An Approach towards Developing Methods to Analyze and Visualize Energy Flow of HVAC System

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ABSTRACT

In the field of building operations, it is essential that building operators understand the dynamics of energy use, control strategies, and occupant comfort in buildings. Nowadays, modern commercial buildings' resource consumption is metered at various levels of spatial and temporal resolution to track and reduce energy use and the associated cost and greenhouse gas emissions. This leads to many data sources at the building level. As a result, lots of data are available but not necessarily in a readily comprehensible form. Furthermore, the current data availability and visualization tools have some limitations in identifying system inefficiencies and possible solutions. This paper proposes a method to estimate and visualize energy flows through different components of heating, ventilation, and air-conditioning (HVAC) system using Sankey diagrams to make data more accessible and to identify inefficiencies. The proposed method is then applied to an 8,000 m^2 multi-zone Canadian university building.

Author Keywords

Energy flows in HVAC; HVAC loads; Sankey diagrams.

1. INTRODUCTION

Energy demand in commercial and institutional facilities across Canada grew by over 35 percent between 1990 and 2004 [1]. In Canada, approximately 56 and five percent of the total energy allocated for residential and commercial energy-use are used for space heating and cooling, respectively [1]. Nowadays, modern commercial buildings utilize energy management and control systems (EMCS) for monitoring and optimizing building systems during operation. Frequently, buildings' resource consumption is metered at various levels of spatial and temporal resolution to track and reduce energy use and the corresponding cost and greenhouse gas (GHG) emissions. This leads to many data sources at the building level. An example of energy dashboard implemented at Carleton University is shown in Figure 1. As stated by [2] and [3], the identification of system inefficiencies through monitoring could lead to an energy savings of between 15 and 40 percent. The improvements in the monitoring and supervision capabilities of EMCS have served to make operational problems more visible and quantifiable to the industry [4].

As indicated by building energy regulations [5], building energy rating systems and certification schemes [6] and [7], and the standardization of inspection, operation and maintenance (O&M) plans of HVAC systems, energy efficiency of heating, ventilation and air conditioning (HVAC) systems has become a priority objective for energy policies [8,9,10].

Figure 1. The existing building dashboard interface implemented at Carleton University

Nowadays, many researchers have been focusing on analyzing and evaluating HVAC systems energy-use. Perez-Lombard et al. [11] proposed a wide-scope analysis of HVAC systems by tracing the energy flow from energy sources to final services and by the examination of the intermediate devices. The aim of the study was to provide guidelines for easier energy analysis in the HVAC field. Another study by Sakulpipatsin et al. [12] presented a method for exergy analysis of buildings and HVAC systems, according to an energy demand from the building side to the energy supply side. Fan et al. [13] evaluated the operation performance of HVAC system based on exergy analysis using simulation model. Another study by Salsbury et al. [4] used simulation predictions as performance targets with which to compare monitored system outputs for performance validation and energy analysis. Mendes et al. [14] presented a generic educational user-friendly environment using mathematical models for simulating HVAC systems and integrating it to a whole building hygro-thermal model.

On the other hand, new diagnostic software tools are becoming available to facilitate the detection and diagnosis of energy and other performance problems for HVAC

systems in commercial buildings [15]. Gayeski et al. [16] described the current metrics and visualization techniques available at different scales ranging from enterprise to project scale. Austin [17] claimed that Trend Analysis is a powerful tool for HVAC troubleshooting. Moreover, Meyers et al. [18] presented data visualization techniques of HVAC and lighting systems, which can help building operators to achieve substantial improvements in energy management.

On the visualization side, the current data availability and visualization tools have some limitations in identifying system inefficiencies and possible solutions. One of the visualization tools that is useful in energy management and performance improvement is Sankey diagrams. A study by [19] proposed several methods to analyze and visualize building-level water, natural gas, and electricity consumption and the upstream environmental impacts using Sankey diagrams and other graphical techniques. Perez-Lombard et al. [11] graphically represented the energy flows in a typical constant air volume systems installed in office buildings in Spain using Sankey diagrams. Another study by [20] used Sankey diagrams to compare and contrast the performance of a domestic legacy gas ducted heating system with a contemporary, well-installed split-system heat pump heating system.

