Introduction: Analysis & Modeling of Energy Systems

"The best thing to do is start simply and then build in complexity. Do the dumbest thing you can think of first."
— O'Neil and Schutt [3]

1 Analyzing energy systems

In an excellent book called *How to Solve It* [2], G. Polya presents a very general approach that can be applied to the analysis of energy systems. [My comments in brackets]

First You have to *understand* the problem. [2] [No small feat for complex energy systems!]

Second Find the connection between the data and the unknown . . . You shoud obtain eventually a *plan* of the solution. [2] [If that connection isn't there, it's time to back up to your data search or collection process.]

Third *Carry out* your plan. [2] [And *evaluate* your progress as you go.]

Fourth *Examine* the solution obtained. . . . Can you *check the result*? [2] [Verification/validation often require critical thinking and creativity.]

2 Working energy system problems

Many of the same techniques that are good for tackling thermal-fluid science or problems will be effective at energy systems problems.

1. Identify the system of interest.
2. Define the question you want to investigate.
3. Determine what you could measure or evaluate to address your question.
4. Determine the level of detail to start with according to the temporal and spatial dimensions of interest.
5. Decide what to measure or evaluate, starting with the simplest option(s).
6. Apply relevant methods for your model or experiment.
7. Assess what you've learned from the model or experiment.
8. Revisit the question you defined, considering whether you want to change it or investigate further.
9. Reassess the level of detail and methods, considering whether you've adequately answered the question.
10. Explain your results, documenting your methods and the analytical process itself.

The fundamental equations guiding the behavior of energy consuming or energy conversion devices often boil down to the first and second laws of thermodynamics. But the fundamental concepts of systems problems are not quite so clear–often the behavior of a number of things working together is not an obvious combination of anything.

I like the quote above ("do the dumbest thing") because they're poking a little fun at us, and engineers or scientists often seem to get ahead of ourselves. I find that often when students say, "I don't know what to do" they actually do have ideas, it's just they're not convinced they're right.

Starting with something that seems dead simple or obvious may give you a concrete starting point for your analysis or optimization, or may leave you with a new understanding that you couldn't have gained without actually trying something yourself. This holds true for building things, experimentation, analytical work and model creation as well.

3 Creating models of energy systems

In his classic modeling text *Mathematical Modelling Techniques*, Rutherford Aris defines a *mathematical model* as "any complete and consistent set of mathematical equations which is thought to correspond to some other entity." [1] Like Aris, we will abbreviate 'mathematical model' to simply 'model' and in this course, we will often be referring to a model that is implemented computationally, where the model is some combination of code and data structures.

> The formulation of the equations of a model is usually a matter of expressing the physical laws or conservation principles in appropriate symbols. [1]

In creating (or 'formulating') a model, we will be concerned with the behavior over time of systems based on the equations governing energy and mass conservation and, to a lesser extent, entropy generation, as these laws describe the conversion of energy and the performance of engineered systems that convert or store energy.

4 Integrated analysis method

(i) Identify the system of interest.

(ii) Define the question you want to investigate.

(iii) Determine what you could measure or evaluate to address your question.

(iv) Determine the level of detail to start with according to the temporal and spatial dimensions of interest.

(v) Decide what to measure or evaluate, starting with the simplest option(s).

(vi) Apply relevant methods for your model or experiment.

(vii) Assess what you've learned from the model or experiment.

(viii) Reassess the question you defined, considering whether you want to change it or investigate further.

(ix) Reassess the level of detail and methods, considering whether you've adequately answered the question.

(x) Explain your results, documenting your methods and the analytic process itself.

See Figure 1, where the iterative nature of the process is illustrated graphically.

5 Important Terms

energy the currency for work, which is a force being moved through a distance, or equivalent quantity. [Units will be force × distance (also electric charge × electric potential) or power × time.]

power rate of delivering energy. [Units will be energy ÷ time.]

validation Do my results line up with observed data?

verification Did I actually do what I think I did?

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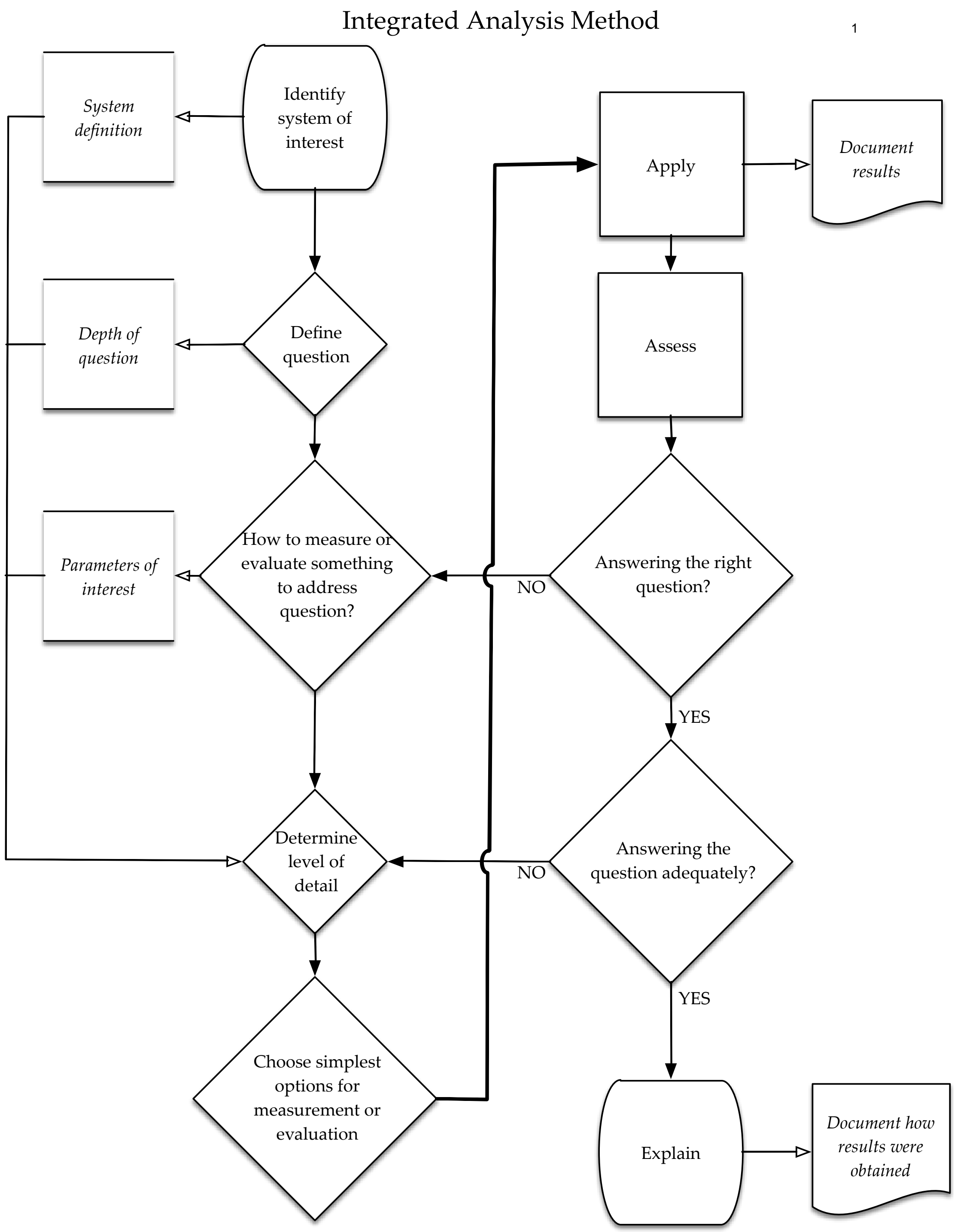

Figure 1: Integrated Analysis Method overview

Lecture 1. Sustainability, Site-Specific Design, Systems Thinking

"System thinkers see the world as a collection of feedback processes."
— Donella H. Meadows [5]

1 What is sustainability?

One of the best known descriptors of sustainability is the call for *sustainable development* from the Bruntland report [1]:

> Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainability is often presented as an umbrella term for a set of concerns about the work that we do, encompassing three pillars or dimensions of the world:

- environmental (ecological)
- social (people)
- economic (prosperity)

Three basic definitions of the world *sustainable* are shown on Dictionary.com [11]:

1. "capable of being supported or upheld..."
2. "pertaining to a system that maintains its own viability..."
3. "able to be maintained or kept going..."

As engineers, designers, or other professionals, and as human citizens of the world, we must think carefully and critically to decide for ourselves what *sustainability* means and what it looks like in our work and all of our daily interactions.

2 What is site-specific design?

In my own research group:

> *Site-specific* means that we think about the unique aspects of a particular place or facility and how they relate to energy demands and energy conversion options. [8]

Therefore, site-specific does not mean restricted to a narrow system boundary at a given site, but rather that the analysis of a system recognizes that it is uniquely integrated with other systems (physical, social, economic, or other) based on its location in space-time. Site-specific *design* means that the actions we recommend affecting a particular place or facility are evaluated within this context.

3 What is systems thinking?

In a review paper called "What is Systems Thinking?", Monat and Gannon tackle the question, although they do not arrive at a single normative definition. Critically, they note that "Systems Thinking is a perspective, a language, and a set of tools. [6]" They pivot to framing systems thinking largely in terms of what it is *not*:

> Systems Thinking is the opposite of linear thinking; holistic (integrative) versus analytic (dissective) thinking; recognizing that repeated events or patterns derive from systemic structures which, in turn, derive from mental models; recognizing that behaviors derive from structure; a focus on relationships vs components; and an appreciation of self-organization and emergence. [6]

In this course, we will attempt to move toward *integrative* thinking by taking a broader perspective on energy systems and taking a greater interest in *relationships* between parts of an energy system, and between energy systems and the surrounding ecological, economic, and societal structures. We will take a broad view of *structure*, meaning not only the shape and placement of matter but rather the way that things are arranged with respect to other things. We will look at *events or patterns* in time-series data and grapple with translating this into meaningful understanding. I hope that as a result you will re-examine your own *mental models* about how things work.

We will use the *linear* models we have gained in our prior educational experience, we will leverage our *analytic* thinking, and we will not forget the *components* that make up the systems we study. Systems thinking will add to, not replace, your current knowledge and cognitive skill set.

3.1 Systems thinking as a questioning mindset

Gerald Weinberg provided 3 Systems Thinking Questions [12]:

1. Why do I see what I see?
2. Why do things stay the same?
3. Why do things change?

This approach to developing a questioning mindset may seem simplistic, but it is a great place to start when you're examining something new, or attempting to examine something in a new way. If you find that it sparks even more and deeper questions, then you are doing real systems thinking!

3.2 Need for systems thinking in engineering and design

In describing a particular environmental crisis (*environment* pillar) involving public health (*society* pillar) in a remote village with limited resources (*economy* pillar), Monat and Gannon state that "What was thought to be a simple engineering problem turned out to be an engineering/socio-economic/logistics/psychological problem. [7]"

I would posit that there are likely no engineering problems which have the ability to impact life on Earth that are truly simple. It is difficult to think of a system which can be altered by engineering or design and is entirely isolated from socio-economic realities, logistics, or human psychology.

3.3 Systems engineering

Monat and Gannon describe *systems engineering* thusly:

> Systems Engineering is an interdisciplinary approach and means to enable the development of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design, synthesis, validation, deployment, maintenance, evolution and eventual disposal of a system. Systems Engineering integrates a wide range of engineering disciplines into a team effort, which uses a structured development process that proceeds from an initial concept to production and operation of a system.

Systems engineering may be studied as an area of focus and treated as its own discipline, but engineers trained in any traditional discipline can also become systems engineers.

3.4 System of systems

Systems engineers or scientists often speak of a *System of Systems* (SoS):

1. Two or more systems that are separately defined but operate together to perform a common goal. (Checkland 1999) [10]
2. An assemblage of components which individually may be regarded as systems...(Maier 1998) [10]
3. A system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems. (INCOSE 2012) [10]

We can, of course, conjure examples of a system of systems of systems, and of a system of systems of systems of systems . . . It's turtles all the way down.

The way we define what 'a system' is, and what systems interact with or comprise other systems, is a matter related to the problem of interest:

> There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion—the questions we want to ask. [5]

It is important to note that the drawing of a system boundary is an analytical or design choice. It will affect the results of our analysis or the product of our design process.

