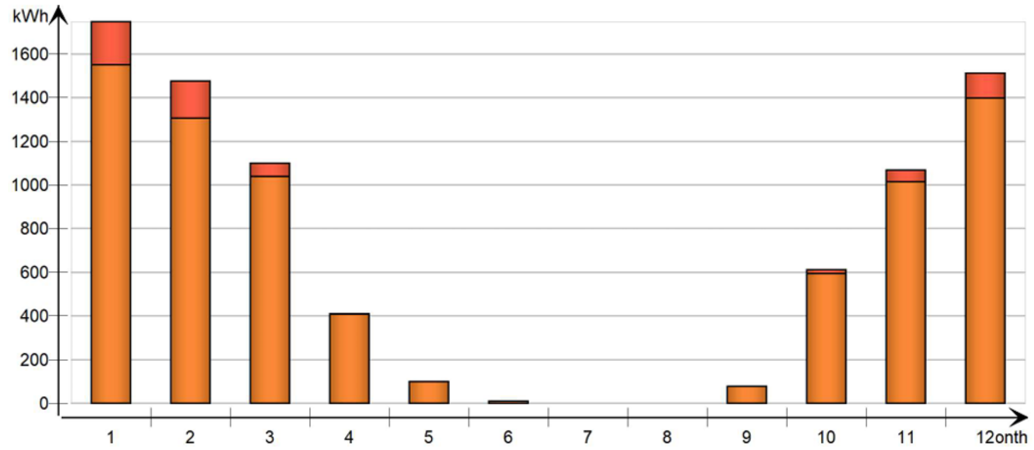
*positive loss when conduit is cooler than building

APPENDIX D – SYSTEM ENERGY – ZONAL CO_2 CONTROL

Used energy

kWh (sensible and latent)

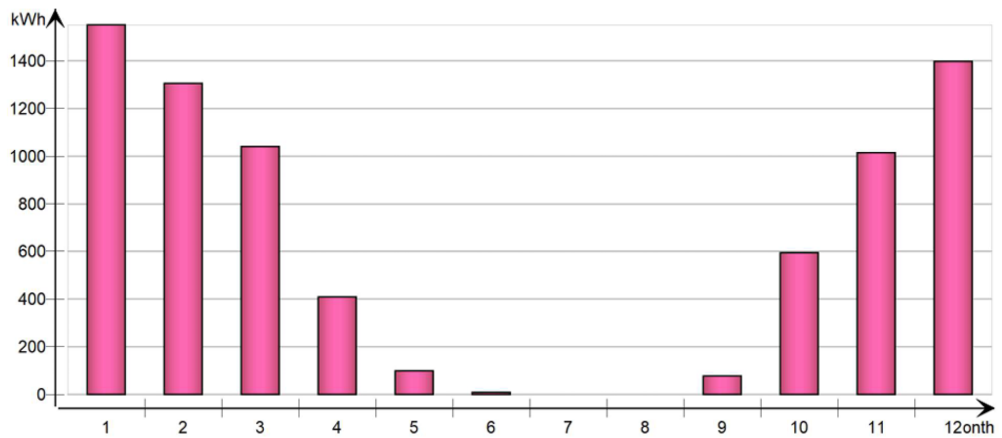
Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	1551.0	0.0	197.0	0.0	0.0
2	1305.0	0.0	168.8	0.0	0.0
3	1040.0	0.0	61.8	0.0	0.0
4	408.3	0.0	2.4	0.0	0.0
5	99.6	0.0	0.1	0.0	0.0
6	9.2	0.0	0.0	0.0	0.0
7	0.3	0.0	0.0	0.0	0.0
8	0.5	0.0	0.0	0.0	0.0
9	77.5	0.0	0.3	0.0	0.0
10	593.9	0.0	17.8	0.0	0.0
11	1014.0	0.0	53.1	0.0	0.0
12	1399.0	0.0	114.8	0.0	0.0
Total	7498.4	0.0	616.1	0.0	0.0



Zone heating by source

kWh (sensible and latent)

Month	From central plant	From other devices
1	0.0	1551.0
2	0.0	1305.0
3	0.0	1040.0
4	0.0	408.3
5	0.0	99.6
6	0.0	9.2
7	0.0	0.3
8	0.0	0.5
9	0.0	77.5
10	0.0	593.9
11	0.0	1014.0
12	0.0	1399.0
Total	0.0	7498.4