This paper proposes a method to analyze and visualize energy flow through different components of a typical air handling unit (AHU) and HVAC loops of commercial buildings using Sankey diagrams. A major contribution of the paper is to convert sparse sensor data into estimated energy flows for each major AHU and HVAC plant component. The objective of this paper is to make operational problems more visible and quantifiable in order to identify opportunities for energy savings and to facilitate the decision-making by building operators, campus planners, and other stakeholders. The proposed method is then applied to a case study: Canal Building at Carleton University campus in Ottawa, Canada using historical data obtained from EMCS.

2. METHODOLOGY
The main objective of this study is to develop a method to obtain, process, analyze, and visualize energy flow of a typical AHU and HVAC loops configurations of a commercial building as shown in Figure 2. The methodology focuses on developing energy balances for AHU components (i.e. heat recovery wheels (HRW), fans, economizers, air filters, and cooling and heating coils) and HVAC loops (i.e. air loop, chilled water loop, refrigerant loop, condensing water loop, and heat rejection loop). Moreover, the study analyzes the feedback loops utilizing spatial and temporal analysis.

The following sections aim to illustrate energy balances for typical HVAC equipment (i.e. boilers, cooling towers, chillers, pumps, and air handling unit (AHU) sub-systems).

The following energy balance equations of each component are written in terms of final energy, making use of the following symbols: thermal load Q, positive for heating and negative for cooling, $\dot{m}$ is the mass flow rate of fluids, C_p is the specific heat capacity, and T and h are the temperature and enthalpy of fluid in and out of the system, respectively. All units are in SI. The equations rely on a set of assumptions. For instance, no internal energy change (i.e. steady-state). Moreover, heat lost from air handling unit (AHU) to the surrounding and frictional losses through the AHU is ignored in the current study.

Contrary to simulation-based studies, energy flows are often not readily available as readings from EMCS. Instead, modern buildings sense fluid flow rates, temperature, humidity, and electrical power. Thus, a contribution of this paper is to convert sparse measurements into a comprehensive set of energy flows.

2.1 Central Heating Plant (CHP)
As many communities and campuses have centralized heating plants in order to reduce equipment size and cost, improve efficiency, and centralize operations. The steam delivered from the central heating plant (CHP) passes through a heat exchanger that uses the thermal energy to provide heat to the hot water-glycol loop as shown in Figure 2. The energy balance across the heat exchanger yields as shown in Equation (1).

$$Q= \dot{m}_{steam} \times (h_{Steam,return}-h_{steam,supply}) =$$
$$m_{HW} \times C_P(T_{HW, avg}) \times (T_{HW,return}-T_{HW,supply}) \qquad (1)$$

2.2 Cooling Towers
Heat from the condenser is carried by condensing water (CDW) to the cooling tower to be cooled and returned to the condenser. This loop is called condensing water loop. Equation (2) shows calculation for the amount of heat extracted from the refrigerant.

$$Q_{CDW} = \dot{m}_{CDW} \times [T_{in} \times C_{p,in}(T_{in}) - T_{out} \times C_{p,out}(T_{out})] \qquad (2)$$

2.3 Chillers
The refrigerant (water-propylene glycol) for the case study building) extracts heat from the water in the evaporator and transfers it to the condensing water by means of a vapour compression cycle. The energy balance across the chiller is shown in Equation (3) [21].

