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Understanding Energy Efficiency as a Dynamic Resource in the Built Environment

Achieve real efficiency gains by modulating the energy flowing throughout your building

BRAINBOX AI

1.0 Introduction

Energy efficiency is a vast and largely untapped energy resource contained within our built environments that is key to meeting our future global energy needs. For over a decade, energy professionals have been talking about this hidden resource and about the magnitude of the potential energy savings for owners of commercial retail spaces, office buildings, manufacturing facilities, and many other conditioned spaces.

For instance, in its 2009 report entitled Unlocking Energy Efficiency in the U.S. Economy, McKinsey Global Energy and Materials determined that "the energy and operational savings from greater efficiency total some $1.2 trillion in present value to the U.S. economy: unlocking this value would require an initial upfront investment of approximately $520 billion [1]." A 2012 analysis by Deutsche Bank Climate Advisors came to a similar conclusion. They found that $279 billion in efficiency investments in the U.S. building sector would result in $1 trillion in savings over the next 10 years [2].

However, because of a number of persistent market barriers, these energy efficiency resources still remain mostly untapped. An annual survey of the global building efficiency market conducted by Johnson Controls shows that the following barriers to energy efficiency remain the same year after year:

- lack of awareness of opportunities for energy savings within the built environment
- lack of technical expertise to design and complete projects
- lack of certainty that promised energy savings will be achieved
- inability of efficiency projects to meet an organization's financial payback criteria
- lack of available capital for investment in projects [3]

In part, these barriers are a function of how built environments are run. In many organizations, decisions about energy efficiency projects are made by various individuals, like sustainability officers, facilities managers, and CFOs, who often have contradictory positions with regards to managing and operating their buildings and facilities. And these different approaches can result in delays or even poor decision-making about how to best implement crucial energy-saving measures [3].

Another key cause of these market barriers is a lack of any clear understanding, within organizations, of energy use in buildings and facilities. Without accurate information about energy use, it is difficult for any organization interested in achieving greater energy efficiency to identify initial energy savings opportunities, design and implement an efficiency project, and then verify if such projects are actually saving energy [3].

1.1 Conceptual Barrier to Energy Efficiency

In addition to these market barriers, there is also a conceptual barrier that must be overcome in order to unlock these potential energy savings. Most organizations adhere to a static operating model of building operations and maintenance and view the built environment as a collection of mechanical equipment or systems that exist in isolation from one another. Therefore, when thinking about energy efficiency, organizations undertake to optimize equipment and the processes within each system, for example, optimizing a boiler to ensure that it is operating under the proper conditions or according to design specifications.

However, adhering to a static model of the built environment makes it impossible to optimize a boiler with regards to changing energy demands, changing weather conditions, or fluctuations in occupancy. In other words, organizations following a static model are only able to modulate equipment independently—or in isolation from the built environment in which they operate—instead of being able to modulate equipment performance dynamically in response to the ways in which the environment is changing over time. As a result of this siloed approach, the vast pool of energy efficiency resources that exists within our buildings remains largely untapped.

1.2 Energy and the River Flow Concept

Organizations looking to achieve significant short-term or long-term efficiency gains have to embrace energy efficiency as a dynamic resource and see the built environment as an ecosystem of interconnected components. In fact, by adopting this holistic and system-wide approach, organizations would be able to effectively manage the flow of energy through their buildings and maintain the right balance between occupant comfort and energy consumption.

One way to understand this conceptual shift is to use the river flow concept to think about the movement of energy through buildings. In physics, the law of the conservation of energy states that energy in a closed system is neither created nor destroyed but instead remains constant. When applied to the built environment, this means that energy, which can occur in different forms, such as electricity or sunlight, is continuously flowing into a building, being transformed into mechanical work or thermal energy, and then flowing out. And, just like the flow of water in a river, this flow rate is dynamic, changing minute-to-minute in response to various factors. In fact, if the flow rate becomes too high, the river of energy will overflow its banks, wasting energy and creating hot/cold spots. Similarly, an underflow of energy will also result in severely reduced comfort levels.

In terms of achieving real energy efficiency, the key is to figure out ways to modulate the flow of this river in order to ensure that the right amount of energy is flowing through a building at any given time—in much the same way that a dam ensures that the right amount of water is flowing in a river, whether to support boat traffic or provide appropriate amounts of water for drinking or agriculture. In addition to promoting a more holistic view of the built environment, the river flow concept also allows organizations to recognize opportunities for energy savings. When you look at building systems from the perspective of energy flow, you begin to see the losses that occur as energy moves from input to output.

Consequently, if you can properly manage the flow of this river of energy, you can achieve balance between occupant comfort and energy efficiency while simultaneously reducing the amount of energy being wasted and decreasing your building's carbon footprint. For instance, if you could predict energy flow requirements over the course of a day, you could keep overflow conditions from occurring, thereby conserving energy and maintaining a constant temperature within your building.

2.0 Energy Use and HVAC Systems in the Built Environment

The amount of energy being consumed by buildings and facilities is staggering. It is estimated that built environments and industry account for 70% of yearly energy consumption in the U.S. [2]. According to the U.S. Department of Energy, heating and cooling (HVAC) systems, including air conditioners, boilers, chillers, furnaces, and heat pumps, account for nearly half of the energy consumed by built environments in the U.S. [4].