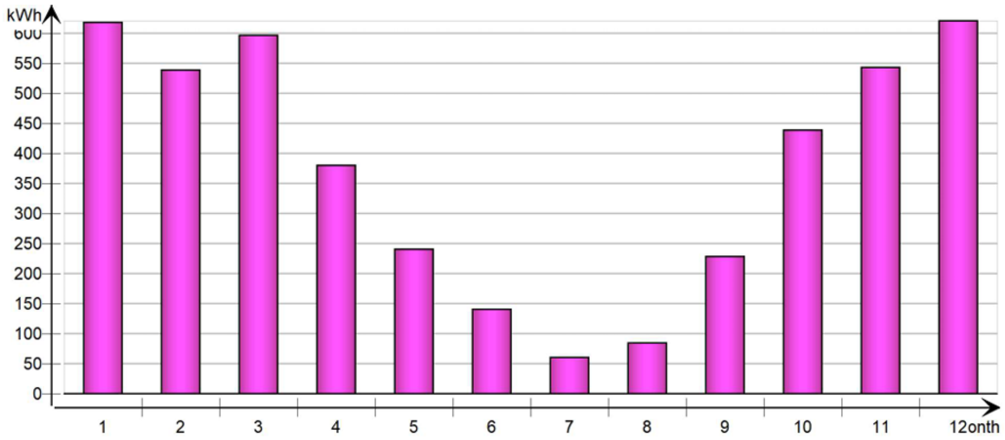


Utilized free energy

kWh (sensible and latent)

Month	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat*	Ambient cold*
1	618.0	0.0	0.0	0.0					
2	538.2	0.0	0.0	0.0					
3	596.5	0.0	0.0	0.0					
4	379.9	-0.0	0.0	0.0					
5	240.7	-0.0	0.0	0.0					
6	140.3	-0.0	0.0	0.0					
7	60.3	-0.0	0.0	0.0					
8	84.2	-0.0	0.0	0.0					
9	227.9	-0.0	0.0	0.0					
10	438.6	0.0	0.0	0.0					
11	542.9	0.0	0.0	0.0					
12	620.4	0.0	0.0	0.0					
Total	4487.9	-0.1	0.0	0.0					

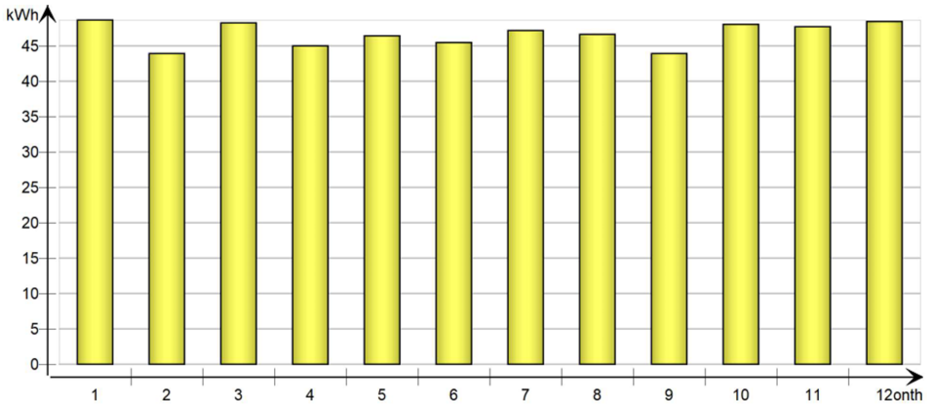
*ambient air may contain a small portion of waste heat from the fan



Auxiliary energy

kWh (sensible and latent)

Month	Humidification	Fans	Pumps
1		48.7	0.0
2		43.9	0.0
3		48.3	0.0
4		45.0	0.0
5		46.4	0.0
6		45.5	0.0
7		47.2	0.0
8		46.7	0.0
9		43.9	0.0
10		48.0	0.0
11		47.7	0.0
12		48.5	0.0
Total		559.8	0.0



Distribution Losses

kWh

Month	Domestic hot water circuit	Heating	Cooling*	Air ducts*
1	42.1			0.0
2	38.0			0.0
3	42.1			0.0
4	40.7			0.0
5	42.1			0.0
6	40.7			0.0
7	42.1			0.0
8	42.1			0.0
9	40.7			0.0
10	42.1			0.0
11	40.7			0.0
12	42.1			0.0
Total	**495.3**	**0.0**	**0.0**	**0.0**

*positive loss when conduit is cooler than building