$$Q_H + Q_L + W=0 \qquad (3)$$

Where, Q_H is the amount of energy transferred from the condenser to the condensed water loop. Q_L is the amount of energy gained from the evaporator and calculated as shown in Equation (4). W is the amount of power consumption by chiller, this value can be obtained from EMCS.
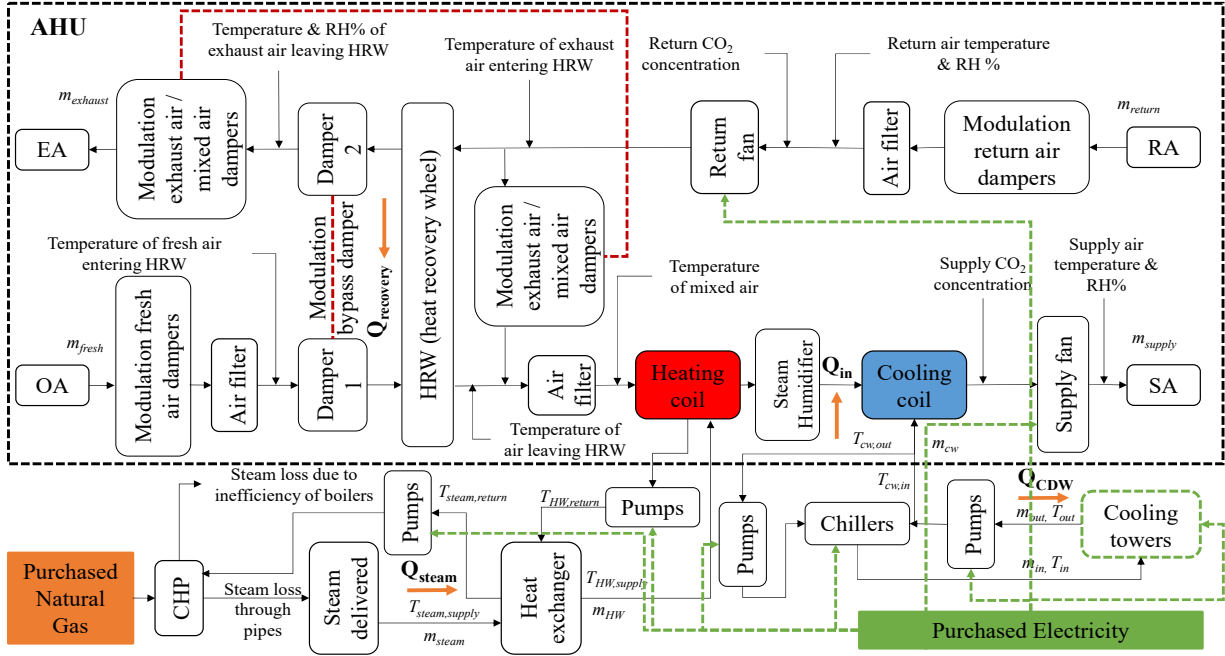
Figure 2. Flowchart showing the main scope of the study on the HVAC system

$$Q_L = \dot{m}_{CHW} \times \left(h_{in} - h_{out}\right) = \dot{m}_{CHW} \times C_p \times \left(T_{in} - T_{out}\right) \quad (4)$$

where, the subscript *CHW* refers to the chilled water.

2.4 Pumps

The pumps are used to increase the pressure and temperature of the return fluids in the chilled water, refrigerant, condensing water, and steam loops. The energy balance through the pump is expressed in Equation (5).

$$P_{el} = \dot{m}_{reference} \times \left(\frac{\Delta P}{\rho_{reference}}\right) + \sum F \quad (5)$$

P_{el} is the electric energy consumption, ΔP is the differential pressure, ρ is the density of fluid, and $\sum F$ is the friction losses through the pump. The subscript *reference* refers to the type of fluid passing through the pumps (i.e. steam, chilled water, condensate water, or refrigerant). Furthermore, by considering the whole piping/pump system as a single pump, and their total mechanical loss as head loss. Then, the high difference between the lowest point and highest point of the fluid loop can be used to calculate the efficiency of the pump as shown in Equation (6).

$$\eta = \frac{\dot{m}_{reference} \times g \times head}{P_{el}} \quad (6)$$

Where, g is the gravity constant (9.81 m/s^2).