These systems, together with lighting, are a major source of energy loss, with even new 'state-of-the-art' commercial HVAC systems experiencing significant losses in operational efficiency post-installation because of the way they are designed, installed, and maintained [5]. This means that achieving HVAC efficiency is a priority for tackling the problem of energy efficiency in the building sector.

2.1 Understanding Energy Efficiency in HVAC Systems

2.1.1 Traditional Approach to HVAC Efficiency

The traditional approach to HVAC efficiency has been to view these systems as groups of independent pieces of mechanical equipment. Every pump, chiller, tower, and air handling unit is understood as a component designed to operate efficiently in isolation and is controlled by a building management system (BMS) that turns it on and off automatically.

However, buildings optimized using this approach to HVAC operation and maintenance are unable to achieve high levels of energy efficiency. Without constant verification, performance degradation or drift is inevitable and often goes undetected for long periods of time because the operating data collected in the BMS is not easily accessible to building operators. And, if the data is available, it is usually in a form that is incompatible with performance measurement or problem diagnosis. The result is increased energy use and higher maintenance costs.

2.1.2 HVAC Efficiency Using the River Flow Concept

Because energy is not traditionally thought of in terms of the river flow concept, most people remain unaware of the inefficiency of the transformative processes that move energy from source to destination or usage. In fact, these processes are so inefficient that any significant improvement in flow efficiency would dramatically help to stop the trend in rising temperatures around the world due to climate change.

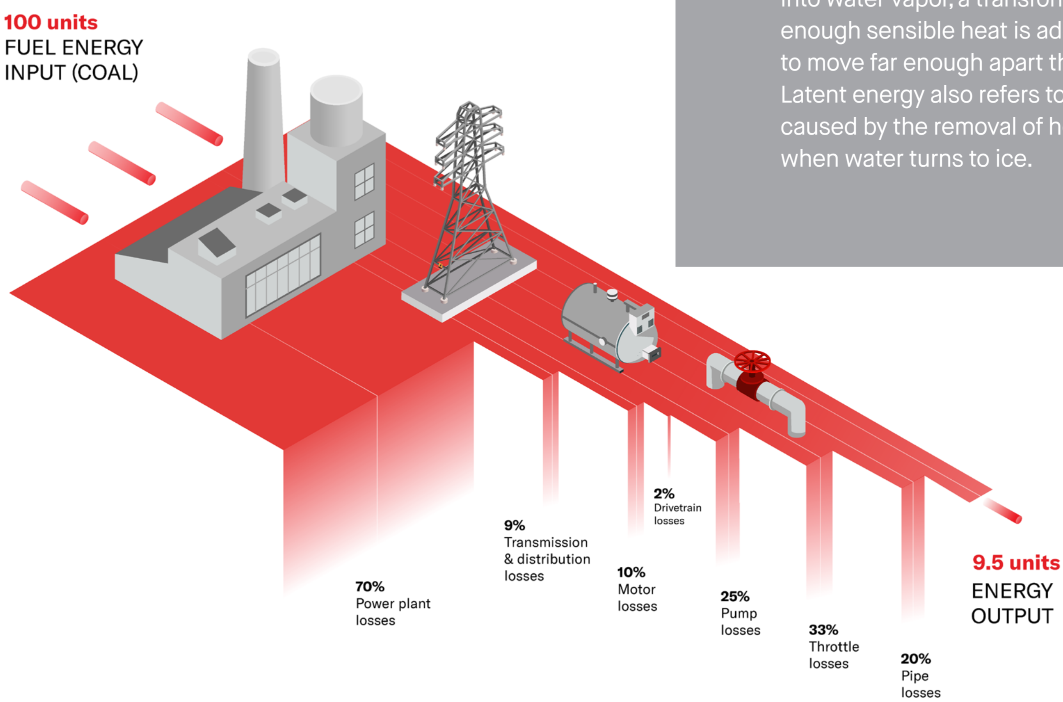
Sankey Diagram

A Sankey diagram is a flow diagram that visually represents the various flows of energy in a system.
It is used to identify the major sources or contributions to an overall energy flow. The width of the arrows in the diagram is proportional to the quantity of energy produced, utilized, or lost: the thicker the arrow, the greater the amount.

Figure 1 uses a Sankey Diagram to illustrate the process of burning coal to produce electricity that will activate a pump serving a fresh water network. It shows how, in this process of energy flow, more than 90% of the initial energy contained in the coal is wasted before the energy reaches its destination and becomes useful work. Within the built environment, the energy consumed is transformed and transferred from one form into another. In general, a building will purchase an energy source and transform it immediately into another form, such as heat, light, cold air, or mechanical movements. And the best opportunities for significant energy savings come from unlocking the potential efficiency located in these processes of transformation.

However, being able to recognize these opportunities requires looking at the built environment from the perspective of the river flow concept. Using this approach, organizations can significantly improve their energy efficiency because they will be able to analyze these transformation processes in their buildings and determine where the energy is going and the amount of energy being lost as it moves through the environment.

Figure 1: Three-dimensional Sankey Diagram of Energy Losses



The Physics of Eneregy

The law of the conservation of energy states that, within an isolated system in a given frame of reference, the total energy remains constant. Energy within a closed system, therefore, is neither created nor destroyed but is only transformed from one form to another, such as from mechanical to thermal energy.

Mechanical energy refers to the energy used to produce physical movement, such as forcing a liquid or gas through a pipe. In most instances, mechanical energy is released or lost by being transformed into thermal energy.