3.5 Complex systems

Many thinkers from many different disciplines have attempted to describe *complexity* as a phenomenon. Complexity theory is a field unto itself, recently popularized by Geoffrey West of the Sante Fe Institute [13]. Complexity is a major concept behind the development of computer science as a discipline [4], but *complexity science* is inherently interdisciplinary [3].

A paper presented at a systems engineering conference several years ago by Clark and Jacques states intriguingly:

> There are hints that energy plays a role in defining complexity. As a general rule, systems commonly recognized as complex process more energy than less complex ones. [2]

I might add that complex energy systems often perform energy conversion, transfer, or storage in ways that result in emergent behaviors.

The study of complex systems may also be called *systems science*:

> the field of science that studies the nature of complex systems in nature, society, and science. [9]

4 Conclusion

I hope you begin to see that buildings themselves and all of the energy conversion and storage systems that are part of the human-built environment are ripe for exploration using the concepts of sustainability, site-specific design, and systems thinking. We will return to these concepts often to frame our thinking and develop our analytical methods.

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Lecture 2. Review of General Thermodynamics of Energy Systems

"Economies, chemical reactions, ecosystems, and solar systems organize around energy gradients—natural differences in temperature, pressure, and chemistry that set up the conditions for energy flow."
— Eric D. Schneider & Dorion Sagan [3]

"Imperfection (friction, heat leaks, etc.) acts as a brake on the engines (the designs) that drive flow."
— Bejan and Zane [1]

1 First Law

First Law, Closed System:

$$\Delta E = \Delta U + \Delta KE + \Delta PE = Q - W$$

Mass Conservation:

$\dot{m} = \rho V_{avg} A$ (for uniform ρ) $\dot{V} = V_{ave} A$ General: $m_{in} - m_{out} = \Delta m_{sys}$

First Law, Open System, per unit time:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}(h + \frac{V^2}{2} + gz) \sum_{out} \dot{m}(h + \frac{V^2}{2} + gz)$$

Mass and Energy Balances, Steady State (Steady Flow) Process with negligible ΔKE, ΔPE:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

$$0 = \dot{Q} - \dot{W} + \sum \dot{m}_i h_i - \sum \dot{m}_e h_e$$

First Law Simplifications

Closed system, heat transfer at constant volume: $\boxed{q_{ab} = u_b - u_a}$

Closed system, heat transfer at constant pressure: $\boxed{q_{ab} = h_b - h_a}$

Closed system, isentropic compression or expansion: $\boxed{w_{ab} = u_a - u_b}$

(*where* a and b represent two states in the cycle.)

Open system, heat addition or rejection: $\boxed{q = h_e - h_i}$

Open system, isentropic compression or expansion: $\boxed{w = h_i - h_e}$

(*where* i and e represent inlet and exit states of a device in the cycle.)

First Law, Open System, Transient Process from state 1 to state 2 with negligible ΔKE, ΔPE:

$$(m_2 u_2 - m_1 u_1)_{system} = Q - W + \sum m_i h_i - \sum m_e h_e$$

1.1 Efficiency

First Law efficiency is a ratio between the benefit to us of a particular process (such as work) and the cost to us to run that process (such as thermal or chemical energy).

Heat Engines:
General efficiency: $\eta = \frac{W_{net}}{Q_{in}}$ Ideal cycle: $\eta = 1 - \frac{Q_{out}}{Q_{in}}$ Carnot cycle: $\eta = 1 - \frac{T_L}{T_H}$

Refrigerators:
Coefficient of performance: $COP_R = \frac{Q_L}{W_{in}}$ Ideal: $COP_R = \frac{1}{Q_H/Q_L - 1}$ Carnot: $COP_R = \frac{1}{T_H/T_L - 1}$

Heat Pumps:
Coeff. of performance: $COP_{HP} = \frac{Q_H}{W_{in}}$ Ideal: $COP_{HP} = \frac{1}{1 - Q_L/Q_H}$ Carnot: $COP_{HP} = \frac{1}{1 - T_L/T_H}$

2 Second Law

Clausius inequality: $\oint (\frac{\delta Q}{T}) \leq 0$

Reversible (Ideal) Processes and the Property Entropy
Clausius definition of entropy: $S_2 - S_1 = \int (\frac{\delta Q}{T})$ Heat transfer: $Q = \int T dS$ per unit mass: $s = \frac{S}{m}$

Irreversible (Real) Processes
$S_2 - S_1 = \int (\frac{\delta Q}{T}) + S_{gen}$ $\Delta S_{sys} = S_{in} - S_{out} + S_{gen}$ Rate form: $\frac{dS_{sys}}{dt} = \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen}$

Increase of entropy principle: $\Delta S_{sys,isolated} \geq 0$

Isentropic Efficiencies (Steady-flow Devices)

Turbines

$$\eta_t = \frac{w_a}{w_s} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Compressors and Pumps

$\eta_c = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$ $\eta_p = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \approx \frac{v(P_2 - P_1)}{w_a}$

Entropy Transfer
$S_{heat} = \int (\frac{\delta Q}{T}) \approx \sum \frac{Q_k}{T_k}$ for each location k $S_{mass} = ms$

2.1 Efficiency

Second Law efficiency is a ratio between the performance of a particular device or system and the ideal theoretical performance for the same device or system.
$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}}$ $\eta_{II} = \frac{COP}{COP_{rev}}$

2.2 Entropy generation

Entropy generation is a quantitative measure indicating how irreversible an actual process is. See Chapter 7 of [2].

Entropy Balance
Closed: $S_2 - S_1 = \sum \frac{Q_k}{T_k} + S_{gen}$

Open: $S_2 - S_1 = \sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen}$ Rate: $\frac{dS_{sys}}{dt} = \sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{gen}$

2.3 Exergy destruction

Exergy destruction is proportional to entropy generation. The difference is that it's quantifying the *lost available work*, which is a measure of the reduction in (theoretically) available work due to the condition of the system and its surroundings. See Chapter 8 of [2].

3 Heat Transfer

Energy transferred due to a temperature difference falls under the category of heat transfer. I will assume you have familiarity with the basic modes of heat transfer (conduction, convection, and radiation) along with the fundamental equations describing them (Fourier's Law, Newton's Law of Cooling, Stefan-Boltzmann Law). This basic material is summarized in this video from LearnChemE: https://youtu.be/NwOZ1tSe9hs.

For students who have not yet taken a heat transfer course, or those who want to refresh, I recommend:

1. Read the Topic of Special Interest section called "Mechanisms of Heat Transfer" at the end of the second chapter of our undergraduate thermo text [2].
2. Familiarize yourself with the idea of view factors as described in this video from LearnChemE: https://youtu.be/UIfRBB49MC4.

To begin connecting heat transfer concepts with building science, I recommend that you view this video on solar orientation from Solar Schoolhouse: https://youtu.be/OR8EQ0DWpPw.

4 Fluids

Energy and mass transferred due to fluid movement fall under the category of fluid mechanics. I will assume you have familiarity with the basic characteristics of a fluid and are able to formulate a control-volume analysis for a system with fluid flows. This basic material is summarized in this video from LearnChemE: https://youtu.be/-1DVqWmZ9tU. A simple control-volume mass conservation problem (solving for flow rate) is solved in this video from Water and Wastewater Courses: https://youtu.be/CzyWNamGizA.

Fluids are used to transfer energy to, from, and within buildings, primarily using just a few common fluid types:

- air
- water
- refrigerants

To begin connecting fluid flow concepts with building science, you will be assigned in the future to watch a video on HVAC systems from our first guest speaker, professional engineer Jane Guyer (https://youtu.be/Kt1j_aAApwg).

5 How thermodynamics affects energy systems analysis

The conservation laws that express the First Law and the limitations imposed by the Second Law are critical to include in a physics-based analysis. Energy conversion also has implications for the way that humans interact with energy systems, for the financial costs and benefits of energy systems, and for the environmental impacts of energy systems.

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Lecture 3. U.S. Energy Sector, Power Generation, and Built Environment

"We consume electricity, transportation, and heat, not coal, nuclear, or solar power. And we want energy delivered with certain attributes—namely, energy that is inexpensive, dependable, and safe. To the typical American, even to most U.S. companies, the energy choice is not really about the fuel used."
— Stephen Ansolabehere in *Cheap and Clean* [1]

1 U.S. Energy Sector

The **primary energy** sources in the U.S. are:

- fossil fuels (petroleum, natural gas, coal);
- uranium (nuclear fuel);
- biomass (plant- and animal-derived fuels); and
- water, wind, sun, and geothermal resources;

and the use of energy falls into four main sectors (in addition to the electricity generation sector, which itself serves each of the four sectors listed below):

- transportation,
- industrial,
- commercial, and
- residential.

You can see the most recent estimates for U.S. energy use, and which sectors it went to, in the famous Sankey diagram published by Lawrence Livermore National Lab [7], shown in Figure 1.

Remember from thermodynamics that 100% efficiency is often not possible, even with theoretically perfect devices (e.g. a Carnot engine), so "rejected energy" does not necessarily mean "wasted energy" and does not even necessarily correlate to lost available work (inefficiencies). The flows from left to right on this diagram represent many types of thermodynamic processes and devices: combustion, nuclear fusion, heat engines, electrochemical energy conversion, electromechanical energy conversion, and many more. They often include combinations of multiple energy conversion processes, for example: natural gas combustion (blue box on the left, Fig. 1) to create electric power (orange box, Fig. 1) to charge an electric car battery and eventually run its motor for personal transport (pink box on the bottom right, Fig. 1).

2 Power Generation

"America isn't making electricity the way it did two decades ago."
— Nadja Popovich in the New York Times [9]

Electric power produced in the U.S. still comes mostly from natural gas, coal, and nuclear plants. In general, we can categorize these electricity generation facilities as

- **thermoelectric** power generation (coal-fired, gas-fired, and nuclear),
- **hydroelectric** power generation, and
- other renewable/alternative forms of power generation (solar PV, solar thermal, wind, biomass, and others).

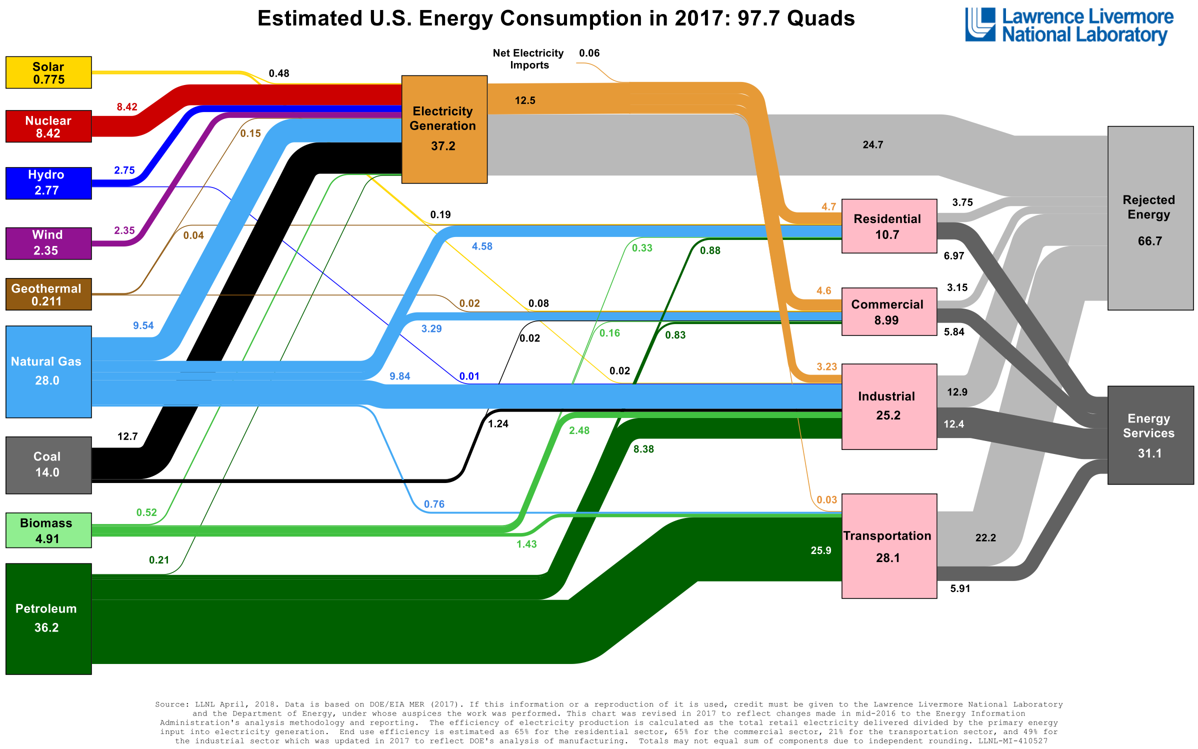

Figure 1: U.S. energy flow chart for 2017 from LLNL [7]

Hydropower, wind, and solar are the next largest contributors to U.S. electricity generation, though relatively small compared to gas, coal, and nuclear. What is *not* reflected in Figure 1 (2017) is that natural gas was estimated to have contributed to more electricity generation than coal as of last year (2018). The use of natural gas has increased somewhat steadily since 2013, while coal plants are being retired and little to no new coal-fired generation is coming online. The makeup of generators serving the grid is changing rapidly. Explore interactive graphs from the U.S. Energy Information Administration (EIA) for yourself at `https://www.eia.gov/electricity/data/browser/`.

