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Visualizing the exergy destructed in exergy delivery chain in relation to human thermal comfort with ExFlow

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ABSTRACT
Exergy analysis is an important tool to fully appreciate the usability of energy at different levels and has been widely applied in the building system analysis domain. It has became more useful as low temperature heating and high temperature cooling began to attract more attention both in Europe and the United States. Using low-grade energy to supply for these systems have, in return, led to an increase in awareness of low exergy (LowEx) system designs. The possibility of modeling the last missing link in the system that is to delivery thermal comfort, the human body, have therefore became a topic that increasingly draws the attention of many more researchers. Due to the complexity of these human body exergy models, it is very rare for these models to be linked back to building systems and produce an exergy efficiency for occupants' thermal comfort. Attempting to fill in the blanks of overall system exergy efficiency on delivery occupant thermal comfort, we have developed a visualization algorithm that could visually assess the exergy efficiency in comfort delivery. Using the ExFlow tool, it is much clearer and easier to determine the relationship of how much primary energy input is eventually converted to the energy that is used to condition for the occupants' comfort.

KEYWORDS
exergy analysis; thermal comfort; energy delivery; visualization

INTRODUCTION
The efficiency of systems to maintain a certain built environment is very often categorized by their energy efficiencies. How much primary energy input or levelized costs is necessary to deliver to the end of the chain where the users' demands are met. A common tool used to visualize this process is the Sankey diagrams (or occasionally referred to as the flow charts), where the total input and outputs can be visualized. Exergy analysis has gained popularity among many researchers as an addition to the existing analysis method during the last 20 years due to its capability of gauging not only the amount of energy, but also the usability of the energy.

With the growing popularity of systems that utilizes the low grade heat, or otherwise known as the low exergy (LowEx), exergy analysis has begun to receive a growing amount of attention from researchers. While the heat demand from the occupants stays the same, the same amount of exergy can be delivered with water warmed up by waste heat of a nearby factory than that heated with a gas boiler. Similar concepts of heat harvesting at stages of processing to be reused have been extensively used in chemical plants. This is particularly true for the domestic systems where the required water temperature rarely exceeds 75˚C, but are often supplied by primary energy sources that has high exergy and experience large amount of heat loss during distribution.

Acknowledging the magnitude of the question at hand, a tool named ExFlow was developed dedicated to visualize the exergy flow through a building systems' energy supply chain towards the occupants' thermal comfort. Basing off existing methods of calculating steady-state exergy consumption during the energy delivery for occupants, this tool specializes on visualizing both the exergies that are 'consumed' and the exergies that are used provide thermal comfort. Applying the ExFlow tool to three different types of building systems, a parametric study of an office study focusing mainly on its exergetic performance of components and thermal comfort is presented in this paper.

METHODS

Performing steady-state exergy analysis on a office building, we simulated the energy and exergy delivery chains for an office building, as was presented in Annex 37 for the heating case. Using simplified building geometry and thermal properties as inputs, the heat losses, heat demand and the amount of primary energy necessary to produce the heat necessary to maintain the room air condition can be calculated. Simplified system components assumptions were made including their inlet/outlet and operation temperatures as well as their individual efficiencies and required auxiliary energy consumptions. These parameters were then combined with the calculated energy consumption and heat losses along the energy delivery chain so that the exergy delivery chain can be determined.

Volume, net floor area and indoor air temperatures as well as the area and thermal transmit tan ce information of the envelope were used to generate basic estimation of the transmission heat losses. The ventilation heat losses is then determined through the designated air exchange rate and heat exchanger efficiencies. The solar heat gain is then calculated by assigning a window-wall ratio and pre-determined solar radiation rate per area. Internal heat gains were then obtained by using the number of occupants while the specific internal heat gains from equipments were obtained using equipment density per floor area. Same applied to lighting energy consumption and total ventilation power necessary. Subtracting the total heat gain from the heat loss, we then obtain the total building heating demand.

Splitting the energy delivery process into six distinctive stages, namely primary energy input, generation from primary energy input, distribution system from the generation system, emission system and room air towards envelope. The fundamental calculation behind the visualization algorithm of ExFLOW calculates the energy and exergy available at every stage of the delivery.