Commonly referred to as heat, **thermal energy** is produced by the microscopic movement of atoms and molecules. There are two types of thermal energy.

The first is **sensible energy**, which is produced by agitating the molecules in a substance. The more movement produced in the molecules, the hotter the substance becomes, and one is able to sense the presence of heat in the substance by directly or indirectly touching the substance.

Latent energy is the second type of thermal heat and refers to the energy required to make a substance change from one form into another. It is, for example, the energy that must be added to transform a substance like water into water vapor, a transformation that occurs when enough sensible heat is added to force the molecules to move far enough apart that they eventually separate. Latent energy also refers to the transformation in state caused by the removal of heat from a substance, like when water turns to ice.

3.0 Energy Flow in HVAC Systems

Heating and cooling are thermal processes that produce and distribute thermal load throughout the built environment. Rarely optimized, these building energy processes are significant sources of energy loss. Most of the energy they consume is lost or released outside of the built environment without adding any value to the processes themselves.

But, before being able to develop and implement an effective energy efficiency project, it is important to evaluate the amount of energy lost in each process. The following descriptions of building energy processes are taken from the Energy Audit Manual and Tool published by the National Research Council of Canada. The study was conducted by the Canadian Government and provides an extensive analysis and evaluation of the energy flow within different types of building systems.

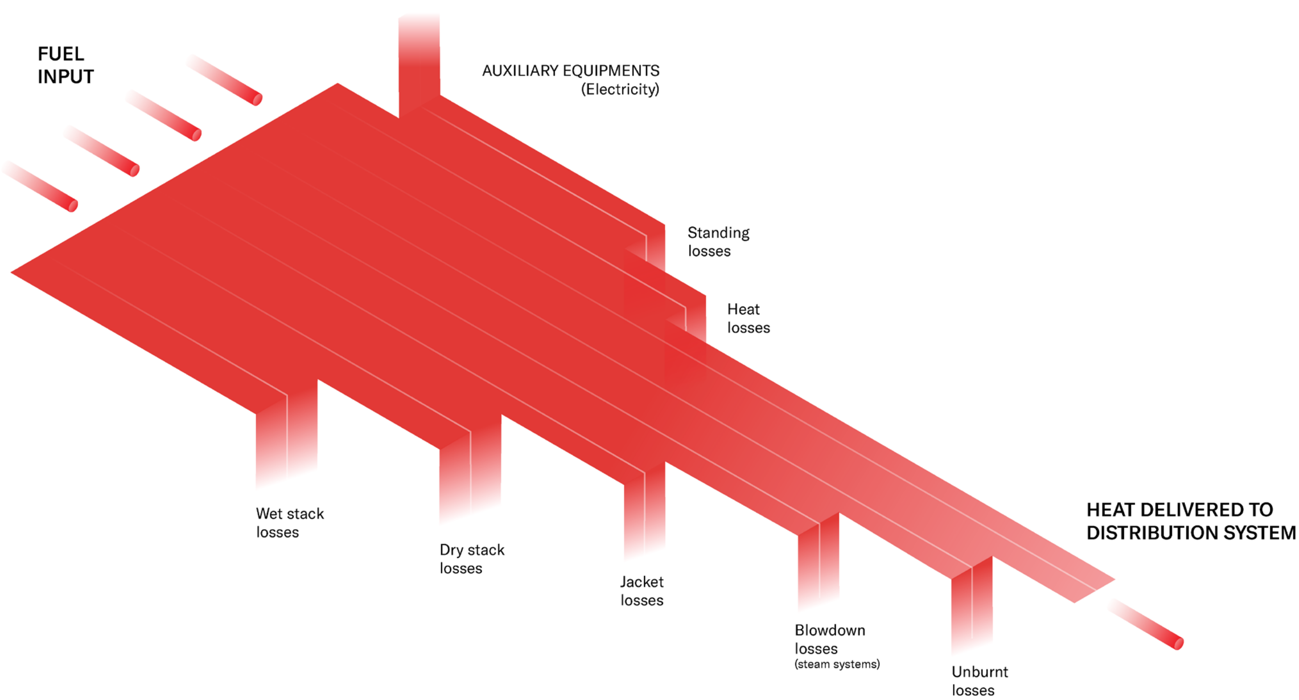
3.1 Boiler Plant Systems [7]

Generating steam and hot water for space heating and process requirements, the boiler plant is the largest consumer of energy in most built environments. Fuel is the major energy input, which the burner mixes with air in a combustion process that produces heat. This heat is then transferred to the system's major energy output, either steam or water. The system may also have a minor electrical input to operate auxiliary equipment, like blowers.

In terms of thermal output, boilers usually operate during their lifecycle at partial load, producing only a fraction of their maximum output. Therefore, "the efficiency of a boiler varies significantly with load. Consequently, it is important to evaluate boiler plant performance and efficiency over the range of actual or partial loads that the boiler experiences [7]."

