Preliminary Investigation of the Use of Sankey Diagrams to Enhance Building Performance Simulation-Supported Design

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Keywords: Building performance simulation, high-performance building design, user interface, design tools, Sankey diagrams

Abstract

Building performance simulation (BPS) is a powerful tool for assessing the performance of unbuilt buildings to improve their design. However, numerous obstacles resulting from limited resources of designers and poor presentation of results reduce the applicability of BPS to design practice. This paper introduces the concept of using Sankey diagrams to represent building energy performance data obtained from BPS tools. While being simple upon first examination Sankey diagrams are complex and reveal many questions that BPS tool users should be considering, including: appropriate spatial and temporal boundaries and model resolution; and it answers questions about how a particular design aspect or technology integrates into the whole building. The paper is a first investigation into the suitability of the application of Sankey diagrams as a tool to communicate BPS data to building designers.

1. INTRODUCTION

Building performance simulation (BPS) tools provide a means to accurately predict a building's performance (e.g., energy use, renewable energy generation, thermal and visual comfort, etc.) long before its construction commences. For the past 40 to 50 years, BPS tools have become more capable (e.g., accuracy and number of building technologies) and more efficient to use (e.g., better user interfaces and software interoperability). However, encouraging the use of BPS tools in early stage building design remains a challenge. This is partly because many BPS tools require detailed design specifications (which take significant time to collect and input) to be operated and because the form of output is not geared at informing designers how to improve upon a design.

One of the most valuable features that design tool developers can provide building designers with is a "big picture" education about how a proposed building performs. One of the most significant barriers to simulation use is communication of results, rather than being purely technical in nature. There is tremendous value in answering the *why*, *when*, and *how* questions and not merely presenting the aggregated predicted building performance data (e.g., total annual energy consumption). This allows "what if" questions to be answered without necessarily performing incremental (one-change-at-a-time) simulations.

Sankey diagrams, which are typically used to represent material or energy flows, have existed for over a 100 years (Schmidt 2008). However, there are very few instances of their application to building energy performance and particularly with the intent of supporting the design process. Those that exist, tend to be simplified and aggregated, and therefore, fall short of educating designers about the operating energy of buildings. Only one building design tool was found that includes Sankey diagrams: CASAnova (IDEAS, 2002). However, its Sankey diagrams are relatively simple and somewhat difficult to follow.

Sankey diagrams have a major advantage over simpler representations of energy use distributions: they show the interrelationships between subsystems. For instance, improving lighting efficiency not only reduces electricity use for lighting, but it also affects the heating and cooling energy of buildings because of the radiant heat gains from lighting. Other advantages to using Sankey diagrams for building design, particularly in the context of modern performance standards, is that they identify and quantify several important metrics such as solar fraction (the fraction of total building energy use that is supplied with solar energy) and the net energy level (difference between energy use and on-site renewable energy generation).

The objective of this paper is to preliminarily address major issues involved in creating Sankey diagrams to represent building energy flows, including: establishing a definition for usefulness of internal and solar heat gains, representing energy conversation processes, representing feedback processes, addressing temporal and energy storage issues, and choosing the appropriate level of model resolution. The theoretical background is supported by an example Sankey diagram for a high-performance solar house. This example demonstrates that creating a Sankey diagram from BPS data is surprisingly difficult and that, without some form of automation of the process, would be impractical to apply in practice at the present.

2. METHODOLOGY

The ultimate objective of this paper is to establish a methodology for converting a BPS model to a Sankey diagram to represent its energy flows. The first step in the process, other than creating a BPS model of a specific building, is to list all sources of heat gains, heat losses, and heat transfer or energy conversion processes and mechanisms. Examples of these that pertain to the example of a passive solar house discussed throughout this paper are shown in Table 1.