2.5 Air Handling Unit (AHU)

The air handling unit is used to condition and distribute air to building zones as part of an HVAC system. In the context of Canal Building, the air handler contains fans, heating and cooling coils, filters, humidifier, economiser,

heat recovery wheel (HRW), and dampers [22]. The energy balance for the AHU is expressed in Equation (7) [23].

$$m_{return} \times h_{return} + m_{fresh} \times h_{fresh} + Q_{recovery} + Q_{in} = \\ m_{supply} \times h_{supply} + m_{exhaust} \times h_{exhaust} + L \quad (7)$$

The term Q_{in} refers to heat added or extracted from the system, thus it can be positive for heating and negative for cooling. On the other hand, $Q_{recovery}$ refers to the recovered heat by the heat recovery wheel and L is the losses in the system (e.g. frictional losses through AHU ducts). Moreover, the recirculated air is controlled by a modulation damper. The following discussion focuses on the amount of heat added or extracted and recovered in the AHU.

Heat Exchangers
Heat exchanging devices (such as heating and cooling coils) linking thermal loops (water coils, evaporators and condensers) do not use energy but destroy exergy (second-law of thermodynamics) [11].

For the cooling coils, the water-propylene glycol absorbs heat from the air stream passing through the cooling coils and returns to the chiller evaporator to be cooled. This loop is called chilled water loop which is driven by pumps. The energy balance through the cooling coil is shown in Equation (8). The enthalpy is used in this equation to account for sensible and latent heat.

$$Q = \dot{m}_{CHW} \times \left(h_{in} - h_{out}\right) = \dot{m}_{air} \times \left(h_{in} - h_{out}\right) \quad (8)$$

The energy balance across the heating coil can be expressed as shown in Equation (9). Heat is transferred from the hot

glycol water to the air stream running through the exchanger.

$$\dot{m}_{HW} \times C_P(T_{HW,\ avg}) \times (T_{HW,return} - T_{HW,supply}) = \dot{m}_{air} \times$$
$$C_P(T_{air,\ avg}) \times (T_{air,leaving\ heating\ coil} - T_{air,entering\ heating\ coil}) \quad (9)$$

The hot water return from the heating coil runs through another heat exchanger by means of water pumps. Furthermore, the performance of the heat exchanger should be considered in the analysis. Increasing transfer area of exchanging devices reduces temperature differences, and thus increases exchanging effectiveness [11]. The effectiveness of heat exchanger is calculated as shown in Equation (10).

$$Effectiveness = \frac{Actual\ heat\ transfer}{Maximum\ possible\ heat\ transfer} \quad (10)$$

Actual and maximum possible heat transfer for a heat exchanger are shown in Equations (11) and (12), respectively. Cold and hot fluids refers to the colder and hotter fluids entering and leaving the heat exchanger, respectively. For instance, the steam entering the heat exchanger is the hot fluid as it losses heat to other fluid (in this case the hot glycol water).

Actual heat transfer =
$$\dot{m}_{cold\ fluid} \times C_P(T_{cold\ fluid,\ avg}) \times (T_{cold\ fluid,out} - T_{cold\ fluid,in}) \quad (11)$$

Maximum possible heat transfer =
$$[m \times C_P(T)]_{minimum} \times (T_{hot\ fluid,in} - T_{cold\ fluid,in}) \quad (12)$$

Heat Recovery Wheel (HRW)
An enthalpy wheel allows both sensible and latent energy to be recovered from the exhaust air stream. Equations (13)(13) and (14) show sensible heat recovery and latent heat energy recovery by energy wheel, respectively.

$$Q_{recovery} = \dot{m}_{return} \times (1 - \%OA) \times C_P(T_{air,\ avg}) \times (T_{air,exhaust} - T_{air,return}) \quad (13)$$

$$Q_{recovery} = \dot{m}_{return} \times (1 - \%OA) \times (h_{air,exhaust} - h_{air,return}) \quad (14)$$

Where, h_{da} and h_g are the specific enthalpy for dry air and specific enthalpy for saturated water vapor, respectively. W is the humidity ratio and T is the temperature in Celsius. The enthalpy (h) including moisture is shown in Equation (15) [21].

$$h_{moist} = h_{da} + W \times h_g \approx T + W(2501 + 1.805T) \quad (15)$$

Fans
In this study, a variable volume fan is discussed. The aim is to calculate the efficiency of the fan and to determine the

state of air exiting the fan. The rate of electrical energy consumption by fan's motor is shown in Equation (16).