Boiler efficiency depends on maintaining the optimum fuel to air ratio. Failing to maintain the proper ratio leads to significant energy losses as shown in Figure 2: for example, "a lack of air leads to incomplete combustion, resulting in losses of combustibles in the flue gas, [and] excess air needlessly increases the dry flue gas losses [7]." Another source of potential energy loss in a boiler plant system is related to the temperature of the flue gas, which depends on the effectiveness of the heat

Figure 2: Sankey Diagram of Losses in Boiler Plant Systems [7]



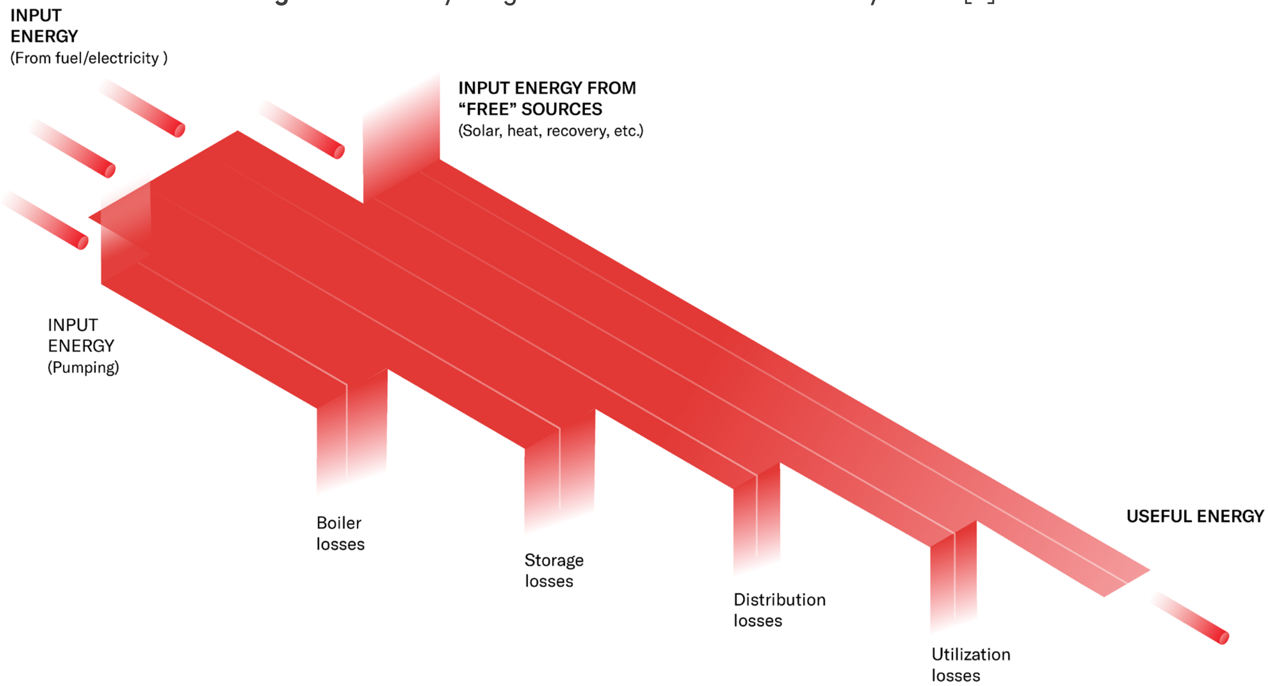
transfer in the boiler. So, flue gas temperature is an excellent indicator of the level of performance of the internal transfer surfaces.

3.2 Hot Water (HW) Systems [7]

Central Hot Water (HW) systems can have the same energy sources as regular boilers, including gas, oil, electricity, and biomass, or can also use other sources like solar, recovered waste heat, and heat pumps. Regardless of the source, the production losses within HW systems are the same as outlined in the section above for boiler plant systems.

In order to identify energy saving opportunities in HW systems, organizations need to critically assess existing energy usage and focus on losses related to such processes as storage and distribution, as shown in Figure 3.

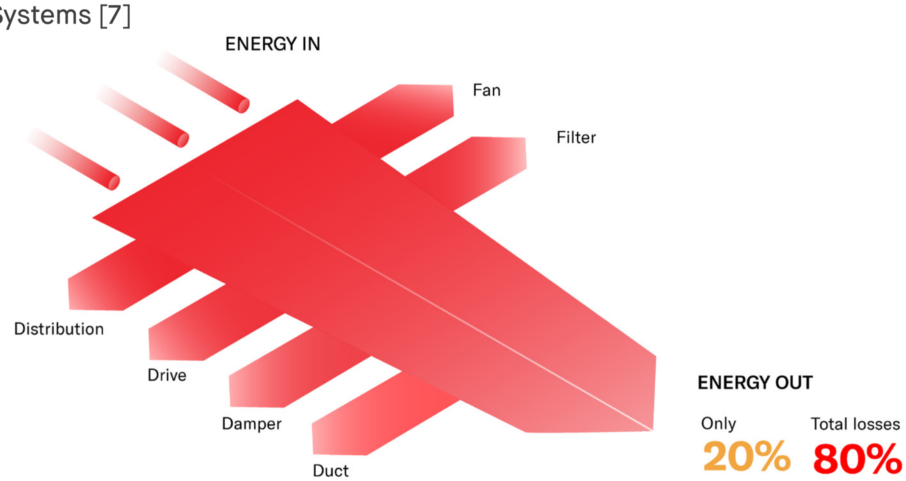
Figure 3: Sankey Diagram of Losses in Hot Water Systems [7]



3.3 Fan and Pump Systems [7]

Fan and pump systems share many characteristics; for instance, both are driven, either directly or through a belt or gearbox, by a motor. This means that fans and pumps can be analyzed from an energy perspective in similar ways. In terms of efficiency, "identifying energy savings opportunities in fan and pump systems involves critically assessing the existing energy use [7]."