Previous investigations towards increasing the acknowledgement of the exergy consumption during the energy delivery process includes the I Schmidt, 2007), "Low Exergy Systems for Heating and Cooling of Buildings", Annex 49 , "Low Exergy Systems for High-Performance Buildings and Communities" (Angelotti & Caputo, 2007) and Annex 64, "LowEx Communities" (Schmidt, 2014). Annex 37, in particular, devised an excel tool that calculates steady-state flow of the energy as well as exergy when energy is being delivered to specific building cases. As a general rule of thumb, the exergy was calculated by multiplying the energy necessary with quality factors. These factors vary from 1.0 for electrical energy and mechanical energy, to 0.9 for fossil fuels and 0.06 for thermal energy at 40 degree Celsius. To determine the thermal exergies that are associated with different sources, their quality factors can be written as the following Equation 1, where T_j and T_i are respectively the temperatures of the temperatures of the temperature generated and the temperature necessary at input.

$$F_p = 1 - \frac{T_j}{T_i} \tag{1}$$

As we are able to determine quantitatively both the energy and the exergies during the energy and exergy delivery to households, it is important to associate the resulting parameters with the human body exergy consumption models. Since the air temperature and the envelope temperatures were considered homogeneous per the original assumptions for the model, it is possible to be introduced into the human body exergy consumption models constructed by previous researchers. Among the three existing major human body exergy consumption hubs (Shukuya, Prek and Mady), the results were comparable as most resulted in a 4~5 W/m^2 for an adult man weighing 80 kg and 1.8 m^2 surface area of the body where the air temperature sits at about 21˚C. This points to a total of 7~9 W for a single occupant, and with an assumed number of occupants at 13 for the entire building, this points to a 91~117 W for the entire building. Since the analysis is steady-state, it is reasonable to assume that the human body exergy consumption will remain constant as the other parameters of the building that is being simulated (Shukuya et al., 2010).

Specifically relating to the case study that we are examining within the scope of this paper, we are simulating an office building with the an overall volume of 6882.35 m3 and 2202.35 net floor area. For the indoor environment, we will be assuming indoor temperature was to maintain at 21˚C while the outdoor temperature (or reference temperature for the calculation of exergy) remains at 0˚C, we can simulate the energy and exergy required at every single level of the energy delivery (Sakulpipatsin & Schmidt, 2003).

To better understand the performance of ExFLOW as a tool to visualize both the energy and the exergy flow, three different variations of said building is considered and qualitatively compared between. We will be focusing mostly on how the generation level and the distribution level performance differences could have led to different scenarios of energy and exergy deliveries towards the end-goal, the human thermal comfort. More specifically, we would like to examine the possible implications in deploying larger surfaces for heat exchange (floor heating/radiators) vs. air-based heating and cooling as well as harvesting the primary energy generation/conversion systems through either standard boiler or taking in heat directly from district heating networks. These systems and their different parameters can be found in the following Table 1.

Table 1. Cases investigated with different building system combinations

Combination	Emission System	Generation System	Sup/Ret T (˚C).	Generation Effi.
1	Floor Heating	District Heating w/ Waste Heat Recov.	35/30	0.89
2	Floor Heating	Standard Boiler	35/30	0.8
3	Air Heating/Cooling	Standard Boiler	35/25	0.8
4	Radiator	District Heating	70/60	0.89

It is important to point out that there are many other sources of primary energy input that would allow a significant decrease in primary energy input as the renewable energy sources essentially makes up the necessary primary energy input - such as various heat pump with different sources, i.e. ground-sourced, air-sourced, etc. We will not be including any of these studies within the scope of this paper due to its length limitation.

RESULTS

Using the ExFLOW tool, it is possible to generate both the energy flow diagrams and exergy flow diagrams qualitatively with quantitative hover information as is shown in Figure 1. Qualitatively speaking, generating an energy flow diagram that includes the waste heat that is generated at different stages is the same with exergy consumption modeled in exergy analysis.