$$P_{el} = \frac{W_{fan}}{\eta_{fan}} \quad (16)$$

W_{fan} is the rate of energy transfer by work from fan to air as shown in Equation (17). The electrical energy consumption can be obtained from EMCS. While, η_{fan} is the efficiency of fan's motor.

$$W_{fan} = \dot{m} \times \frac{\Delta P}{\rho} \quad (17)$$

On the other hand, the frictional losses can be determined as shown in Equation (18).

$$P_{el} = \dot{m} \times \left(\frac{\Delta P}{\rho_{air}}\right) + \sum F \quad (18)$$

Where, P_{el} is the electric energy consumption, ΔP is the differential pressure, ρ is the density of air, and $\sum F$ is the friction losses. Moreover, the state of air leaving the fan is expressed in Equation (19).

$$h_{out} - h_{in} = \frac{P_{el} \times \left[\eta_{fan} + \beta_{motor} \times (1 - \eta_{fan})\right]}{\dot{m}} \quad (19)$$

Where, β_{motor} is the fraction of heat loss from motor that is transferred to the air stream in the AHU as shown in Equations (20) and (21).

$$\beta_{motor} = \frac{\dot{Q}_{motor-to-air}}{\dot{Q}_{motor}} \quad (20)$$

$$\dot{Q}_{motor} = P_{el} - W_{fan} \quad (21)$$

$\dot{Q}_{motor}$ is the rate of heat addition from fan to air due to friction. On the other hand, $Q_{motor-to-air}$ depends on the fan location in the air stream. Thus, the amount of heat gain can be obtained by Equation (22).

$$\dot{Q}_{motor-to-air} = \frac{f \times power\ rated}{\eta_{fan}} \quad (22)$$

The factor f can be determined based on the location of fan in the air stream [24].

Filters
Air filters are used in air handlers to remove the dust from both the ventilation air and the recirculated air. The energy consumption of the air filters typically accounts for approximately 10 to 70 percent, of the total fan energy consumption for typical air handling units [25]. This study focuses on evaluating air filter based on their resistance to air flow. The differential pressure can be obtained from EMCS. Thus, the frictional losses can be calculated as shown in Equation (23).

$$\sum F = \dot{m} \times \left(\frac{\Delta P}{\rho_{air}}\right) \qquad (23)$$

Outdoor Air Fraction

The percentage or fraction of outside air can be estimated by using carbon dioxide (CO_2) concentration of supply, return, and outdoor as shown in Equation (24) [26].

$$OA\% = \frac{CO_{2, supply,air} - CO_{2, return,air}}{CO_{2, outdoor,air} - CO_{2, return,air}} \qquad (24)$$

Due to errors that could be encountered in CO_2 measurement, as in the case of Canal Building, an alternate approach is to estimate outdoor air fraction using temperatures, as in Equation (25).

$$OA\% = \frac{m_{RA} \times \eta \times (h_{RA} - h_{EA}) + m_{MA} \times [h_{RA} \times (1-\eta) + (h_{EA} \times \eta) - h_{MA})]}{m_{MA} \times [h_{RA} \times (1-\eta) + (h_{EA} \times \eta) - h_{OA}]} \qquad (25)$$

where, m_{RA} and m_{MA} are mass flow rates of return air and mixed air, respectively. η is the efficiency of the HRW. While, h_{RA}, h_{EA}, and h_{MA} are the enthalpy of return air, exhaust air and mixed air, respectively.

Humidifiers

The humidification processes is the transfer (addition) of water vapor to air. This process is usually accomplished by introducing water vapor or by spraying fine droplets of water that evaporate into the circulating air stream [27]. The humidification load is computed by Equation (26).

$$\frac{Humidification}{load} = \dot{m}_{air} \times (h_{out} - h_{in}) = \dot{m}_{steam} \times (h_{out} - h_{in}) \qquad (26)$$

Moreover, the mass flow rate of steam $\dot{m}_{steam}$ is obtained from the amount of moisture (W) added to the air stream as shown in Equation (27).

$$\dot{m}_{steam} = \dot{m}_{air} \times (W_{out} - W_{in}) \qquad (27)$$

3. CASE STUDY

The Canal Building (CB) is a seven-story mixed-use academic building with total floor area about 8,000 m^2 as shown in Figure 3.