Heat gains	Heat losses/sinks	Heat/energy transfer and conversion processes
• People • Lights • Equipment and appliances • Solar gains	• Conduction through the foundation or basement	• HVAC equipment • Equipment that converts purchased energy into heat gains • Conduction, convection, radiation through or between building surfaces and/or openings
Heat gains or losses • Conductive gains through the envelope • Short-wave radiation exchange between indoors and outdoors • Ventilation and infiltration heat transfer		

Table 1. Summary of typical heat gains, losses, and energy/heat conversion processes

Next, the BPS tool must be set up to report timestep variables with as much resolution as desired (as explained in Section 2.5). The simulation should be run one or more times (as explained in Section 2.6). A conservation of energy equation must be formulated that contains all building heat sources, sinks, and heat transfer/energy

conversion processes, with the following equation as a starting point.

$$\text{Energy in} + \text{Released stored energy} =$$

$$\text{Energy out} + \text{Stored Energy}$$

An important, and nontrivial, step is to confirm that the BPS results adhere to this balance. Here, the spatial boundaries must be clearly defined, as explained in Section 2.2. For the building envelope, the boundary should probably be within the insulation layer, depending on the construction details. Ideally, it should contain all insulated thermal mass, such that passive storage is included in the analysis, as described in Section 2.4. The boundary for windows is less critical because their magnitude of heat transfer is relatively high compared to their thermal storage capacity. The envelope boundaries should form a bound volume, within which convective heat gains and losses, and all radiant heating and cooling systems exist.

Supposing the conservation of energy is confirmed, the Sankey diagram may be constructed, such as the one in Figure 6. While several commercial software programs exist for creating generic Sankey diagrams, the example was created using MS Visio, for its flexibility. Because Sankey diagrams represent magnitudes of flows by the width of arrows (energy in this case), the conservation can be visually confirmed. The following sections examine various important aspects and complications of creating a Sankey diagram to represent energy flows in buildings.

2.1. Energy Conversion Issues

The relative value of different forms of energy has not been significantly addressed in literature discussing Sankey diagrams. Fundamentally, Sankey diagrams represent a conservation of the quantity being represented (mass, power, energy). In graphical terms, that means that the sum of the widths of all input arrows equals the sum of the widths of output arrows at every process. A number of building processes involve conversion of energy from one form of to another. For instance, ground source heat pumps, which typically deliver (or remove) about 3 to 4 Watts of thermal energy for every Watt of electrical energy input. Note that in the example provided, the energy balance is for thermal energy and that electrical energy input is ultimately converted into thermal energy. It is important to show the sources of energy even if they are not purchased, to

maintain the conservation of energy. In Figure 6, the main source of energy for the heat pump is thermal energy stored in the ground.

An interesting energy conversion issue relates to solar energy, daylighting, and solar heat gains. A Joule of transmitted solar energy may displace a Joule of light energy (e.g., less required electrical lighting) while also reducing heating energy. However, this Joule must not be double-counted; instead, it passes through the system linearly, as shown in **Figure 1**.
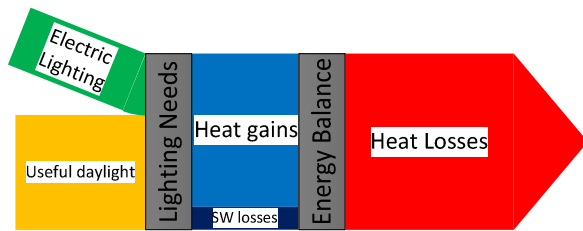

Figure 1. A simple Sankey diagram showing that solar gains used to displace electric lighting eventually turns into heat gains which leaves through a number of mechanisms, including back out glazing in the form of shortwave radiation ("SW losses")

2.2.   Spatial Boundaries

As buildings increase their resourcefulness by obtaining energy from their local surroundings, the question of where to draw the energy boundary becomes more interesting. In the past, the boundary could have been simply drawn at the energy meter (electricity or gas meter) and included the building envelope. However, some newer buildings obtain energy from, or store energy in, the ground (e.g., ground source heat pumps and bore-hole thermal storage). They may also collect solar or wind energy. If these solar collectors are building integrated, the boundary is relatively straightforward. But if the collectors are off-site, care must be taken to ensure that the building gets credit for the energy, and conversely that these energy sources are not double-counted. For example, there are many building-mounted solar collector installations which are operated by a third party. For net-zero energy buildings, for which a thorough examination of definitions (and spatial boundaries) was explored by Torcellini, Pless et al (2006) and Marszal, Heiselberg, et al (2011), a Sankey diagram would clearly indicate that the net purchased energy over a year is zero. One of the visions for the current work is that a Sankey diagram representing individual buildings in a community could be integrated with major energy sources (e.g., electric power plants). This may uncover potential energy

conservation measures, such as mutualistic opportunities like using waste or excess thermal energy from one building to supply another.