2.1 International

Worldwide, most electricity generation comes from from coal, with natural gas gaining very quickly and poised to overtake coal soon. Other significant power sources are: hydro, wind, nuclear, and solar PV [13]. Explore interactive graphs from the International Energy Agency (IEA) for yourself at `https://www.iea.org/weo/`.

A large portion of the power generated in the world comes from the Organisation for Economic Co-operation and Development (**OECD**) countries (over 10,000 TWh in 2015 [3]), which include the U.S., Canada, and Mexico; the United Kingdom; many EU member states (e.g. France, Germany, Italy, Switzerland); Australia and New Zealand; Japan and Korea [6]. China alone forms the next largest portion of worldwide power generation (almost 6,000 TWh in 2015 [3]).

2.2 Utah

From the recent article "How does your state make electricity?" [9]:

> The majority of electricity produced in Utah comes from coal, but coal's share has declined over the last several years as natural gas has increased.

> The state produces more energy than it consumes and sends the surplus to nearby states like California. At least one Utah power plant [5] is switching from burning coal to natural gas to comply with California's stricter environmental regulations.
>
> Solar power grew to become the largest renewable generation source in the state in 2016 [14] and expanded its share again last year. Utah has set a goal for utilities to get 20 percent of the electricity they sell from renewable sources by 2025 [11].

Note that the second paragraph describes Utah as a **net exporter** of electrical power.

2.3 Electrical transmission & distribution

The electrical grid is a complex system-of-systems that comprises physical assets, economic systems, and coordinated networks for communications and operations. It's worth an entire course in and of itself; we have several excellent offerings available through the Department of Electrical & Computer Engineering. You should view the infographic and brief web page at `https://www.energy.gov/articles/infographic-understanding-grid` to familiarize yourself with the big picture if you have not had exposure to the structure and workings of 'the grid' before.

There are a few key divisions within the electricity sector as electrical power makes its way to the end user:

- **generators** (as we have described in this section up to this point);
- **transmission** lines and equipment (high voltage), large and tall structures that move high quantities of power over long distances; and
- **distribution** lines and equipment (lower voltage), usually closer to the ground (and in some places, below ground), that move smaller quantities of power to (or close to) the end user.

There are three main transmission networks across the U.S.:

- Western Interconnection (including Utah),
- Eastern Interconnection, and
- Electric Reliability Council of Texas (ERCOT).

The state of Hawaii is, as you might imagine, on its own, with unique geographical challenges [10].

3 Built Environment

Buildings and facilities are typically divided into three main sectors:

- industrial,
- commercial, and
- residential.

The EIA publishes estimates of energy use in the U.S. in three major survey efforts:

- Manufacturing Energy Consumption Survey (MECS) [8]
- Commercial Building Energy Consumption Survey (CBECS) [2]
- Residential Energy Consumption Survey (RECS) [12]

These surveys provide thorough and detailed estimates based on extensive data collection and processing, but new releases are years apart and therefore they may not have the most up-to-date information.

In this class, we will focus on commercial and residential buildings when we study energy use in the built environment. We all interact with both commercial and residential buildings daily, unless we are fortunate enough to be out on a multi-day camping trip or unfortunate enough to be without a home or shelter. The most recent estimate from the EIA states: "In 2017, about 39% (or about 38 quadrillion British thermal units [quads]) of total U.S. energy consumption was consumed by the residential and commercial sectors." [4]

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Lecture 4 was a video lecture and Lecture 5 was prepared by a guest lecturer. No notes are provided here.

Lecture 6. Energy Evaluation of Building Systems, Modeling Tools

"Systems thinkers use graphs of system behavior to understand trends over time, rather than focusing attention on individual events."
— Donella H. Meadows in *Thinking in Systems* [8]

1 Energy Evaluation of Building Systems

1.1 Pre-Occupancy

1.1.1 Integrated Design Process

In a conventional design process, the client and the architect will begin the design of a building or retrofit project, and the mechanical and electrical engineers may be brought into the process after many important decisions that affect the building's energy systems have already been made. Taking the systems perspective, where interrelationships and interconnections are key to understanding system behavior, the conventional design process can clearly lead to suboptimal decision making at the system and subsytem levels. As Larsson points out in a brief paper outlining the integrated design process, "the resulting poor performance and high operating costs [resulting from a conventional design process] will most often come as a surprise to the owners, operators or users." [7]

An integrated design process, in contrast to the conventional design process, will bring energy evaluation into the design process as early as possible. A range of evaluation options, from simple spreadsheet calculations to fully parameterized whole building energy simulations, may be used at different stages during the design process.

1.1.2 Commissioning

The Whole Building Design Guide published by the National Institute of Building Sciences defines **commissioning** (Cx) in this way:

> Building Commissioning is the professional practice that ensures buildings are delivered according to the Owner's Project Requirements (OPR). Buildings that are properly commissioned typically have fewer change orders, tend to be more energy efficient, and have lower operation and maintenance cost. [2]

They also point out that commissioning is especially likely to yield benefits when buildings are complex [2]. Studies by U.S. national labs indicate significant savings potential from commissioning projects, with an LBNL researcher calling commissioning a "stealth energy saving strategy" and "CSI for energy" [9].

Commissioning a building is a formal practice and there are established guidelines and standards from ASHRAE for how to properly conduct a commissioning project. It may be undertaken to help the building owners obtain a performance rating like a LEED certification, in addition to potentially improved performance with lower costs. Commissioning is its own domain of expertise, with a unique body of knowledge and practices developed among the practitioners. The practitioners may be certified by a professional association lfike the Building Commissioning Association and are referred to as commissioning agents (CxA) or commissioning practitioners (CxP).

1.1.3 New Building Commissioning

Typically, when people talk about a commissioning project, they are referring to a process that is undertaken after the building is constructed but before it is occupied. This may not be a clear line—for example, in 2014 I moved into my current office in MEK on the south hallway (Phase 1) while the north side and middle part of the first floor were still under construction (Phase 2).

1.2 Post-Occupancy

1.2.1 Retrocommissioning

Retrocommissioners use many of the same tools and skillsets to commission buildings that are already in operation. The California Commissioning Guide for Existing Buildings describes the purpose of **retrocommissioning** this way:

> Retrocommissioning is a process that seeks to improve how building equipment and systems function together. [5]

If a building has already been through a formal commissioning process, people would typically refer to the subsequent commissioning as **recommissioning**.

1.2.2 Ongoing Commissioning

Maybe 20 years ago, the building energy community began a serious push for ongoing commissioning—meaning, in its broadest sense, a commissioning program that isn't limited to a (series of) site visit(s) or a defined window of time, but rather is designed to assess and impact the building or facility on a continuous basis.

A useful ongoing commissioning program will include "planning, point monitoring, system testing, performance verification, corrective action response, ongoing measurement, and documentation to proactively address operating problems in the systems being commissioned." [11] It must be integrated with the energy management program for the facility and requires buy-in from a larger group of stakeholders (i.e. anyone involved with operating the building day-to-day) than a new building or retrocommissioning project would require.

Continuous Commissioning®is a term registered by the Texas A&M Energy Systems Laboratory, who describe it this way:

> CC® is an ongoing process to resolve operating problems, improve comfort, and optimize energy use for existing commercial and institutional buildings and central plant facilities. [6]

1.2.3 Measurement & Verification

The U.S. Department of Energy (DOE) has taken some leadership in pushing for established standards for evaluating programs designed to alter (hopefully decrease!) building energy use, particularly energy efficiency measures [10]. In a 2015 report on **measurement & verification (M&V)** guidelines, they define it in this way:

> M&V is the process of quantifying the energy and cost savings resulting from improvements in energy-consuming systems. [10]

They also recognize that obtaining accurate, reliable, actionable M&V information is a trade-off:

> The challenge of M&V is to balance M&V costs with the value of increased certainty in the cost savings. [10]

They then frame the underlying concept as an equation:

$$Savings = (BaselineEnergy - PostInstallationEnergy) \pm Adjustments$$ [10]

Energy **savings** are what we're after. The goals for the project should be quantified, meaning we'd like a picture of where we will end up.

Baseline energy is the energy use associated with the unmodified building. It's like finding the blue dot on your Google Map to get your bearings before you start navigating. Responsible energy efficiency engineers will seek to establish a good baseline—that is, understanding the behavior of the current building as well as they can, and gathering data that will be appropriate to the evaluation they want to conduct.

Post-installation energy is just what it sounds like—the energy use associated with the modified building. It's important to quantify this, ideally using the same type of data used to establish the baseline. It's also normal that more changes are made for a period of months after energy-consuming systems in a building have been changed.

"Adjustments" can be anything else that, according to engineering judgement, should be used to alter the quantified savings. This could mean adjusting for a change in the number (or schedule) of occupants in the building, for an increase in plug loads, or for weather differences during the periods of data collection.

2 Modeling Tools for Building Energy Systems

2.1 Building Energy Modeling

A **building energy model** (BEM) generally refers to a computational representation of a single building or narrowly defined site that captures key features influencing energy performance. A building energy simulation program refers to the computational software that calculates energy use (and often other performance-related quantities like water use, emissions production, or operational costs).

On the DOE's Building Energy Modeling page, they introduce the topic this way:

> Whole-Building Energy Modeling (BEM) is a versatile, multipurpose tool that is used in new building and retrofit design, code compliance, green certification, qualification for tax credits and utility incentives, and real-time building control. [3]

You may also see the related term **building information model** (BIM), which refers to "a digital [typically 3D] representation of physical and functional characteristics of a facility [that] serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle." [4] Energy modeling capabilities are therefore a necessary part of any useful BIM.

2.1.1 Multi-Building Energy Modeling

There is an interesting and fairly new development in the building energy simulation world, which is to go beyond single building energy models entirely, considering them as subsystems within a larger surrounding environment. This is made possible by increasing data availability and computing power, and falls under the larger (and not yet formally defined) heading of multiscale building energy modeling.

There are a few key challenges that commonly appear in modeling a district, city, or region of buildings:

- Computational time and complexity
- Engineering labor to gather and process appropriate data
- Inadequate available data or heterogeneous data

Leaders in the emerging field of urban-scale BEM include Oak Ridge National Laboratory; University College London; and Big Ladder Software, who have published part of their toolkit for creating templates for building energy models in a freely available framework called ModelKit [1].

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Lecture 7. Sustainable and Ecological Design

"Look around you: I mean it. Pause, for a moment and look around the room that you are in. I'm going to point out something so obvious that it tends to be forgotten. It's this: that everything you can see, including the walls, was, at some point, imagined. Someone decided it was easier to sit on a chair than on the ground and imagined the chair. Someone had to imagine a way that I could talk to you in London right now without us all getting rained on. This room and the things in it, and all the other things in this building, this city, exist because, over and over and over, people imagined things."