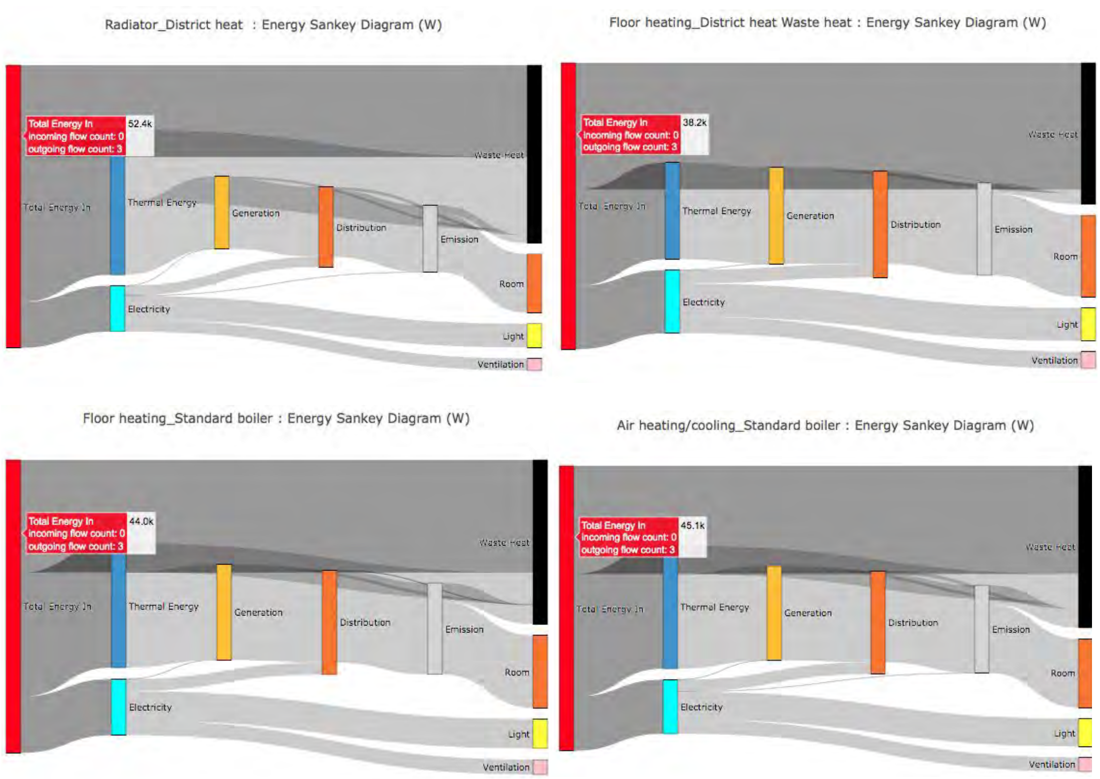

Figure 1. Energy Flow Sankey Diagrams generated by ExFLOW with four different combinations of energy generation and emission systems.

It is not very difficult to observe the discrepancy between the amount of waste heat is not quantitatively equivalent of that of exergy consumed. This is mostly because the amount of waste heat were in fact harvested at different levels of usability - or in other words, different amount of exergy. The total amount of waste heat as is shown in Figure 1 is, therefore, not representative of how much of which could have been harvested for secondary or further utilization.

Another interesting observation from the results generated by ExFLOW is its capabilities of showing how little amount of exergy is actually necessary at the end of the delivery. While the entire exergy/energy delivery chain is dedicated to provide for comfortable indoor conditions for the occupants, much of that is not dedicated to the comfort of the occupants, but rather conditioning the air indoor as is mandated by the design guidelines with respect to the supply and return temperature of the generation/distribution/emission systems.

DISCUSSIONS

The results from the ExFLOW tool brings ample of room for discussing its current and future room of applications. Looking at the similarities and discrepancies between the results of energy and exergy flow diagrams as shown in Figure 1 and Figure 2, the energy and exergy consumption concepts led to a very different understanding of the viability of various systems.