2.3.   Feedback loops

There are several instances of building energy processes where energy is recovered and fed back into buildings. For example, heat recover ventilators (HRVs) use heat exchangers and a fan to recover the sensible energy in exhaust air to pre-heat (or pre-cool) incoming supply air.
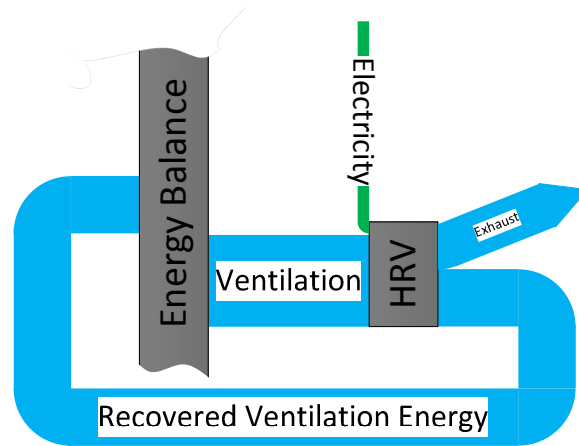

Figure 2. A heat recovery ventilator (HRV) represented as a feedback loop in a Sankey diagram

There is value in representing this process with a Sankey diagram, as it illustrates the relative energy quantities and may identify instances when heat recovery consumes more energy than it uses (i.e., mild climates when the value of fan electricity use exceeds that of the recovered thermal energy).

2.4.   Temporal Boundaries

Traditionally, BPS results have been reported as aggregated values on a monthly or annual level (though for detailed simulation engines, this can be reduced to the timestep-level: seconds or minutes). In understanding the energy flows of a building it is often useful to use a relatively short time period so that designers can focus on one set of weather phenomena at a time. A week was chosen for most examples in this paper for this reason and others that follow. However, there is value in using Sankey diagrams to represent an entire year because this is a single climatic cycle; and ultimately, a high-performance building is one that is robust to all expected weather conditions that it may encounter.

All existing examples of building energy Sankey diagrams that were found in the literature are created with the notion that there is no storage term in the conservation of energy. However, all buildings have some storage (e.g., hot water storage tank), even if it is passive (e.g., a masonry wall). Furthermore, renewable energy systems such as solar thermal systems or electric cars that are connected to photovoltaic systems, include storage. Several buildings or communities have been built to have long-term storage, with thermal storage that takes as long as five years to fully charge or discharge (e.g., Drake Landing Solar Community (Sibbitt et al. 2007)).
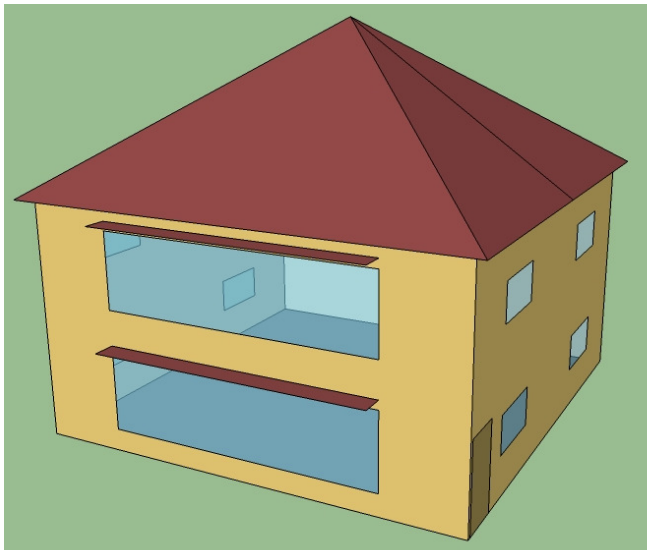

Figure 3. An image of the house that is used for most examples of Sankey diagrams throughout this paper

Sankey diagrams must either be created to represent buildings for long enough periods that the energy storage (or depletion of storage) is insignificant relative to the energy flow quantities or storage must explicitly be shown. For example, consider the house represented by Figure 3. Note that all remaining results in this paper are based on this house in the Toronto climate. A summation of the energy inputs and outputs during the course of a week in the winter reveals that the house passively stored (i.e., within its inherent structural thermal mass and air contained within it) about 35 kWh (as shown at the bottom of Figure 6). This represents a mere 1°C increase in the interior surface temperature and no increase in the indoor air temperature. This example illustrates the importance of representing a sufficiently long period with a Sankey diagram. Otherwise, the solar gains could be under-credited in usefulness

because their benefit extends into the period following that of interest and will not all be realized. It follows that Sankey diagrams can also use storage as an energy source (i.e., entering from the left), just as it is shown as a sink in Figure 6.