— Neil Gaiman [7]

1 Mechanical design for buildings

Let's first look at the major components of a building design process. These apply whether we are beginning the design of a brand new large commercial facility or simply considering a minor change to the structure or operation of a small residence. Grondzik and Kwok divide the process into these pieces [9]:

1. *Design intent*, e.g. "The building will provide oustanding comfort for its occupants."
2. *Design criteria*, e.g. "Thermal conditions will meet the requirements of ASHRAE Standard 55."
3. *Methods and tools*, e.g. design guide or building energy model
4. *Validation and evaluation*, e.g. M&V (as in Lecture 6).
5. *Other influences on the design process*, including:
    - Codes and standards
    - Costs (first costs and operating costs)
    - Energy efficiency or Net Zero requirements

2 What is sustainable design?

"We have an obligation to make things beautiful. Not to leave the world uglier than we found it, not to empty the oceans, not to leave our problems for the next generation. We have an obligation to clean up after ourselves, and not leave our children with a world we've shortsightedly messed up, shortchanged, and crippled."

— Neil Gaiman [7]

Sustainable design usually means that goal of the design encompasses the Brundtland report [3] definition of sustainable development. We first saw this in Lecture 1. Grondzik and Kwok describe this as design that "involves meeting the needs of today's generation without detracting from the ability of future generations to meet their needs." [9]

There is also a newer term called **regenerative** design, which means the goal of the design is "to produce a net positive environmental impact—to leave the world better off with respect to energy, water, and materials." [9] The Living Building Challenge is a performance standard for buildings that provides a framework for regenerative design [10].

3 What is ecological design?

"Until our everyday activities preserve ecological integrity *by design*, their cumulative impact will continue to be devastating."

— Van der Ryn and Cowan [11]

Ecological design means that the designer is concerned with, and has some understanding of, ecology. Our next guest speaker, Prof. Sarah Hinners, is trained as an ecologist and teaches urban planning (or 'ecological planning'—see below). Van der Ryn and Cowan have a broad definition of ecological design: alligator

"any form of design that minimizes environmentally destructive impacts by integrating itself with living processes" [11]

3.1 But what is ecology?

Ecology, because it is a discipline focused on complex systems, can be difficult to grasp when approaching from another discipline. The key pieces that comprise the study of ecology are organisms (anything from a single-cell bacteria to us), environments, and relationships or interactions between these.

I'm also noting here a few other related terms that you may encounter when considering ecological design within the built environment.

alligator

"a branch of science concerned with the interrelationship of organisms and their environments" [4]

"positive benefit[s] that wildlife or ecosystems provide to people" [6]

"planning in harmony with social, economic, and environmental systems to enhance the health and well-being of places and communities" [5]

a field that "helps communities understand the complexity of issues that affect daily quality of life as well as the long-term health of the environment" and focuses on "exploring the interrelationships among social, environmental and economic systems, with an aim toward enhancing the vitality and sustainability of places and communities." [1]

4 A set of sustainable building design principles (Grondzik and Kwok, adapted from Lyle)

Before we jump in, let's note that a **site analysis** should happen before any serious building designing goes on. This helps us "understand the character of a given site [9]" by understanding its existing ecological systems and flows, local climate, solar exposure, local climate, zoning or other political requirements, and more.

The site may be providing valuable ecosystem services to the surrounding land; if these are irreplaceable, why build? If it's a reasonable place to build, are there specific limitations or challenges that we need to understand to inform how and what we build?

Grondzik and Kwok adapted these principles from John Lyle as shown below [9]. Each principle is taken directly from their book, although I have combined principles in a couple of instances. My commentary follows below each principle.

1. Let Nature Do the Work; Consider Nature As Both Model and Context
   This is described as indicating a preference for "passive processes over active/mechanical processes", but could more broadly imply a respect for nature and a reluctance to overdesign when a simple or nature-inspired technology will do.

2. Aggregate Rather Than Isolate
   Be aware that subsystems, in aggregate, can make up complex systems and consider the interactions of different parts of the building throughout the design process.

3. Match Technology to the Need
   One might simply argue that this is the basis of any reasonable technical design at all. Here, it implies that the function of each technology chosen satisfies the design intent and criteria, and that simpler technologies are preferable when they satisfy the appropriate need(s).
4. Seek Common Solutions to Disparate Problems
   Building on the point above, solutions that can provide multiple features or benefits for the building are highly desirable. It helps to have a multi-disciplinary design team filled with curious, creative systems thinkers.
5. Shape the Form to Guide the Flow; Shape the Form to Manifest the Process
   The shape of the building itself can direct things (fluids, people, light) in a way that provides sustainability benefits and meets design goals. Ideally, a building will be understandable to its users—for example, the function of visible equipment will be apparent. The work of mechanical engineer Adrian Bejan [2] provides many areas for applying these concepts in depth.
6. Use Information to Replace Power
   A deep understanding of building science, client needs, occupant behavior, and site ecology will allow the designer to meet design goals more efficiently and effectively than simply adding more equipment.
7. Provide Multiple Pathways
   Think through where your design could fail in critical ways and use redundancy.
8. Manage Storage
   Look at how needs and resources will be distributed through time and space. Be aware that the building itself has **thermal mass**, and understand its energy storage characteristics as best you can to help provide consistent conditioning.

5 A set of eco-minimalism principles (Grant)

> "I'm rather partial to high technology, but I try to remember to oppose inappropriate or unnecessary technology."
>
> — Nick Grant [8]

Grant presents a set of eco-minimalism principles that are applied to building design in the essay cited here [8], but could be applied to any problem on which design skills, engineering analysis, and imagination can be brought to bear. They are, aptly, quite minimal, providing simple guidance for bringing ecological awareness and simplicity to technical design. Again, my commentary follows below each principle.

1. Question
   Be skeptical. Ask bigger questions. Make sure you're trying to solve the problem you should be trying to solve.
2. Reduce
   Seek simpler solutions and look for opportunities to reduce complexity.
3. Order
   Arrange structures in a way that supports design goals. Remove clutter and organize what remains in a logical way.
4. Model
   Use models to compare potential solutions with each other and to test the predictions of your imagination/intuition.
5. Monitor
   Find the ground truth and check your prediction. Where were you wrong and why? He calls this "closing the gap between theory and reality." [8]

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Lecture 8. Building Energy Modeling (BEM): Building and Weather Files

"Model utility depends not on whether its driving scenarios are realistic (since no one can know that for sure), but on whether it responds with a realistic pattern of behavior."

— Donella H. Meadows [6]

1 Building files

An EnergyPlus main input file is a human-readable text file with the suffix ***.idf* (for Input Data File)**. It describes the characteristics of the building, its HVAC system, and its surroundings to a limited extent. This information is the basis for the implementation of equations representing the physics in the simulation, but does not provide a 3-D representation of how everything is arranged.

The most straightforward, least glamorous way to interact with an IDF file is through the IDF Editor (Figure 1), "a simple, 'intelligent' editor that reads the EnergyPlus Data Dictionary (IDD) and allows creation/revision of EnergyPlus Input Files." [3] The IDF Editor is accessed through the EP Launch program (Figure 2), only available for the Windows Platform.

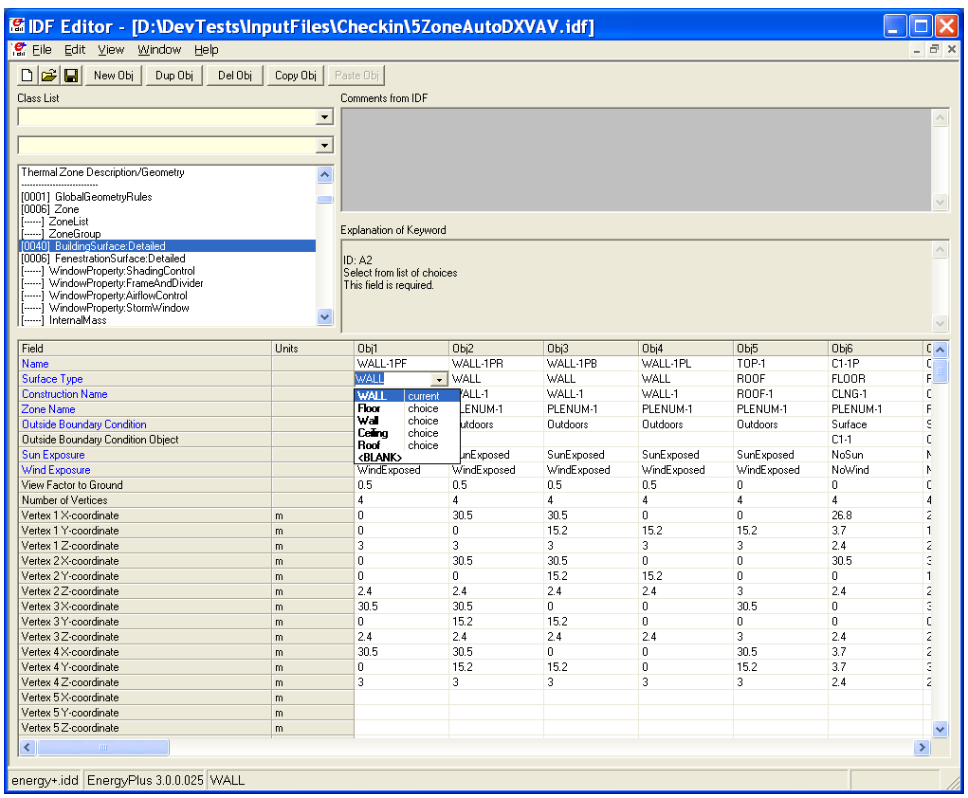

Figure 1: IDF Editor in action [3]

You can also open the IDF with any text editor as it is simply a standard ASCII text file, and most interfaces built on the EnergyPlus engine will just modify the IDF behind the scenes according to your commands. Each item within the IDF file that has data associated with it is called an **object**. A group of related objects forms a **class**. Comments follow exclamation points.

The **Input Data Dictionary (IDD)** is a file that tells EnergyPlus what is allowable and what to expect with the IDF file it will be reading. Refer to "IDD Conventions" in the Input-Output Reference document [3] for a description of what the IDD should look like. Although it is a critical input file, we will not modify the IDD files in our class, instead using existing IDD files and working within the structure they provide for how we present data to the EnergyPlus engine.

For a given simulation, the two key input files we will focus on will be IDF and EPW files, described in the next section. We will stop to take a look at the contents of the IDF files as we learn to run simulations over the next couple of weeks. Even if you don't directly modify the IDF file in practice, it will help your understanding of the EnergyPlus BEM process for you to discover their typical structure, and try to decipher what inputs are affecting what simulation outcomes based on what EnergyPlus is actually reading from the input files.

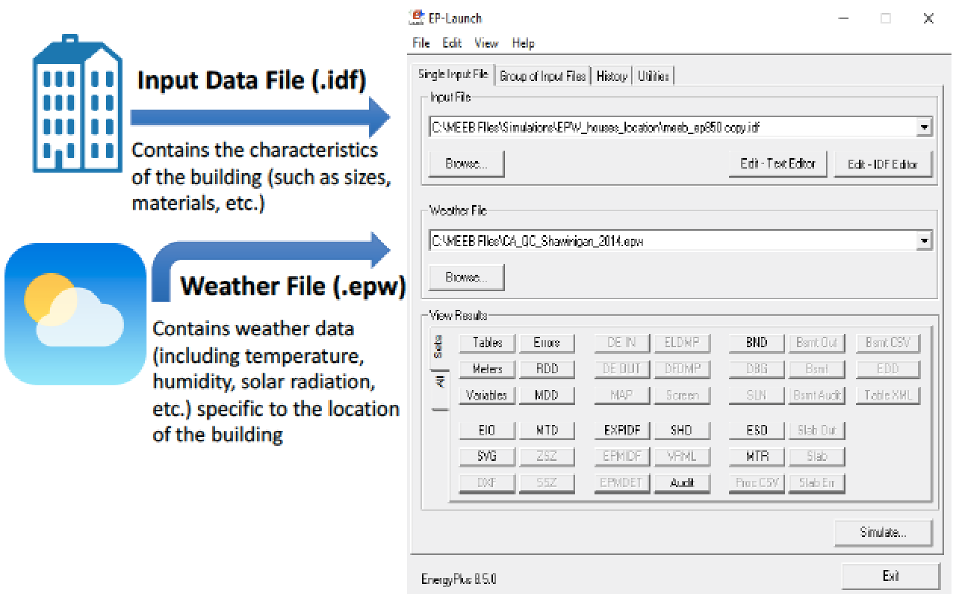

Figure 2: EP Launch Program [2]

2 Weather files

A weather file tells the software what the simulated building will "experience" throughout the simulation. This assumes that the weather is uniform around the building—not always a great assumption, and one that my research team and collaborators are helping to evaluate quantitatively. If you've had heat transfer, this means that the dry bulb temperature provided by the weather file would be your T_∞.