Figure 3. Canal Building

The building began its operation in 2011, including a large variety of functional space such as private offices, open-plan offices, lecture rooms, computer labs, design labs, research labs, conference rooms and other facility rooms. There are four air-handling units (AHU). Two small AHU are designated for the mechanical rooms, while the rest of the building is conditioned by two separate air-handling units. This paper will be focusing on one of the AHUs installed. The heating system uses campus steam generated at a central plant. The cooling system uses a 60% water-40% propylene glycol loop. This building is equipped with two chillers (ElectricEIRChiller Centrifugal Carrier 19XR 1407kW/ 6.04COP/ VSD), which supply cooling to CB and one of the adjacent buildings. Both chillers operate in parallel. Thus, the first step is to identify the chiller consumption assigned to the building.

This was done by obtaining data for water-propylene glycol flow rate for Canal building as shown in Equation (28). The air distribution system is single-duct variable air volume (VAV) with reheat and radiant panels to reduce cold surfaces.

$$\begin{matrix} Chiller\ consumption \\ for\ a\ specific\ building \end{matrix} = \begin{matrix} Chillers\ total \\ consumption \end{matrix} \times$$
$$\left(\frac{Flow\ rate\ for\ a\ specific\ building}{\begin{matrix}Total\ flow\ rate\ for\ all\ buildings \\ sharing\ the\ same\ chillers\end{matrix}}\right) \qquad (28)$$

4. SANKEY DIAGRAMS

Sankey diagrams are a useful graphical tool for mapping energy and mass flows including losses for a system. Sankey diagrams are comprised of arrows of varying widths, where the width indicates relative magnitude of flow and the direction indicates the connection between sources and sinks for each flow. Sankey diagrams allow resource flows to be visualized within complex systems with interacting subsystems. This study applies Sankey diagrams on HVAC sub-systems to visualize energy flows through each component and stage in the system.

Sankey diagrams were rendered in a browser using Scalable Vector Graphics (SVG). The layout was derived from D3's Sankey layout code developed by Google Developers that provided more flexibility in organizing nodes, colors, and font sizes [28]. In order to create nodes with the connection links, a set of rows containing data for source, target, and magnitude for each flow was created using comma-separated values (CSV) format.