2.5.   Model Resolution

A question that every building energy modeller should be constantly asking themselves is: how detailed should the model be? There is often an inverse relationship between detail and accuracy; but one with diminishing returns (O'Brien et al. 2011). For instance, a model that integrates two systems that barely interact is cumbersome, yet offers little benefit or insight. Therefore, building modellers must determine the required level of accuracy in the context that achieving greater levels of accuracy may be time-consuming (and costly).

In representing building energy flows with a Sankey diagram, the objective is to inform the designer of strengths and weaknesses of the energy systems components and their integration. Therefore, in general, processes over which the designer has the greatest amount of control should be represented in the most detail. For example, a simple off-the-shelf component (e.g., a furnace) need not be represented in vast amount of detail because the main concern of the designer is overall system performance (e.g., efficiency of primary to secondary energy conversion). In contrast, the designer may have much more control over a wall construction, in which case, showing such details as thermal bridging through framing elements could be useful.

The convenient feature of Sankey diagrams is that they permit the level of model resolution may vary from subsystem to subsystem within a single diagram. For example, one could imagine a user interface in which users could zoom into a particular part of the diagram to investigate it more deeply. One major limitation is that the Sankey diagram cannot be represented in more detail than the underlying BPS model. And, in fact, the tool must also report state variables to sufficient detail. For this reason, detailed BPS engines such as EnergyPlus, ESP-r, TRNSYS, and DOE-2 are favourable over simpler tools.

A major, though understandable, limitation of most BPS tools is that certain quantities are internally aggregated and reported as such. As a result, the ultimate objective of this work to track every Joule of energy from the point it enters

to the point in leaves the building is challenging. For instance, Figure 6 shows all of the heat sources entering the house and sinks to the environment. But it does not specify whether any given Joule entering via the glazing ultimately leaves through the glazing or via some other route. EnergyPlus, which was used for all simulation here, performs an energy balance about the air node, where it is effectively mixed and aggregated. There is a minor exception to this limitation: short-wave radiation can be tracked from source (e.g., light bulb or solar gains) to the point where (and if) it exits a non-opaque surface (e.g., a window).

2.6. Useful, Adverse and Neutral Heat Gains

Buildings encounter many sources of heat gains, including solar gains, electrical equipment and lighting, and metabolic heat of occupants. While usually not being an efficient or intentional source of heating, waste heat from these sources does contribute to heating and can offset purchased heating energy; however, it can also contribute to cooling loads. Under certain conditions, usually in the shoulder seasons, it is possible for these internal gains to not affect heating or cooling loads, if the indoor air temperature remains between the heating and cooling setpoint or if the heat gains the affect the magnitude heat losses (e.g., an elevated indoor air temperature results in greater heat loss from ventilation and infiltration).

Generally speaking, it can be assumed that all energy input into electrical devices (e.g., lights, appliances, equipment) in a building is eventually converted to heat gains in that building. However, several notable exceptions occur, including:

- Short-wave radiation (including the visible range) emitted from lights and displays (e.g., computer monitors) that is transmitted through glazing.

- Appliances that directly exhaust warm and/or moist air to the outdoors (e.g., stovetops and clothes dryers).

- Domestic hot water (DHW) heaters and appliances that heat and then drain water (e.g., dishwashers). It is standard practice to assume that all DHW heating energy is lost through drains without incurring heat gains indoors (Barnaby et al. 2005).