An EnergyPlus weather file is a human-readable csv text file with the suffix ***.epw* (for EnergyPlus Weather)**. The top of the file contains headers, site information, design conditions, and some information about holidays and daylight savings time. It contains weather data over a period of time (usually 1 year) at intervals of at least one hour (although higher-resolution data can be included).

The following variables are included:

- Dry Bulb Temperature
- Dew Point Temperature
- Relative Humidity
- Atmospheric Station Pressure
- 6 fields of radiation data
- 4 fields of illuminance data

- Wind Direction
- Wind Speed
- 4 fields relating to cloud cover and visibility
- 6 fields relating to precipitation

Refer to EnergyPlus documentation, Auxiliary Programs section for details [3].

2.1 Impact of weather on building energy use

Some buildings are more 'weather driven' than others, for reasons you might guess, such as:

- high **skin ratio** (surface area-to-volume ratio for the building envelope),
- high **window-to-wall ratio**,
- low insulation values (small U values),
- instances of **thermal bridging** (easy pathways for heat transfer between conditioned space and the outdoors),
- **natural ventilation** (i.e. not mechanically forced) or high rates of **outdoor air** as opposed to recirculating air,
- or simply having low indoor loads (e.g. low plug loads, low occupant density)

The types of HVAC systems that condition the building and their efficiencies and maintenance schedules will also affect how much a building is affected by hot, cold, or changing weather conditions outside. There is also simulation-based evidence that buildings in cold climates are more affected by weather than those in warm climates [5].

2.2 Typical Meteorological Years

The **typical meteorological year (TMY)** is a conceptual "representative" weather year for a given location.

> To calculate a TMY, a multiyear data set is analyzed and 12 months are chosen from that time frame that best represent typical conditions. [7]

The TMY files are designed to illustrate what a building's performance might be, on average, in a certain climate. While they are compiled using statistical techniques starting with actual observed weather data, they don't represent any given consecutive yearlong period in historical time. By definition, they don't capture unusual weather patterns, which leads to an important cautionary note:

> Because TMYs represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location. [7]

A TMY file is not necessarily provided in EPW format, as TMY files do exist for other applications. We will download EPW files from the EnergyPlus website [11], which are TMY weather data in the form of EPW files, ready for use in EnergyPlus building energy simulations. You may see options for TMY, TMY2 or TMY3 data. TMY3 data sets are the most recent, derived from 1991–2005 weather, and provide more geographic locations than previous TMY versions [12]. TMY2 data sets are less recent, based on 1961–1990 weather [9], but still widely used. The original TMY data sets were produced using 1952–1975 weather [12]. TMY3 will be our preferred type of TMY data.

It's also important to note that the observed data usually come from the airport nearest to the named city, which may not be well correlated with the weather data in the urban center [1]. Take a look at weather observations from DarkSky [4] or MesoWest [8] right now–can you find a downtown station and one at SLC airport? How different are their readings?

2.3 Actual Meteorological Years

An **actual meteorological year (AMY)** is simply the actual weather detected in a given place during a historical year. For building model **calibration**, which involves comparing model output to actual performance data, an AMY weather file is necessary. There are companies that sell AMY files using historical weather data that has been processed into the EPW format [10]. We also now have an open source solution, described below.

2.3.1 Localized AMY File Creator (LAF)

NREL engineer and former Site-Specific Energy Systems Lab researcher Dr. Carlo Bianchi created a weather file converter to take MesoWest [8] observed weather data and present it in the EnergyPlus–friendly EPW format, ready for use in EnergyPlus building energy simulations. This software is our first release of the weather file creator.

Download and install the LAF app for your platform at `https://energysystems.mech.utah.edu/laf/`. You can also grab the Python code directly at `https://github.com/sseslab/laf/`. We're working on the next version of LAF and your feedback is appreciated.

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Lecture 9. BEM: Climate Zones, Commercial and Residential Buildings

> "Discussions of sun, air, and water resources available on a site are influenced both by the 'private' needs of a building and the 'public' patterns of resource availability, which should remain accessible to all."
> — Grondzik and Kwok [6]

1 Climate

> **Climate** is a long-term statistically derived picture of weather. **Weather** is what happened today or yesterday, while climate has historically been a picture of what happened over the past 10, 15, or 20 years. [6]

The climate where buildings and distributed energy resources are located will determine the external conditions they experience during their lifetime, and thus influence how they perform. Architects and engineers need an understanding of the climate that will influence a particular site to make good design decisions for a building (e.g. selecting the proper size air conditioning unit, choosing insulation and vapor barriers for walls, or placing windows and shading on the building). Engineers, designers, and operators also need to evaluate the "sun, air, and water resources available" to make good decisions about whether and how to select distributed generation and storage or to implement demand-side energy measures, which we'll discuss later with distributed energy resources.

Modelers need to have weather data that represents the climate that is expected, a need usually served by the TMY files mentioned in Lecture 8. If a particular year's weather is of interest (or relevant to a calibration effort), then the modeler needs an AMY file as mentioned in Lecture 8. There are existing research efforts to provide future weather year files [3], incorporating projections for climate change, but these are rarely used in practice.

1.1 Microclimate

> Local variations constitute microclimates, which have some characteristics distinctly different from the conditions prevailing in the larger macroclimate. The characteristics of a microclimate are influenced by the interaction of the site conditions with the macroclimate. [6]

The **microclimate** represents the 'local' weather for a restricted local area, which could be as small as an area at the corner of an external wall (where changing airflow patterns will affect the observed meteorology). It is highly related to the surrounding climate, but unique conditions can affect the temperature, humidity, wind speed, radiation, and other weather-related variables, such as:

- Presence of walls, windows, and overhangs
- Human interaction with the building or landscape
- Presence of concrete, asphalt, or different types of ground cover
- Changes in ground cover or other surface characteristics
- Presence of other buildings or structures

1.2 Urban Heat Island

> The most obvious reason for a city's relative year-around warmth is its concentration of heat sources: the air conditioner condensers, furnaces, electric lighting in buildings, and internal combustion engines in cars. ... It appears that cities and industrial regions of the world release less internal heat per capita as people live and work closer together—although the heat density (temperature) is greater. [6]

The term **urban heat island (UHI) effect** is a recognition of the observed data showing that temperatures in urban areas are higher than surrounding suburban or rural areas, even if the larger climate and meteorology they experience is similar. This is due to more concentration among heat sources, and less opportunity to reject heat away from the built environment [6].

2 Climate Zones

> Our most familiar names for climates describe their most severe season . . . This is a convenient means of description, but it can be misleading for designers. "Cold" climates can have very hot, sometimes humid, summer days; hot-arid climates can have bitterly cold winter conditions. Before designing buildings that will interact with exterior conditions to provide indoor comfort, we should know in some detail the character of those conditions. [6]

Because both dry bulb temperature and moisture are important or building design and performance, these are the key features used to classify a **climate zone**, an identified geographic region that experiences similar climate patterns. At its most detailed, we divide the contiguous United States into 7 climate zones, Figure 1, and assessments are made county by county. Alaska has an additional Climate Zone 8, which is extremely cold. There is also a Climate Zone 0, which is extremely hot, existing near the equator but not within the U.S. You may also see these referred to as 'climate regions' or 'ANSI/ASHRAE/IESNA climate zones' as they are part of standards published by these organizations. For more about the technical meaning and determination of climate zones, see the DOE's Climate Zones page [4].

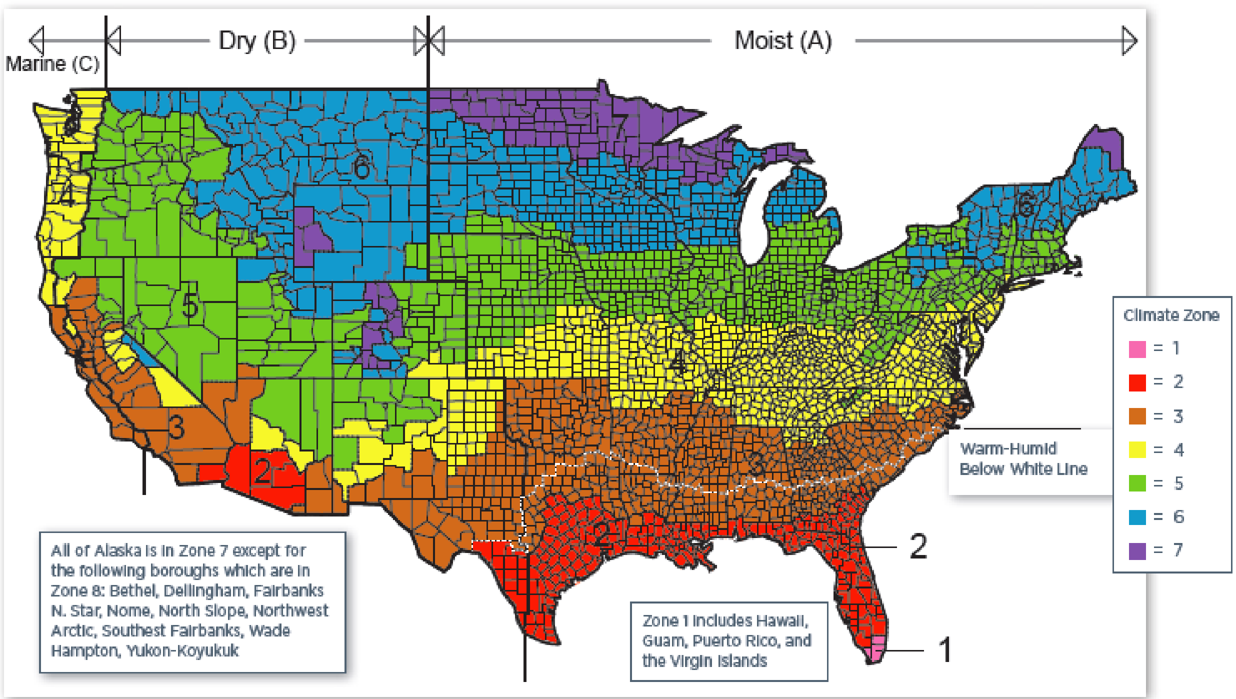

Figure 1: International Energy Conservation Code (IECC) Climate Zones in the Lower 48 States [1]

Living in Utah near the mountain ranges, you can probably think of a place where more than one climate zone exists within the same county. For example, Alta is located within Salt Lake County, yet you might have had the experience of visiting Alta and seeing notably lower temperatures, or seeing snow falling at Alta while rain falls on Salt Lake City. So even though Alta falls within the Climate Zone 5 region on the map, a thoughtful engineer might choose to follow design criteria that are targeted at Zone 6 instead.

3 Commercial Buildings

For building energy modeling purposes, the DOE provides a set of example building models called the **Commercial Prototype Building Models**: https://www.energycodes.gov/development/commercial/prototype_models. These are based on the CBECS survey mentioned in Lecture 3. You may also come across the precursors to the Commercial Prototype Buildings, called the Commercial Reference Buildings [5].

They are designed for different code years of ANSI/ASHRAE/IES Standard 90.1, "Energy Standard for Buildings Except Low-Rise Residential Buildings" [8], which is often adopted and incorporated into formal building codes. The DOE has a reference page on www.energycodes.gov where you can learn more about building codes [2].

The main designations for building types within this sector are:

- Small Office
- Medium Office
- Large Office
- Stand-alone Retail
- Strip Mall
- Primary School
- Secondary School
- Outpatient Healthcare
- Hospital
- Small Hotel
- Large Hotel
- Warehouse
- Quick Service Restaurant
- Full Service Restaurant
- Mid-rise Apartment
- High-rise Apartment

We will use them as a starting point when we need examples of commercial buildings to use in our modeling work.

4 Residential Buildings

For building energy modeling purposes, the DOE provides a set of example building models called the Residential Prototype Building Models: https://www.energycodes.gov/development/residential/iecc_models. These are based on the RECS survey mentioned in Lecture 3. They are designed for different code years of the International Energy Conservation Code (IECC) [7].

There are only two major designations for residential prototype models:

- Single-family detached house
- Multi-family low-rise apartment building
  (Remember that mid- and high-rise apartments are classified with commercial buildings).