Figure 4: Sankey Diagram of Various Losses from Fan and Pump Systems [7]

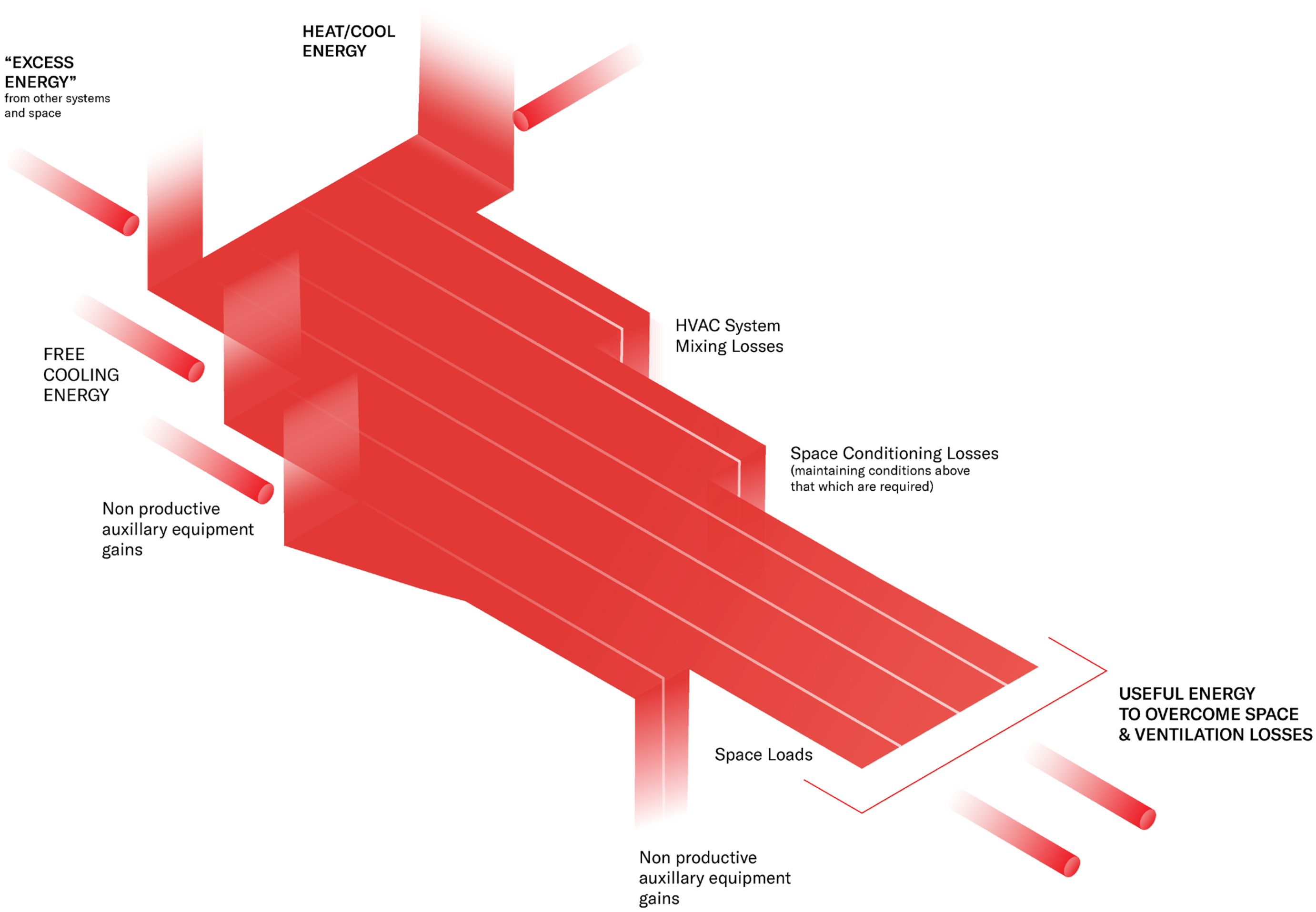


3.4 Heating, Ventilating and Air Conditioning (HVAC) Systems [7]

Because HVAC systems have a wide range of operating modes that depend on various factors, including outdoor ambient conditions and occupancy schedules, ensuring efficient processes depends on "a good understanding of how a system is designed to operate as well as how it is operating [7]." To evaluate the performance of an HVAC system in many different operating conditions, organizations should analyze "historical operational information from logbooks or conduct interviews with operators [7]."

Simply restoring an HVAC system to its design conditions is one way to achieve substantial energy savings. But, "the greatest savings in HVAC systems can be attained by matching the conditioning of the space to occupancy (schedules and levels). This is generally accomplished by system scheduling and control, preferably by means of closed-loop (feedback from the space and outside air) control strategies [7]."