Sankey diagrams should be read based on the direction of the flow (i.e. from left to right). All energy inputs come from the left side, while energy outputs leave rightward. For instance, during winter, heat is added to the building. While during summer, heat is extracted from the building.
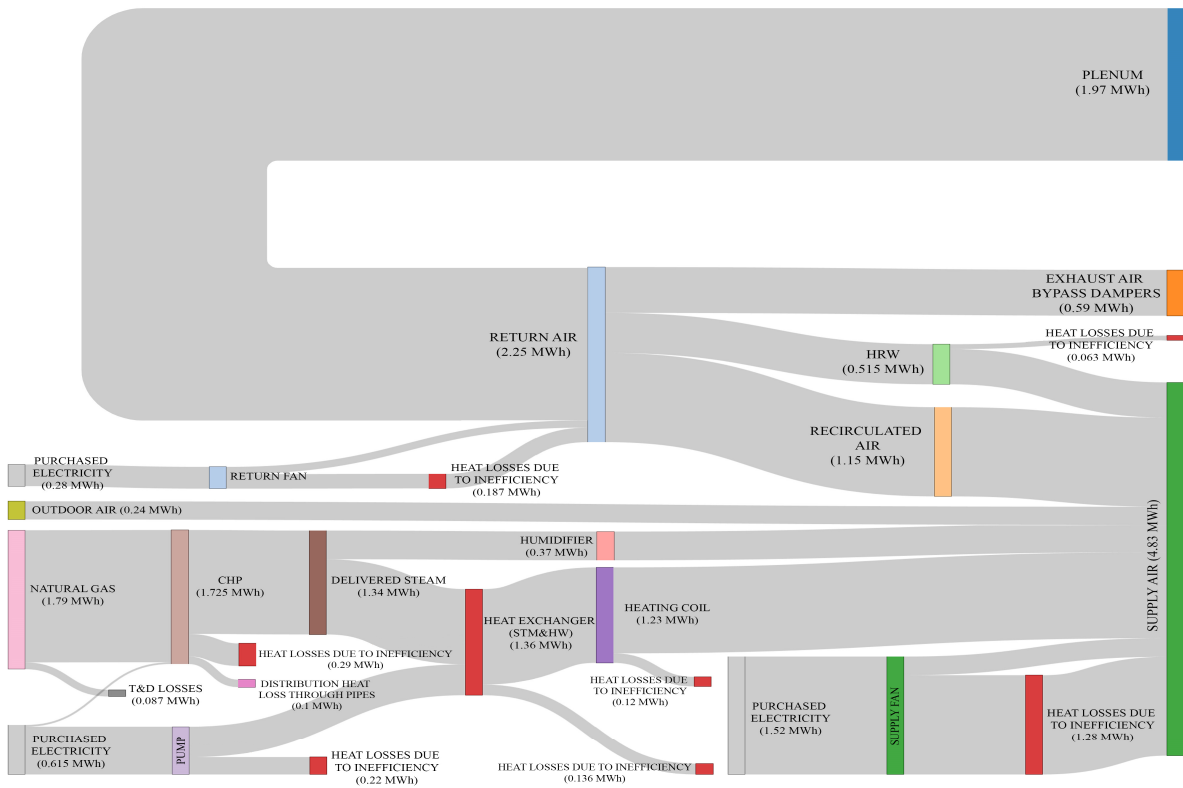
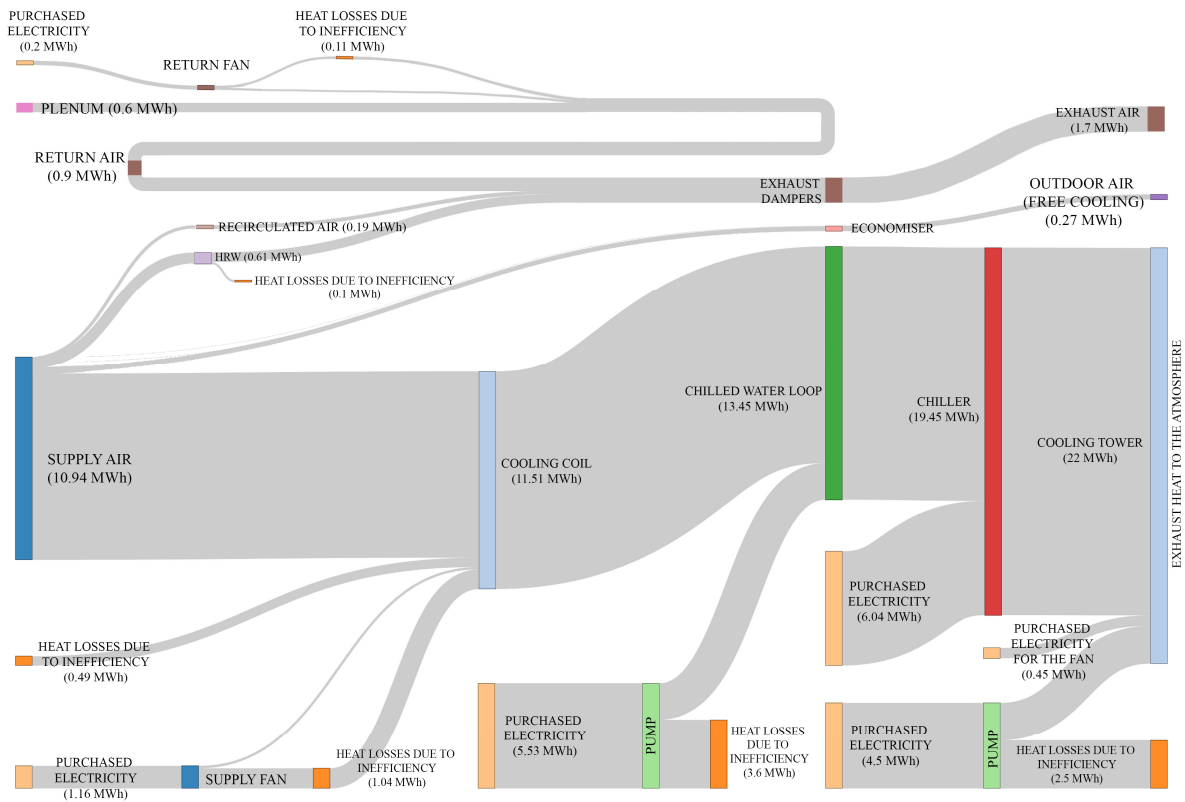**Figure 4.** Sankey diagram showing AHU energy flow during two winter weeks