If you download the residential files available for Utah, you will see that in addition to the code year, you have a few more options to choose from:

- Gas furnace, oil furnace, electric heat or heat pump
- Crawlspace, slab, heated basement or unheated basement

We will use them as a starting point when we need examples of residences to use in our modeling work.

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Lecture 10. BEM: Simulation Control

"Simulation is cheaper than constructing the wrong building!"
— Dru Crawley, in a 2014 presentation to the Utah ASHRAE Chapter

1 Using the OpenStudio interface

When you work with the OpenStudio application, all of the tabs on the left side will affect the building energy model or the way you interact with it. The OpenStudio Introductory Tutorial [5] provides a PDF of the OpenStudio Quick Start Guide, which contains a Basic Workflow Guide that is a visual map of the graphical user interface (GUI). The tab with an arrow is where the action happens—when you click Run, OpenStudio reads the instructions you've given it, calls the EnergyPlus engine, and starts simulating.

The rest of this lecture will focus on key pieces of information provided to the EnergyPlus engine that determine how the simulation will be conducted, concluding with a description of measures that act on OpenStudio or EnergyPlus models.

2 Version

Each IDF has an object (see Lecture 8) called **Version** that indicates the version of EnergyPlus that the IDF file was created for. An error will result if you are simulating the file in a different version of EnergyPlus, but will not necessarily stop the simulation. The simulation may crash if, for instance, the version of EnergyPlus you're using can't find something in the IDF file that it is looking for.

Note that an EnergyPlus version is different from an OpenStudio version. The EnergyPlus software is much older, and we're currently on Version 9.0, which runs under the hood of OpenStudio Version 2.7.

3 Run Period

An IDF has an object called **RunPeriod** that tells EnergyPlus how to match up the simulation with the weather file. It contains information like the month, day, and year when the simulation will begin and it determines how long the simulation will run for (assuming a fatal error doesn't stop it along the way). If the weather file contains information about Daylights Savings time or holidays, the RunPeriod object will tell EnergyPlus how to use that data.

4 Time Step

The basic time step for a simulation is provided in the number of timesteps per hour. You may choose any integer that divides into 60, from 1 (meaning an hourly timestep) to 60 (meaning a timestep of 1 minute). A value of 6 (timestep of 10 minutes) is commonly used, as it settles in the middle of the trade-off between quick simulations (longer timesteps) and capturing more of the building's dynamic response (smaller timesteps).

Remember that the weather data are typically provided in hourly timesteps (8760 rows of entries). This is not a problem for simulations because EnergyPlus will automatically interpolate the weather data between the data points it has and, as explained in the Input-Output Reference:

> Many aspects of a model have time scales that differ from the that of the weather data. A goal of the modeling is to predict how the building will respond to the weather. However, the building's response is not governed by the time scale that the weather data are available at, but rather the time scales of the dynamic performance of the thermal envelope as well as things like schedules for internal gains, thermostats, and equipment availability. [3]

Technically, EnergyPlus is working with two important timestep values that are not necessarily the same:

- **Zone timestep**—the basic timestep for solving general heat transfer equations, for example. It dictates the smallest time scale on which results would be available. This is consistent throughout the simulation.
- **System timestep**—the timestep used internally for solving an HVAC system model, for example. Its maximum value will be the zone timestep value, but it may be smaller as needed for EnergyPlus to reach convergence. It does not affect the time scale on which results would be available. This can change throughout the simulation.

As end users, we will only modify the zone timestep, although we could indirectly force changes in the system timestep by adjusting the convergence limits.

5 Simulation Control

Each IDF has an object called **SimulationControl** that tells EnergyPlus what simulations it will actually perform. We have several options, including:

- Sizing calculations for the zone and system design loads (defaults to No)
- Sizing calculations for plants, such as a central chiller loop or cooling tower (defaults to No)
- Simulation for the weather file run period, as in Section 3 (defaults to Yes)
  This is what we typically think of as an EnergyPlus 'run'.
- Simulation for specific advanced sizing calculations for HVAC equipment (optional field; default is to ignore it, which is essentially a No)

6 Design Day

A **design day** simulation is chosen to provide conditions that will result in load calculations demonstrating loads that the equipment needs to be able to meet. That is, it is a representative day used for design (e.g. equipment sizing). Often more than one design day is used in the process of sizing and selecting equipment for a building—for example, one summer design day representing extreme hot weather conditions and one winter design day representing extreme cold weather conditions are frequently used. For more about the concept of design days or their implementation in EnergyPlus, refer to the ASHRAE Handbook [2] or the EnergyPlus Input-Output Reference [3].

An IDF has an object called **SizingPeriod:DesignDay** that provides information about what design day simulation(s) to conduct. Information includes the month and day, maximum (dry bulb) temperature, daily temperature range (difference between high and low dry bulb), humidity conditions, and more.

7 Location

An IDF has an object called **Site:Location** that provides relevant information about the building site, such as latitude, longitude, local time zone, and elevation. If information given here conflicts with any location data provided in the weather file, the weather file takes precedence.

8 Building

An IDF has an object called **Building** that provides basic information about the building itself. The includes information like the building's orientation (defined as an offset of the building's north axis from true North) and the type of terrain surrounding it (such as 'city' or 'suburbs')

It also contains a field for the name of the building, which doesn't affect the simulation itself, but will be used with output from the simulation. This will come in handy when you're digging through output files days or even months later.

9 Variables

EnergyPlus holds on to information about the simulation as internal variables. These could be items like the air temperature in a certain zone (in Celsius), the electricity used for lighting (in J), or the gas used for the whole facility (also in J). The specific variable names that are available for a given building simulation are shown in two "eplusout" output files. That means EnergyPlus doesn't know all of the variables it might be possible to report on before it's simulated anything. An experienced user who puts together their own IDF may know on the front end what variables they will be able to ask for; as for us, we will sometimes need to run an input file to get a list of possible variables. We'll talk more about controlling what output you get from a simulation (i.e. "Input for Output" [3]) in the next lecture.

10 Measures

Within the OpenStudio platform, we can leverage scripts to automate the process of altering our model.

> A **measure** is a set of programmatic instructions that makes changes to an energy model to reflect its application. [For] example, the measure might find the default construction used by roof surfaces in the model, copy this construction and add insulation material to the outside, then set the new construction with added insulation as the default construction to be used by roof surfaces. Measures can be written specifically for an individual model, or they may be more generic to work on a wide range of possible models. [1]

The underlying code is written in Ruby, but by leveraging the Building Component Library [4] as described in the OpenStudio Introductory Tutorial [5], we can use measures without having to create or alter the code ourselves. I do recommend taking a look at the script for a measure (look for 'measure.rb') just to get a sense of what it looks like. Try to alter it and see what happens when you run it again if you are already familiar with Ruby or just feel adventurous [6].

When you reach the Measures interface in the OpenStudio GUI, you will see options for OpenStudio measures, EnergyPlus measures, and reporting Measures. The first two affect input files, as described below, and the last affects your output, as discussed in the next lecture.

10.1 OpenStudio

An OpenStudio measure is written to alter the *.osm* file, the OpenStudio model. It could change the way the currently open model will run, or could change the entire simulation workflow of the OpenStudio Application.

10.2 EnergyPlus

An EnergyPlus measure is written to alter the *.idf* file, the input data file for the EnergyPlus engine. It might change each object of a given type in a consistent way, for example.

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Lecture 11. BEM: Simulation Output

"Patterns extracted from building historic data and simulation data provide deep insight into the way building occupants consume energy."

— Yu, Haghighatb, and Fung [7]

1 Variables

Variables within EnergyPlus work like variables in any computational simulation: they store information as the simulation progresses and can be used to "report" this information back to the user in different ways (like summary reports that are shown to you or files that are placed in the simulation directory). If you want to know what variables are available for a given simulated building, you go to the *eplusout.rdd* file (Section 5).

> Variables available, to some extent, depend on the simulation input. Variables are 'set up' during the initial 'get input' processing done within the modules. Therefore, an item that is specific to a certain type of coil would not be available if that coil were not used during the simulation
>
> ...
>
> There are two flavors to output variables: ZONE or HVAC. ZONE does not mean that it is a zone variable – rather, it is produced at the Zone Time Step... HVAC type variables, likewise, are produced at the HVAC [or system] timestep. [1]

Although the default time step for providing variables is the zone time step, we may be able to inspect what's happening at the system time step for variables where that is relevant: "Report variables that use the 'detailed' frequency show results at the system time step time scale." [3]

2 Meters

Just like a physical meter that tracks energy use in a real building, an EnergyPlus meter is keeping track of how much energy is used over given intervals within the simulation. If you want to know what meters are available for a given simulated building, you go to the *eplusout.mtd* file (Section 5).

> Appropriate variables are grouped onto 'meters' for reporting purposes.... If the 'Output:Meter' input object is used, these results written out to both the eplusout.eso and eplusout.mtr files. This allows easy graphing and comparison with "normal" values (such as Zone Temperature or Outdoor Temperature). [4]

Broadly speaking, there are two ways meter variables would typically be reported:

- Metered variable is reported at the time step interval requested.
- A cumulative value for that variable up to that point in the simulation is reported.

We could request output in more specific ways—see Input-Output Reference for details [4].

The Input-Output reference also has tables in the sections on Output:Meter and Output:Meter:Cumulative that illustrate what types of metered resources (e.g. electricity gas), end uses (e.g. interior lights, exterior lights), and overall meter types (facility or zone) can be provided [4], given that the resource or end use is appropriate to your simulated building.

3 EnergyPlus Annual Building Utility Performance Summary

The **Annual Building Utility Performance Summary (ABUPS)** is a high-level quick look at the overall performance resulting from a given simulated building. It "produces a report that is an overall summary of the utility consumption of the building" and consists of a set of tables: [4]

- Site and Source Energy
- Building Area
- End Uses
- End Uses By Subcategory
- Utility Use Per Conditioned Floor Area
- Utility Use Per Total Floor Area
- Electric Loads Satisfied
- On-Site Thermal Sources
- Water Source Summary
- Setpoint Not Met Criteria
- Comfort and Setpoint Not Met Summary (These are your 'unmet hours.')

4 Viewer

OpenStudio has a built in tool for visualization and custom reports called **DView** that you can open from the Results Summary tab. It offers you the option to view results in I-P (English) units—this is a convenient post-processing feature, but remember that EnergyPlus internally holds values in SI units and we're just asking for them to be converted before they're presented. You can choose items to display on a time series graph, and you can right click on your graphs and select "Save to csv" to get a spreadsheet file that can be imported into Excel, Google Sheets, Python, Matlab, or whatever post-processing platform you like.

5 Files

These are most of the files that result from a simulation. You will find them in the same directory on your computer where you ran the model from; remember to move them out if you plan to change the model and run it again and you need to have your old results.

Most of the files listed here are just text files, but you may have to tell your computer to use a text editor to open them since they don't have a *.txt* suffix. I like to use Atom because you can download a package from Big Ladder Software that will recognize the structure of EnergyPlus IDF objects [5], but you can use any text editor you're familiar with, or you may choose to find or build your own tools to help you use these files.

eplusout.audit "Echo of input"
: Gives you a high-level audit of what went into the simulation (e.g. number of report variables, number of node connections). [4]

eplusout.eio "One time output file" [4]
: You can check things like your minimum system timestep or whether zone sizing was performed.

eplusout.err "Error file"[4]
: You'll see warnings and errors and some information about them (e.g. what EnergyPlus object was involved in the error). The levels of error you may see are, in order of severity:

  - Warning
  - Severe
  - Fatal (why the simulation stopped).

eplusout.eso "Standard Output File (contains results from both Output:Variable and Output:Meter objects)" [4]

eplusout.mdd Display of meter variables [4]
You can open this one like a *.csv* file.

eplusout.mtd "Meter details report – what variables are on what meters and vice versa." [4]

eplusout.mtr "Similar to .eso but only has Meter outputs" [4]

eplusout.rdd Display of regular variables [4]
You can open this one like a *.csv* file.

eplusout.sql "A time series database of simulation results used by plotting software like DView." [2]

eplustbl.htm Contains the ABUPS report, followed by a table of contents that links to a bunch of different reports that have tables summarizing things from the simulation.
This one will open in a browser like a webpage.

eplusssz.csv "Results from the System Sizing object with extension noted by the Sizing Style object. This file is 'spreadsheet' ready." [4]

epluszsz.csv "Results from the Zone Sizing object with extension noted by the Sizing Style object. This file is 'spreadsheet' ready." [4]

in.idf Input Data File.
This is the input for an EnergyPlus simulation, but you will also receive it after running your OpenStudio model. It's provided so that when OpenStudio translates what you want into EnergyPlus-speak, you can check it and see exactly what the EnergyPlus engine saw.

in.osm OpenStudio Model.
This is the input for running an OpenStudio model (which, of course, involves an EnergyPlus simulation). Technically it is "the final OpenStudio Model prior to calling EnergyPlus." [2] You may interact only with the OpenStudio interface and never see the text of the model, but the OSM is an ASCII text file similar to an IDF that shows you exactly what OpenStudio is seeing.

stdout-energyplus Shows what happened in the simulation.