Figure 5: Sankey Diagram of Various Losses from HVAC Systems [7]

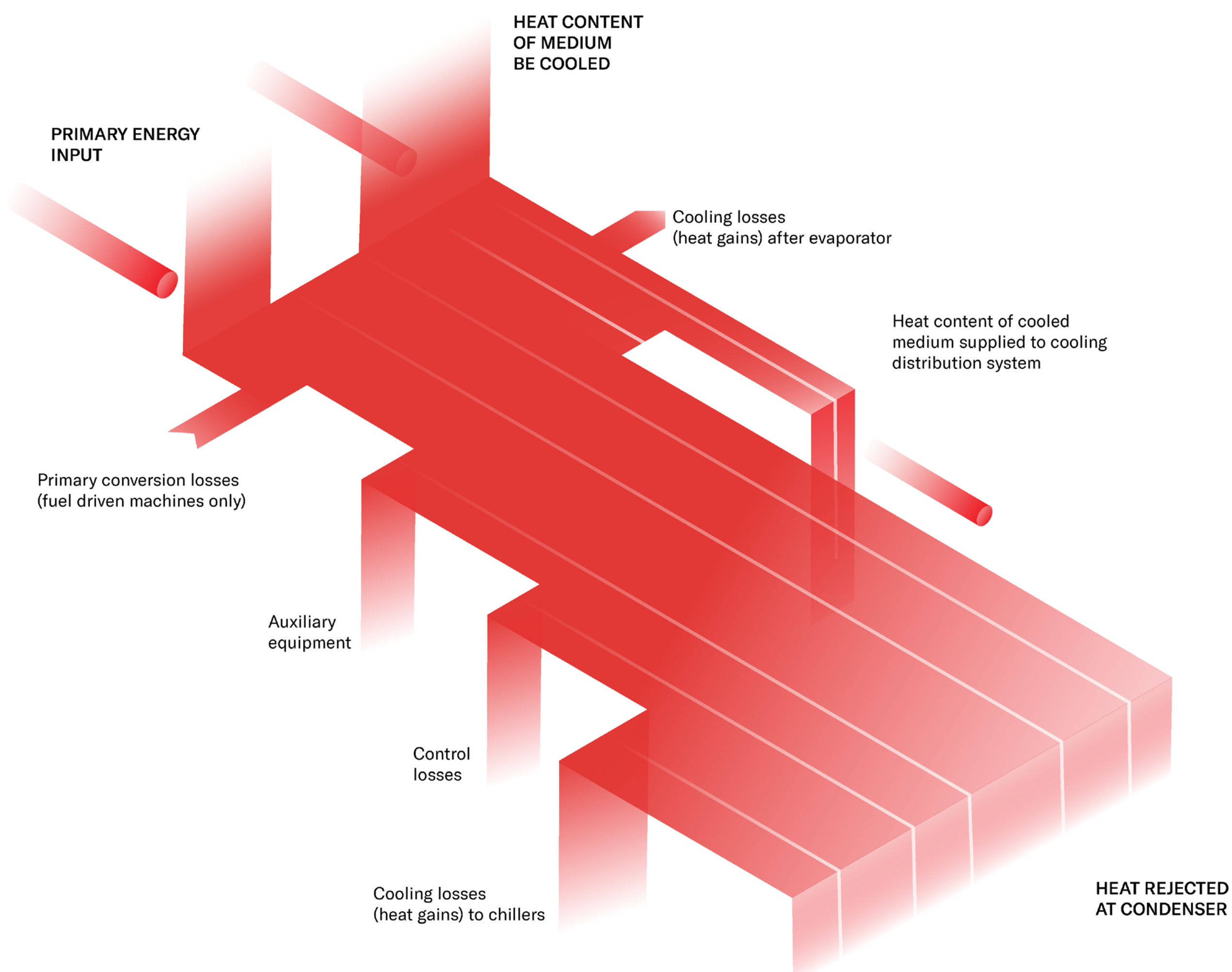


3.5 Refrigeration Systems [7]

Operating conditions have a significant effect on the efficiency of refrigeration systems. While typically rated for a maximum cooling load, these complex systems often operate for the duration of their lives at partial load, producing only a fraction of their design output. In addition, since the efficiency of a refrigeration system depends on load and on the capacity control method being used, "it is important to evaluate system performance and efficiency over a range of actual loads [7]."

When evaluating refrigeration systems, it is also important to understand that "the energy required to run a cooling system is proportional to the temperature difference between the heat source and the heat sink. Therefore, reducing the temperature difference between the cooling medium (e.g. refrigerated storage) and the condensing (e.g. cooling tower) temperature has a substantial effect on the energy input to the system [7]." There are a number of different measuring devices, including a wattmeter, thermometer, or pressure gauges, that can be used to evaluate the cooling efficiency of refrigeration systems.

Figure 6: Sankey Diagram of Various Losses from Refrigeration Systems [7]



3.6 Steam and Condensate Systems [7]

Boiler systems commonly use steam to distribute heat to its destination or end use. The process begins once steam is generated in the boiler and is then "delivered under pressure to the load by the steam distribution system [7]." At this point in the process, "the latent heat in the steam is typically converted in a heat exchanger and the steam is condensed (returned to a liquid state). This hot condensate is returned via the condensate return system to the boiler make-up water to be reheated and start the cycle again [7]." In some steam and condensate systems, no condensate is returned to the boiler because live steam is injected directly into the process.

The most common losses in these systems are "steam leaks, including stuck-open steam traps and poorly insulated or uninsulated pipes [7]." This means that optimizing the process comes down to finding ways to minimize losses while getting the steam to its destination and the condensate back to the boiler.