A beneficial calculation before creating a Sankey diagram is to quantify all heat gains in terms of useful, adverse, and neutral. The approach used here is to sequentially perform simulations with and without each type of heat gain. The gains that decrease the purchased heating energy are considered *useful*, the gains that increase the purchased cooling energy are considered *adverse*, and the gains that do not affect heating or cooling are considered *neutral*. The equations used to determine the useful, adverse and neutral heat gains from people are shown below. The same approach is used for all other forms of internal heat gains and solar gains.

$$G_{people,useful} = E_{heating}|_{no\ people} - E_{heating}|_{people}$$

$$G_{people,adverse} = E_{cooling}|_{people} - E_{cooling}|_{no\ people}$$

$$G_{people,neutral} = G_{people,total} - G_{people,useful} - G_{people,adverse}$$

This procedure adheres to the procedure proposed by Balcomb (1992) to quantify the useful solar gains. Specifically, his approach involves performing two simulations: one with the solar gains and one without. This was implemented by creating a modified weather data file with zero solar radiation. It is important to note that it would be inappropriate to limit the analysis to steady-state (e.g., determining the usefulness of solar gains on whether mechanical heating is required at that instant) because solar gains may not be useful at one moment, but may contribute to reducing purchased heating in the future.

There could be many instances where different sources of heat gains "compete" for usefulness. To overcome this, gains are prioritized in order from those that are a given to those that the building designer has control over: people, equipment, lighting, and solar gains. That is, the designer cannot control occupancy as much (assuming that the building is to perform a certain function) as lighting and solar gains. This order is selected considering one of the objectives of this work: to inform designers of building energy performance.

Using the aforementioned procedure, Sankey diagrams were created for the example house for a week in January and a week in July, as shown in Figures 4 and 5, respectively. In the winter week (Figure 4), the majority of the heat gains are useful; owing to the fact that Toronto's

winter climate is cold and thus, heating is on throughout most of the day to compensate for heat losses. Regardless, about 15% of the solar gains do not reduce the heating energy and are deemed "neutral". This 15% is either a result of elevated air and surface temperatures that actually increase heat losses relative to a case without solar gains or that some of the solar radiation is reflected back out the glazing. The heat losses that are not fed by naturally-occurring heat gains must be supplemented with purchased heating (i.e., the heat intentionally delivered by the HVAC system). Note that this analysis is premised on the fact that thermal comfort is considered equivalent for any conditions between the 21 and 25°C setpoints.
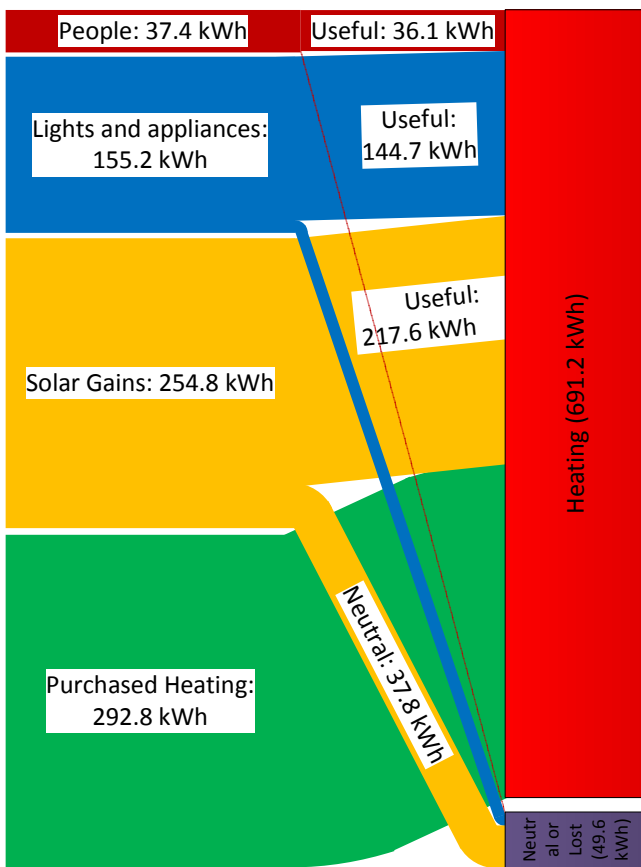

Figure 4: Useful, neutral, and adverse heat gains a mid-winter week.