6 Reporting Measures

Reporting measures "generate reports on the input and output of a given energy model" [6]. These measures are designed to provide output that will help you understand what went into the simulation or show more detail about the simulation result.

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Lecture 12. BEM: Building Systems, Part I
Envelope, Zones, Interior

"Commercial buildings are complicated thermodynamic objects."
— Samuelson, Ghorayshi, and Reinhart [5]

1 Envelope and Construction

The building envelope, or "skin" of the building, protects the building and its occupants from the elements and from a control-volume, single-building perspective, it defines your system boundary for the building.

The building's construction, including the envelope as well as interior walls and structures, can be specified to EnergyPlus as [4]:

- Surfaces grouped into zones
- Individual structures like:
  - Walls
  - Roofs
  - Ceilings
  - Floors
- Individual materials
- Groups of materials, called Constructions or Construction Sets in EnergyPlus-speak.

As an EnergyPlus building simulation comes together, information from the IDF, organized according to the IDD, will be expected by EnergyPlus to fall into a hierarchy of data for processing. The hierarchy for the building's envelope is shown in Figure 1.

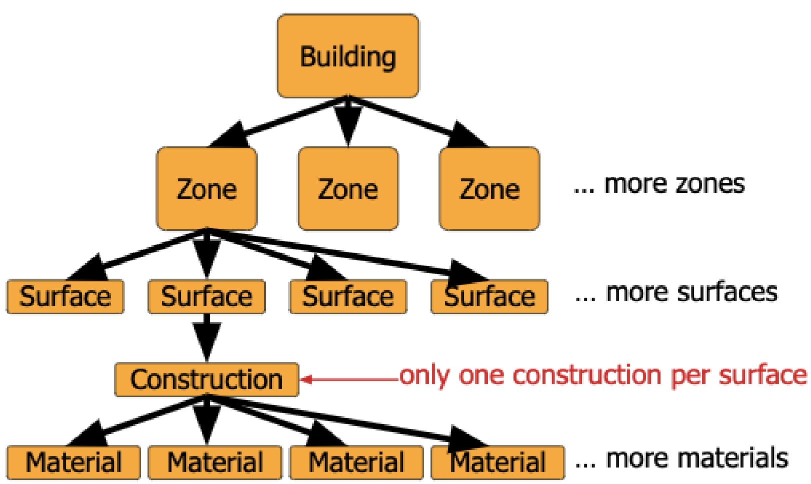

Figure 1: Envelope Hierarchy in EnergyPlus [4]

It is a best practice to use "as few surfaces as necessary" [4], meaning that you define a construction or surface and reuse for multiple walls if possible. This will require knowledge of the materials and methods used for construction, and an understanding of important phenomena at the interface of building constructions (like thermal bridging; see Lecture 8).

2 Thermal Zoning

Remember that the thermal zones, simply called Zones in EnergyPlus-speak, are not geometric entities but rather groups of things that will interact thermally. According to the Getting Started documentation:

> The **thermal zone** is defined as a volume of air at a uniform temperature. [2]

This leads to one general rule:

> Use the number of fan systems (and radiant systems) not the number of rooms to determine the number of zones in the building. [2]

It is best practice in any case to use "as few zones as necessary" [4], meaning that you have just enough zones to adequately capture the phenomena that will help you make decisions based on model output, but no more zones which would add to model complexity or computational time (or likely both).

The rule above can be expanded toward a more systems thinking-type view of the buiding:

> The minimum number of zones in a general simulation model will usually be equal to the number of systems serving the building. The collection of heat transfer and heat storage surfaces defined within each zone will include all surfaces bounding or inside of the space conditioned by the system.

Making zoning decisions beyond these guidelines will require deep engineering knowledge about the interactions between building constructions, mechanical systems, occupants, and the thermal masses within the building as a whole. Furthermore, the exact same building might actually need more zones for a model that requires greater differentiation in thermal conditions within the building than it would for another, more general, model. The key is to understand how the information produced by the model will be used.

3 Interior Environment

3.1 Internal Gains and People

People in a building are referred to as **occupants** in the world of building science. People are a type of **internal gain**, meaning that they add heat to the building's interior. For example, our skin can dissipate latent heat through sweating (evaporation) and sensible heat by convection or radiation.

Sensible heat energy addition associated with (dry-bulb) temperature change in zone [4]

Latent heat energy addition associated with moisture/humidity change in zone [4]

There are three major categories of drivers for **sensible heat gains** typically seen in buildings [4]:

Convection "instantaneous additions of heat to the zone air" [1]

Thermal (long wave) radiation

Visible (short wave) radiation

When heat is added to the interior spaces via radiation, "Radiant gains are distributed on the surfaces of the zone, where they are first absorbed and then released back into the room (with some fraction conducted through the surface) according to the surface heat balances." [1]

When there is **latent heat gain** in the interior spaces because of evaporation, "Latent gains must be handled by ventilation or air conditioning equipment." [1]

There are a few different ways we can provide information about the number of people in a zone [3]:

- Number of People [person]
- People per Zone Floor Area [person/m^2]

- Zone Floor Area per Person [m^2/person]

We will also need to provide some additional information to help EnergyPlus know how to deal with the people as it implements energy and mass balances. A few key fields are shown here, but the full set of options and their default values, where applicable, can be found in the Input-Output Reference [3].

- Fraction Radiant [unitless, 0 to 1]—"used to characterize the type of heat being given off by people in a zone . . . The remainder of the sensible load is assumed to be convective heat gain. Note that latent gains from people are not included in either the radiant or convective heat gains." [3]
- Carbon Dioxide Generation Rate [m^3/(s-W)]
- Clothing Insulation Calculation Method [key/choice field]—"tells which of the next two fields are filled and is descriptive of the method for calculating the clothing insulation value of occupants." [3]

3.2 Lighting

Lighting is a type of internal gain, notably radiant in the visible region (short wave radiation). However, lights will transfer even more radiant energy in the form of thermal (long wave) radiation [1]. The visible radiant gain will be a larger fraction compared with the thermal radiant gain for energy efficient lighting fixtures.

We use a Lights statement to provide information to EnergyPlus about lighting at the zone level. "A zone may have multiple Lights statements. For example, one statement may describe the general lighting in the zone and another the task lighting. Or you can use multiple Lights statements for a zone that has two or more general lighting systems that differ in design level, schedule, etc." [3] A few key fields are shown here, but the full set of options and their default values, where applicable, can be found in the Input-Output Reference [3].

- Design Level Calculation Method [key/choice field]—"tells which of the next three fields are filled and is descriptive of the method for calculating the nominal lighting level in the Zone." [3]
  - LightingLevel [W]
  - Watts/Area [W/m^2]
  - Watts/Person [W/person]
- Fraction Visible [unitless, 0 to 1]
- Return Air Fraction [unitless, 0 to 1]—"fraction of the heat from lights that goes into the zone return air" [3]

3.3 Equipment

Equipment is a type of internal gain, often radiant in the form of thermal (long wave) radiation. We could technically include lighting as a type of equipment, but since lighting is its own end-use category, often evaluated separately from the equipment types shown here, EnergyPlus groups non-lighting related equipment together.

3.3.1 Electric equipment

Electric equipment encompasses "plug loads" such as computers, TVs, microwaves, or anything else the occupants have plugged in. Similarly to lighting, above, a few key fields are shown here, and the full set of options and their default values, where applicable, can be found in the Input-Output Reference [3].

- Design Level Calculation Method [key/choice field]—"tells which of the next three fields are filled and is descriptive of the method for calculating the nominal electric equipment level in the Zone." [3]
  - EquipmentLevel [W]
  - Watts/Area [W/m^2]

- Watts/Person [W/person]

- Heat Gains from Electric Equipment
  - Fraction Latent [unitless, 0 to 1]
  - Fraction Radiant [unitless, 0 to 1]
  - Fraction Lost [unitless, 0 to 1]—e.g. "electrical energy converted to mechanical work or heat that is vented to the atmosphere." [3]

3.3.2 Other equipment

Other equipment types in EnergyPlus that have same input format as Electric Equipment (just a different keyword):

- Gas Equipment
- Hot Water Equipment
- Steam Equipment
- Other Equipment ("provided as an additional source for heat gains or losses directly to the zone with a fuel type that is configurable." [3])

3.4 Schedules

Schedules describe *when* things happen in the simulated building, e.g. occupancy density, illumination, thermostats, and more.

Internal gains can be "described to EnergyPlus as a design or peak level with a schedule that specifies a fraction of the peak for each hour" [2]. EnergyPlus uses a nested set of schedule pieces to build unique schedules [4]:

- **Day Schedule**: 24 hour period of schedule values
- **Week Schedule**: Consists of various Day Schedule definitions for an entire week
- **Schedule**: Consists of various Week Schedule definitions for an entire year

These can also be designated as a certain **ScheduleType**: an "optional feature that allows for some validation and limitation of schedules." This could indicate things like minimum and maximum limiting values, or allowing continuous v. discrete numbers within a given range. [4]

The **Schedule:Compact** object allows for entering a schedule (with each of the components above) in one, rather than multiple, objects.

Schedule information can also be pulled from a separate file using the **Schedule:File** object, as long as the file is a "text file with values separated by commas (or other optional delimiters) with one line per hour" [3]. Note that although hourly values are provided for schedules, there are optional fields allowing for the schedules to be interpolated at each timestep, or provided in intervals of a prescribed number of minutes [3].

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Lecture 13. BEM: Building Systems, Part II
Heating, Ventilation, & Air Conditioning

"A study of 60 buildings by Lawrence Berkeley National Laboratory showed that, before intervention, at least half had problems with their system controls, a minimum of 40% had faulty HVAC equipment, and 25% or more had problems with specific 'green' HVAC features (Piette, Nordman, Greenberg, 1994). One group of researchers estimated that finding and fixing these types of problems can save $18 billion or more per year in commercial buildings in the U.S. alone (Mills et al., 2004)."
— Samuelson, Ghorayshi, and Reinhart [8]

1 EnergyPlus

To allow EnergyPlus to incorporate HVAC equipment, we need to provide it with information about [5]:

- Equipment types
- Operating schedules
- Control information

There are many more types of HVAC systems than we could hope to cover, even having an entire semester to study HVAC. However, if you have a very basic amount of technical knowledge on a certain type of system, the Engineering Reference document [3] contains the basic math describing how it's implemented in EnergyPlus. Unless your system is very unusual or new, it's likely someone has implemented it in EnergyPlus already. Figure 1 shows a simple abstracted illustration of a VAV system (Guest 1 Lecture), and the documentation explains the mathematical implementation of this system in EnergyPlus at the building level, zone level, and down to the coils in an individual VAV box [3].

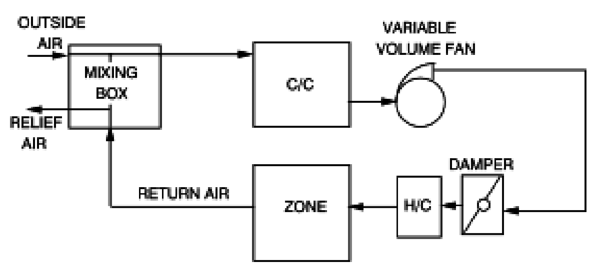

Figure 1: Simplified Variable Volume Air System from EnergyPlus Engineering Reference [3]

2 OpenStudio

In OpenStudio, the HVAC Systems tab shows us a representation of the air systems distributing air through a building, or other "plant loops" circulating fluids (e.g. hot water or chilled water) within the building. In this tab, we can leverage templates that are already compiled (e.g. BCL [1] or libraries added through File -> Load Library), which gives us a lot of drag & drop functionality and ways to quickly set up HVAC systems.