4.0 Building Management Systems (BMS) and Energy Inefficiency

Today, the operation and maintenance of most large buildings are performed using BMS. By considering an HVAC system as a collection of independent pieces of mechanical equipment, these systems provide operators with clear and accurate data about equipment operating conditions. **However, because the BMS market focuses on optimizing the performance of individual pieces of equipment instead of on energy flow and loss, these systems fail to achieve truly significant gains in energy efficiency.** In fact, our own research, which we have been conducting for the last 10 years, shows that BMS solutions still release more than 50% of the thermal energy produced in a building into the environment.

In the last ten years, the HVAC industry has tried to address BMS inefficiency by deploying variable frequency drives (VFDs). These devices make it possible to vary the operating speed of equipment in order to benefit from the savings that can be achieved by running equipment at partial loads. And, using new control methods, all the equipment in an HVAC system can be optimized by networking them and then "intelligently matching air temperature requirements to equipment speeds [5]." Unfortunately, buildings optimized using a BMS and VFDs fail to maintain their promised efficiency over time and experience drift, which leads to higher energy use and increased maintenance costs.

Commissioning can improve efficiency in the short-term. Our research shows that, through physical inspections and maintenance, commissioning can increase building operating efficiency anywhere from 5%-20%. But it works by focusing only on a single point in time, meaning that, even if constantly maintained at the highest levels, these buildings will experience drift until re-commissioned. It also misses many opportunities for optimization related to weather condition considerations since commissioning summarizes weather conditions in a seasonal schedule instead of in real time.

5.0

Re-thinking Building Management: The Next Disruptive Innovation

Disruptive innovations, like the iPhone, have the capacity to radically transform industries and markets. The most recent disruptive innovations for the building industry were the invention of the elevator in 1851 and the thermostat in 1883. The former introduced vertical construction to building construction, and the latter signaled the beginning of building automation.

Dynamic modulation systems driven by Artificial Intelligence (AI) engines are the next disruptive innovation in the building industry. The traditional approach to building management has been to add intelligence to the different control systems in a building. However, these existing systems remain isolated and do not work together. By combining these systems with the outside environment and occupant behaviors, dynamic modulation represents an important paradigm shift in the world of building management by bringing together the Internet of Everything (IoE) and AI.

The first step towards implementing dynamic modulation is to use non-expensive edge computing to harness data from every chiller, boiler, and pump as well as from an entire array of control points. Similar technology is already being used to collect data from such devices as cars and aircrafts. But, in its raw state, this data is not useful, so the next step is to refine it using AI tools to ensure that the output can be used to perform dynamic modulation on the energy flow in a building. Following this methodology, the dynamic optimization of a building can be achieved using real-time environmental conditions and its internal load, making it possible to maintain the optimal positioning of all mechanical systems 24/7.

In fact, results obtained from our pre-commercialization clients show that small facilities can cut total energy use from 25-35% by using the existing data available in their buildings to manage different systems in real time. By combining this data with AI engine and current advances in computing, dynamic modulation could reliably yield savings of up to 50% for all major HVAC sub-systems—regardless of equipment brand, control system (BAS), setting, or complexity.

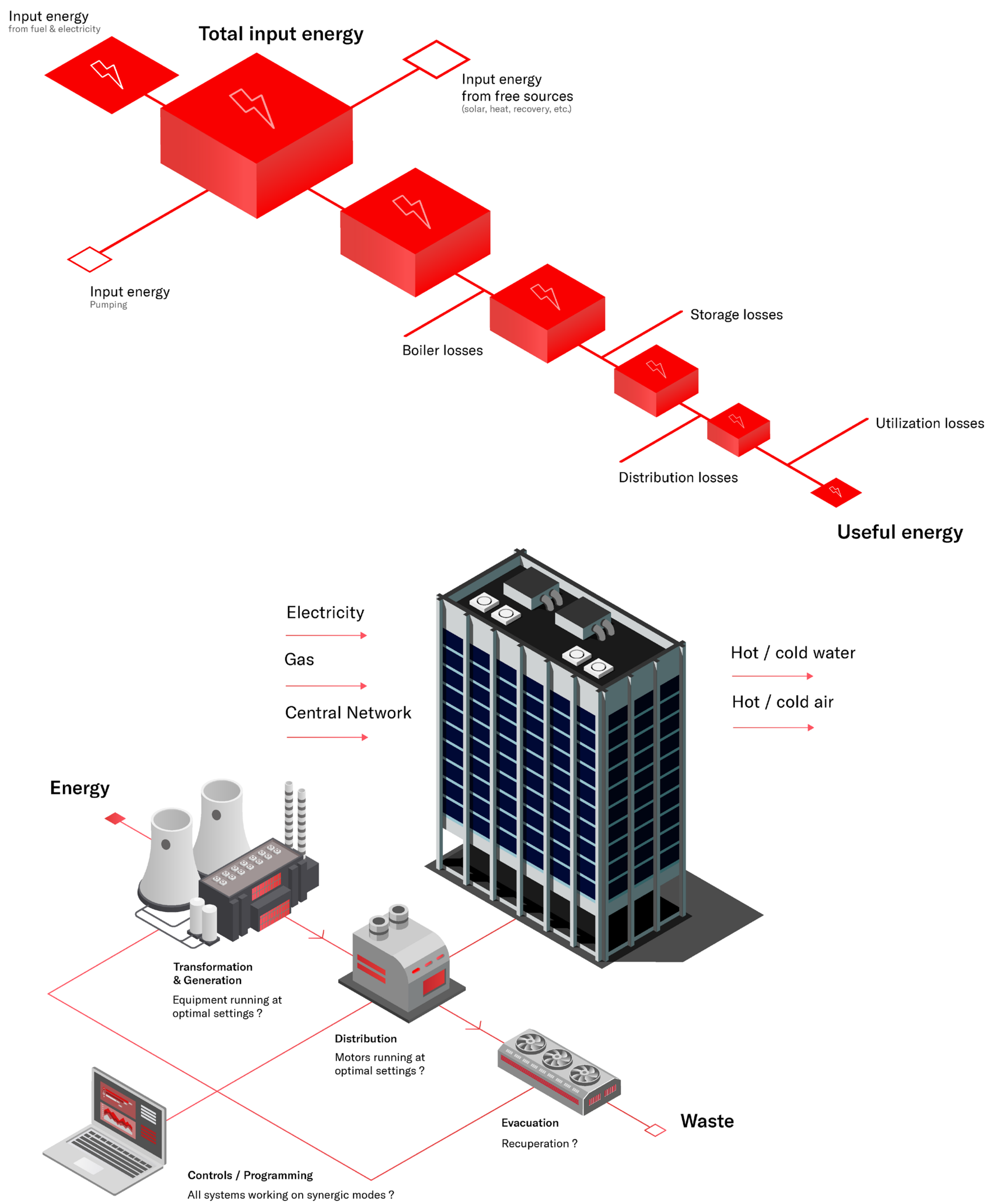
5.1 The Dynamic Thermal Equilibrium Process [7]