The summer week (Figure 5) demonstrates that, in fact, without any heat gains, a modest level of heating is required. Furthermore, even with the heat gains from people, lighting, and appliances, the necessary purchased heating is not eliminated. However, the addition of solar gains changes the balance to having a cooling load; and thus, there is a need for some mechanical cooling (50.4

kWh) to maintain comfort throughout the period. The large amount of neutral heat gains indicate that the majority of heat gains are lost before they cause the indoor air temperature to exceed the cooling setpoint.
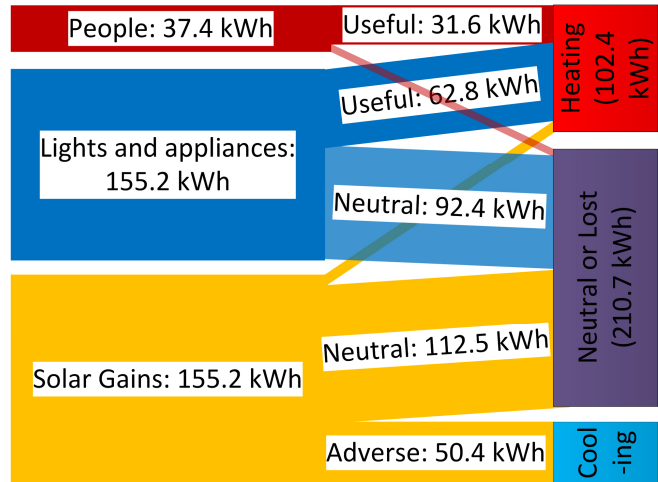

Figure 5: Useful, neutral, and adverse heat gains a mid-summer week.

An important metric for solar buildings (those that meet a significant portion of their energy needs with solar energy) is "solar fraction". Solar fraction is normally defined as the fraction of energy needs that are met by useful on-site collected solar energy. In general, solar fraction is calculated by:

$$f = \frac{useful\ solar\ energy\ collected}{total\ energy\ needs\ of\ the\ sytem\ without\ solar}$$

Where "useful solar energy collected" is the magnitude of the collected solar energy that *actually* reduces purchased energy – not the total amount collected. Solar fraction is frequently quoted for solar thermal systems, but rarely for passive solar performance. Using the Sankey diagram methodology, the passive solar fraction can be efficiently extracted because the diagrams explicitly show useful solar gains. For example, in Figure 5, the total heating energy without the solar gains is found to be 510.4 kWh (the sum of useful solar gains and purchased heating). A second simulation with the solar gains included shows that the heating energy is reduced to 292.8 kWh. Given that the solar gains displace 217.6 kWh of the heating energy, the solar fraction is 43% [217.6/(217.6+292.8)]. This definition of solar fraction for cooling is not applicable because the solar gains clearly have a net adverse effect.

3. APPLICATION OF SANKEY DIAGRAMS TO BUILDING DESIGN

The ultimate objective of this work is to apply Sankey diagrams to inform building designers of the impact of different design decisions. Several methods in which they could be applied to early stage design are:

- Identify the major energy sources and sinks and prioritize those as potential opportunities to reduce purchased energy use;

- Quantify the electrical and thermal interactions between a particular subsystem (e.g., HRV, PV array, window) and the rest of the building.

- Visually compare the energy performance of two different building designs.

4. CONCLUSION AND FUTURE WORK

This paper proposed the outline for a methodology for creating Sankey diagrams to represent energy flows in buildings, with the eventual intent that the methodology be integrated into a software tool. Though Sankey diagrams are a relatively simple means to visualize complex energy flows, the underlying creation process, when performed manually, can be quite complex and requires a high level of understanding of building physics and simulation methodologies. For instance, the first attempt at creating the Sankey diagram in Figure 6 took about four days of research and analysis, despite the fact that the model uses a single zone and ideal HVAC equipment and controls. Much of this was devoted to identifying exactly which variables (e.g., conduction through walls at the inside surface) should be reported and ensuring that the energy into the house equaled the energy out plus stored energy. The greatest challenge was in quantifying total solar heat gains (i.e., transmitted solar energy that eventually flows into the zone via convection and long-wave radiation) and not just transmitted (short-wave) solar radiation. Future steps for this research initiative include:

- Automating the process using a software toolkit that automatically creates a Sankey diagram from a BPS input file;

- Applying the methodology to a more complex, multi-zone building;

- A zoomable Sankey diagram in which designers can view a large range of detail levels from whole-building performance to component level (e.g., individual windows) to a high level of detail (e.g., heat transfer through window frames, spacers, glazing, etc.);

- Standardized representations for certain building energy processes (e.g., heat pumps and HRVs);

- Inclusion and representation of intermediate steps of energy flows within a building (e.g., long-wave radiation between interior surfaces and short-term passive storage is massive floors) rather than merely the entry and exit points, as shown in the example in Figure 6;

- Different methods for configuring Sankey diagrams, such as superimposing the flows with a graphical schematic of buildings; and,

- A software-based user interface that allows a designer to inspect instantaneous heat transfer and power use in a building at any given time; and in video form over a finite period.