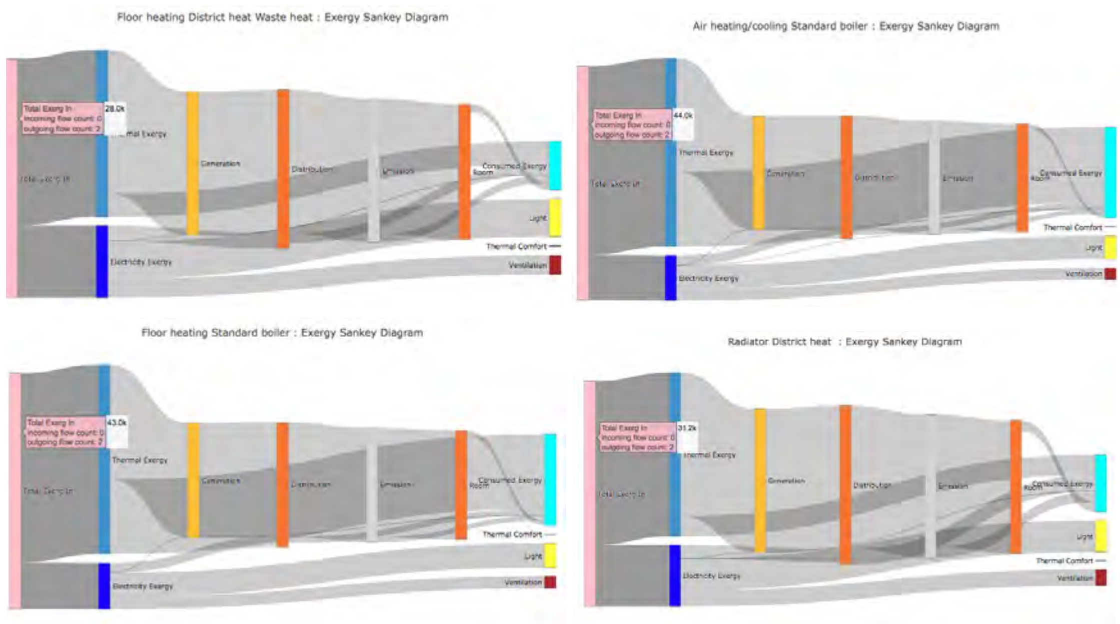

Figure 2. Exergy Flow Sankey Diagrams generated by ExFLOW with four different combinations of exergy generation and emission systems.

Combination of the floor heating system as emission system and district heating with waste heat harvesting was found to be the most energy and exergy efficient system of all four combinations. This is to be expected since their necessary supply temperatures are much lower and can benefit from generation system with a much smaller exergy input. The energy input then increases for the floor heating and standard boiler combination, further for air heating/cooling and standard boiler, and the largest for the combination of radiator and district heating combination. For the exergy side, this changes as the radiator plus district heating was found to require exergy input that was slightly larger than that of floor heating with district heating. This demand increases dramatically for floor heating and standard boiler combination, while the air heating and cooling was the least exergy-efficient combination of all four combinations.

Comparing the final exergy consumption at the human body reveals some even more interesting findings, where we can observe the final stage of exergy consumption being split into four categories, exergy consumed by system components, exergy consumed by the human body to maintain thermal comfort, and exergy required to maintain proper lighting and healthy ventilation. The energy that is necessary to maintain thermal comfort appears to be much smaller than that of the other three, while the light and ventilation exergy consumption remains the same since they are not subject to any change by any input parameters. This brings up a very interesting research question, as to whether we have positioned our energy assets in appropriate locations to achieve the maximized system efficiency. More importantly, can we design systems that can deliver the same amount of comfort to the occupants without resulting with the same amount of exergy that is consumed by the transformation and distribution.

CONCLUSIONS

We developed a visualization tool for the energy and exergy flow to deliver satisfying indoor environment to occupants. Understanding the challenges of avoiding the stove-piped disciplines in understanding the overall system design, we compared four different combination of systems that could be used for a specific building with ExFLOW and quantitatively and qualitatively compared the results obtained from ExFLOW. Since exergy flows are by definition describes the quality of the energy flows, we were able to quantitatively understand the amount of exergy that are being consumed by the processes and compared against the necessary exergy consumption of a hypothetical human to understand the overall scope of comfort delivery.

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