Effectively managing the thermal equilibrium of a building using dynamic modulation is a complex process that requires continuously optimizing energy flow to ensure occupant comfort and maximum energy efficiency. In addition to understanding how much energy flows in and how much is lost due to leakage, maintaining a building at equilibrium also requires understanding how various factors that impact energy flow change over time, including occupancy, weather conditions, and demand. Figure 7 illustrates the complexity of the process.

The dynamic thermal equilibrium process is based on an understanding of the built environment as an ecosystem of interdependent systems. In order to maintain energy balance, you need to calculate all of the energy flowing into the building, including purchased energy and appliances, lighting, and people, and balance those inputs with thermal losses due to such factors as ventilation and infiltration as well as drain water. Since these factors are dynamic, not static, the thermal equation for a building—and each building has its own unique equation—is constantly changing as conditions change. To effectively maintain a building at equilibrium, you would also need to predict how these inputs and outputs change over time and ensure that all systems react to these predicted changes in the best possible way.

Because of its complexity, managing the energy equilibrium of a building manually is far too complicated. But it is perfectly suited for AI. Other industries are already using AI to help improve the safety or efficiency of various processes traditionally

Figure 7: The Dynamic Thermal Equilibrium Process in the Built Environment



undertaken by individuals; for instance, airlines are now relying on AI to fly their airplanes, and, in the field of medicine, AI is proving to be better than doctors at detecting the presence of cancer in patients. In the built environment, significant efficiency gains can be achieved by implementing a dynamic thermal equilibrium process using AI as the driver. The potential energy savings that can be unlocked from a building's existing HVAC equipment by using AI are well above 30% of HVAC energy consumption. In addition to making buildings more environmentally-friendly, this approach creates value by saving money and also reduces occupant complaints, equipment alarms, and periodic re-commissioning.

The use of AI to manage the dynamic thermal equilibrium process signals the beginning of a new era in building management. Instead of relying on human engineers, this approach uses AI algorithms to holistically optimize all the equipment within an all-variable flow HVAC system (chillers, fans, pumps, etc.). These algorithms use the least amount of power required to maintain occupant comfort levels with control set points being automatically calculated based on real-time building load information inputs and the weather conditions prevailing outside of the building. The result is a global thermal load management strategy for a building instead of one focused on managing equipment.

This approach works because the advanced control AI algorithms match the weather pattern with the thermal load requirement of a building in real time. This layer of dynamic algorithms, together with deep learning engines, manages energy demand by first analyzing building occupancy, the thermodynamic patterns within the built environment, and the outside weather conditions. The heating and cooling of different zones in the building are then adjusted to the optimal levels in real time, resulting in significant reductions in energy per thermal ton ratio.

So, regardless of the type of building or facility, AI can monitor the different parameters for all equipment and sensors in order to deliver continuous, automatic adjustments to the system based on the building's load. The goal is to generate:

- energy usage savings (kWh/yr.),
- demand savings (kW),
- heating/cooling load (Therms),
- cooling tower water usage savings (gal/yr.),
- carbon footprint reductions (lbs./yr.), and
- Power Usage Effectiveness reductions (PUE).

In addition to achieving greater energy efficiency and reducing a building's carbon footprint by 20-40%, these algorithms also provide real-time system adjustment recommendations, identify operational inefficiencies, and perform building re-commissioning 24/7, 365 days a year.

6.0 Conclusion

BrainBox AI is the future of building automation. We have developed an AI-driven dynamic thermal equilibrium process that enables you to achieve thermal balance performance levels in your buildings. Using deep learning, cloud-based computing, and our proprietary process, our solution optimizes existing HVAC control systems for maximum impact without human intervention.

In our next white paper, we will explore how, using AI to predict future changes in energy flow, our dynamic thermal equilibrium process allows you to maintain energy balance by transforming the future into what you want it to be.

Interested in learning more? Visit our website
www.brainboxai.com

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