Figure 5. Sankey diagram showing AHU energy flow during two summer weeks

Hourly system operation and energy data for HVAC sub-systems have been collected from EMCS. On the other side, the steam consumption was recorded from meters installed in the building. Raw data were reported on a server operated by the Facilities Management and Planning (FMP).

The obtained data were used in the equations mentioned in the methodology section in order to create Sankey diagrams. Some modest errors were associated with some of the sensors such as missing or incorrect data points. Thus, for short time-periods (<6 hours), it is recommended to use simple interpolation to generate missing values. While for long time-periods, the data was excluded from the analysis.

5. RESULTS AND DISCUSSION

The aim of this study is to analyze and visualize energy flow through different components in the air handling unit and their impact on primary energy use. The study focused on hourly data for two weeks in winter (1st to 15th of February, 2015) and summer (1st to 15th of July, 2015). Figure 4 and Figure 5 show the energy flow and feedback loops for the AHU in the winter and summer periods, respectively. Due to limited data for relative humidity for the state of air entering and leaving the HRW, the latent energy term is excluded from the study.

During winter, it was noticed that the supply fan energy is unexpectedly high and the heat introduced from the motor is similar in magnitude to the heating of the airstream from the heating coil and humidifier. Approximately 28 percent and eight percent of the heat is added by the heating coil and steam humidifier, respectively. While, heat added from the recirculated air and the HRW are 24 percent and nine percent, respectively. This is due to the high internal gains from equipment, lighting, occupants, and heat added by VAV-reheat coils and radiant panels installed in some of the perimeter zones. However, it was observed that the HRW is infrequently used.

During summer period, the latent energy was neglected. It was observed that the HRW did not contribute significantly to recovering energy as it was rarely turned on. As mentioned above, due to the high internal gains and heat gains from building envelope, only a small amount of the recovered energy was recorded from the recirculated air. Furthermore, while the coefficient of performance (COP) of the chiller is approximately three, the 1.65 units of electricity were required for every unit of heat removal from the building. The building also relies on free cooling (i.e., cooler outdoor air instead of mechanical cooling) when the outdoor temperature is below 22°C.

Moreover, the supply fan consumes a large amount of energy, this appears to be due to high frictional losses recorded through the air filter installed before the heating and cooling coils and also the pressure losses through the ducts.

6. CONCLUSION

The aim of the proposed method was to analyze and visualize energy flow by different components of an air handling unit in multi-zone Canadian university building. The aim of this proposed method was to make use of real-time and historical data obtained from EMCS to facilitate the decision making by building operators to manage the operation of building system level. This was achieved by converting sparse sensor data into estimated energy flows for major components of AHU and HVAC plant.

The implication of this work is that it would help in making operational problems more visible and quantifiable in order to identify opportunities for energy savings.

More sensors will be installed in the near future to obtain more information regarding the state of air at different locations in the AHU.

Future planned work includes a survey that will be applied to building operators to test the proposed visualization effectiveness. More analysis on the secondary air handling unit (i.e. VAV-box in this case) will be involved in the future.

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