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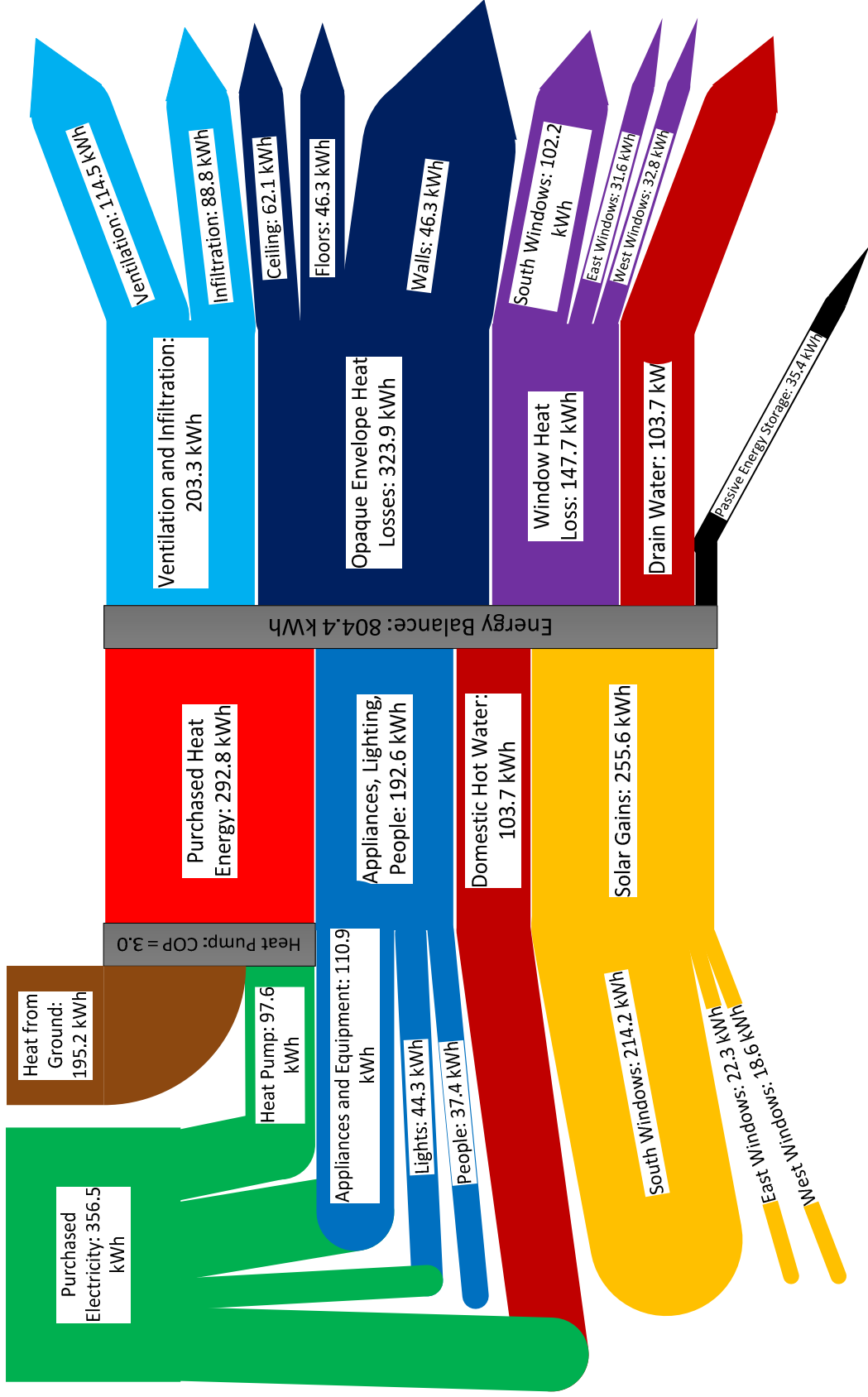
Figure 6. Sankey diagram representing the energy balance for a house for a mid-winter week