We have three sub-tabs within the right panel:

My Model displays items that are part of your model already. [7]

Library includes components and measures that come with the application or are downloaded from the Building Component Library (BCL). [7]

Edit allows you to select certain components and edit the settings for that component. It is used in the HVAC tab to edit component settings, assign thermal zones to loops, and to add plenums. [7]

The "Creating Your Model" page in the OpenStudio documentation [7] shows examples of your options for air and plant loops in the OpenStudio interface–click on Air, Plant and Zone HVAC Systems.

3 Ventilation

The EnergyPlus documentation defines ventilation and explains the minimum information needed to model it:

> **Ventilation** (Object: ZoneVentilation:DesignFlowRate) is the purposeful flow of air from the outdoor environment directly into a thermal zone in order to provide some amount of non-mechanical cooling ... Simple ventilation in EnergyPlus can be controlled by a schedule and through the specification of minimum, maximum and delta temperatures. [3]

The outdoor air used for ventilation can be quantified by [9]:

- CFM (cubic feet per minute) per person
- CFM per square foot (area) of the space
- Air Changes per Hour (ACH)
- Percent of total supply air

The collections of fans, heating and cooling coils, and terminal units shown in OpenStudio's HVAC tab make up an air loop:

> In EnergyPlus an **air loop** is a central forced air HVAC system. The term 'loop' is used because in most cases some air is recirculated so that the air system forms a fluid loop. The air loop is just the 'air side' of a full HVAC system. The input objects related to these air loops begin 'AirLoopHVAC.' For simulation purposes the air loop is divided into 2 parts: the primary air system (representing the supply side of the loop) and the zone equipment (representing the demand side of the loop).

When we talk about ventilation, we also have to acknowledge **infiltration**, which is "air leakage" or more generally any air flow to the interior that isn't directed by design (such as through mechanical systems bringing air in through an air handling unit). This needs to be included in the model for the airflow and overall heat balance models to be correct.

4 Sizing HVAC equipment

EnergyPlus has a "sizing manager" module that can do sizing calculations for equipment, including some newer advanced options for HVAC equipment. The general method includes [3]:

1. A zone by zone heat balance load and air-flow calculation for multiple design days;
2. Significant user control with modest input requirements;
3. Zone, system and plant level calculations of design heating and cooling capacities and fluid flow rates;
4. Modular, component-specific sizing algorithms for each HVAC component.
5. Options for monitoring how the initial sizes operate over multiple design days and then making adjustments and repeating plant level calculations

5 Controls and temperature setpoints

EnergyPlus has many ways to implement control of HVAC systems, some of which might correspond directly to an actual piece of equipment that implements control logic, and some which are more abstract or much more high-level. One simple type of control which you will be familiar with and may interact with in your simulation models is the thermostat controlling a zone. Because a zone is assumed to be at uniform temperature (Lecture 12), this is the most detailed level of thermostat control that's possible.

This is managed in EnergyPlus using the ZoneControl:Thermostat object, which has a few valid types of control:

0 Uncontrolled (No specification—temperature will be determined using energy balances but the equipment will not attempt to reach or maintain a temperature)

1 Single Heating Setpoint (No cooling specification)

2 Single Cooling SetPoint (No heating specification)

3 Single Heating/Cooling Setpoint (Same setpoint whether in heating or cooling mode)

4 Dual Setpoint (Heating and Cooling) with deadband

6 Heating

Here are a few types of equipment that you may see in HVAC models for heating [4]:

Baseboard Heat baseboard heating system, controlled by a thermostat and heated with hot water or electric resistance heating.

Heat Pump generic term for a device that moves heat from a cold source to a hot sink—like a refrigerator, but we're interested in Q_H instead of Q_L [2].

Boiler heating device that heats up water to provide thermal energy, often by burning natural gas

Furnace heating device that heats up air, often by burning natural gas

7 Cooling

Here are a few types of equipment that you may see in HVAC models for cooling [4]:

Chiller generic term for a device that removes heat from a liquid, often water

Vapor-compression chiller a chiller that operates on the vapor-compression refrigeration cycle (and here we care about Q_L)

Chilled beam a heat exchanger at ceiling level, as seen in the MEK building. Basic idea:

> Warm air from the space rises toward the ceiling, and the air surrounding the chilled beam is cooled, causing it to descend back toward the floor, creating convective air motion to cool the space. This allows a passive chilled beam to provide space cooling without the use of a fan. [6]

8 Ideal System Air Loads

EnergyPlus has a useful capability to study the "loads" or demands on an HVAC system without being tied a given type of system. This is handled within the ZoneHVAC:IdealLoadsAirSystem object.

> It is not connected to a central air system—instead each ZoneHVAC:IdealLoadsAirSystem object supplies cooling or heating air to a zone in sufficient quantity to meet the zone load or up to its limits, if specified . . . It is modeled as an ideal VAV terminal unit with variable supply temperature and humidity. The supply air flow rate is varied between zero and the maximum in order to satisfy the zone heating or cooling load, zone humidity controls, outdoor air requirements, and other constraints, if specified. [3]

Note that because it's "ideal" you won't get proper quantification of the costs and needs of an actual HVAC system (e.g. fan energy, electricity or fuel costs).

> The energy required to condition the supply air is metered and reported as DistrictHeating and DistrictCooling. [4]

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Lecture 14. Occupants and Buildings
Thermal Comfort, Environmental Quality, and Productivity

"Thermal conditions and indoor air quality tend to affect performance 'across the board', suggesting that it is the ability to concentrate and to think clearly that is affected."
— Wargocki and Wyon [4]

1 Thermal Comfort

Both passive (e.g. insulation) and active (e.g. air distribution) systems within the building contribute to the general conditions of thermal comfort that are sensed by the occupants.

If you've ever lived (or even gone on a road trip) with someone who preferred temperatures a lot warmer or cooler than you do, you're instinctively aware that different people perceive thermal comfort differently. However, there are some reasonable generalizations we can make about how comfortable we would expect a population to be under a certain set of thermal conditions. Simply put:

> Thin clothing and warm air is equivalent to warm clothing and cool air, in terms of the resulting effect on both performance and thermal comfort. [4]

Researchers have also firmly established that thermal comfort can affect both a person's subjective experience of their environment and some objective measures of productivity, but:

> It is not proven that subjective acceptance of indoor environmental conditions leads to optimal performance. [4]

There are six key variables that influence the thermal comfort of an occupant:

1. Air temperature (dry bulb)
2. Humidity (typically indicated by relative humidity; could also be a humidity ratio or wet bulb temperature)
3. Air velocity
4. Mean radiant temperature
5. Clothing insulation
6. Activity level or metabolic rate

The first four are *environmental variables*, relating to the occupant's environment. In an air conditioned building, these are controlled for directly (usually 1 and 2) or indirectly (3 and 4, which are a result of the passive and active components of building design and operation).

You may not have heard of **mean radiant temperature**, which is measurement that incorporates radiation heat transfer to indicate "how much cooling (or warming) you get from the exchange of radiant heat to all the objects in the room" [3]. For a brief but more technical description, see the Designing Buildings Wiki page: `https://www.designingbuildings.co.uk/wiki/Mean_radiant_temperature`.

Each person is different in terms of their metabolic rate, which determines how much heat they generate (and reject to their surroundings) as a result of a given activity. Cultural expectations and personal preferences also determine a person's subjective experience of comfort in a given thermal environment.

In addition to differences between individuals experiencing the same thermal conditions, conditions can vary even within a thermal zone. Although EnergyPlus has defined a thermal zone as "a volume of air at a uniform temperature" (Lecture 12), and will simulate it as such, it is not possible in a real building to keep variables 1–4 perfectly constant throughout a defined area. If the building has been zoned thoughtfully and designed and controlled well, the thermal environment within a zone will be much more similar to other locations within that zone than it is to locations in other thermal zones.

The last two are *personal variables*, relating to the occupant. Your physiological metabolic rate drives heat transfer away from the body (unless you're somewhere extremely hot!), but is not something you can immediately control for, or even measure accurately without significant equipment and inconvenience. Your clothing level (i.e. thermal insulation) and activity level (i.e. driving rate for heat generation) can change from day to day or even throughout the day.

ASHRAE publishes Standard 55 which "specifies conditions for acceptable thermal environments and is intended for use in design, operation, and commissioning of buildings and other occupied spaces" [1]. Clothing level is quantified in ASHRAE 55 in units of **clo**, and activity level is quantified in ASHRAE 55 in units of **met**.

There are two simple ways to quantify the expected thermal comfort satisfaction prescribed by occupants. A number of models for quantifying thermal comfort exist, with some additional complexity beyond the PMV and PPD methods described below. ASHRAE 55 also specifies an adaptive thermal comfort model that applies to "naturally conditioned" (i.e. not air conditioned) spaces [1].

1.1 Predicted Mean Vote

The **predicted mean vote (PMV)** index gives a statistical prediction of how a population would vote on its thermal comfort under a certain set of thermal conditions. Votes are considered on a 7 point scale [1]:

-3 Cold

-2 Cool

-1 Slightly cool

0 Neutral

1 Slightly warm

2 Warm

3 Hot

A negative PMV would indicate that more occupants found the space to be cool than warm; a positive PMV would indicate that more occupants found the space to be warm than cool. A PMV of zero would indicate that, on average, the votes for coolness or warmness were equal, although no information is directly provided about the spread of the data, so that many people could still be dissatisfied even when the PMV is technically 'neutral.'

1.2 Percentage of People Dissatisfied

The **percentage of people dissatisfied (PPD)** index gives a statistical prediction of how many people (out of 100) would indicate that they are thermally uncomfortable under a certain set of thermal conditions. If you want at least 85% of your occupants to indicate that they are comfortable, you would want a PPD of 15 or less. A PPD of 0 would indicate that absolutely everyone is happy with their thermal environment, so as you might imagine, it's rare to set that as your goal—the lower the better, though.

2 Indoor Environmental Quality

Thermal comfort is the result of one aspect of a broader metric for the suitability of an interior for an occupant called **indoor environmental quality (IEQ)**. We focus most extensively on thermal comfort because it is particularly relevant to thermal simulation, building energy use, and HVAC; it is necessary but not sufficient for providing a quality indoor environment.

To support productivity and health for its occupants, the indoor environment, as a whole, should include consideration of each of these aspects:

- Thermal environment
- Indoor air quality
- Lighting
- Acoustics

An occupant who is able to enjoy the indoor environment without concern or health risk would be thermally comfortable, while breathing air that is free of pollutants and excessive CO_2, enjoying adequate lighting for their tasks without unpleasant glare, and free from excessive noise.

ASHRAE publishes Standard 62.1 which "specifies minimum ventilation rates and other measures for new and existing buildings that are intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects" [2].

3 Health, Productivity, and Wellness

In recent years, the conversation around indoor conditions has shifted from minimizing discomfort and avoiding pollutants to maximizing human *wellness*.

One organization publicizing this approach to building design and operation is the International WELL Building Institute. Like LEED, they provide certifications in silver, gold, and platinum, but their standards focus on making buildings *beneficial* for their occupants in many ways.

> Nature has long been our caretaker. With intentional design, our buildings can be too. [5]

The WELL v2 Building Standard is accessible online, currently as a pilot version, at `https://v2.wellcertified.com/`. It is comprised of ten concepts [5]:

- Air
- Water
- Nourishment
- Light
- Movement
- Thermal Comfort
- Sound
- Materials
- Mind
- Community

Notice that Thermal Comfort, Air, Light, and Sound are paraphrased versions of the traditional four aspects of IEQ listed in the previous section. This particular standard goes beyond this list of concerns and also addresses these concerns within the built environment [5]:

- Availability of clean drinking water and water management within a building
- Availability of fresh food and transparency of nutritional information
- Promotion of movement and physical activity, reducing sedentary behaviors
- Safe, low-emission materials, reducing exposure to hazardous or toxic materials
- Promotion of mental health, both cognitive and emotional well-being
- Access to healthcare, family accommodations, social equity, and civic engagement

These categories, while far from the traditional concerns of building scientists and engineers, encompass more of the factors that influence the productivity of occupants. Thermal comfort is only one particular perception that will connect with a person's physical, mental, emotional and social experiences to define their perception of the indoor environment and their performance therein.

References

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Lecture 15. Building Energy Use: Efficiency, Productivity, Conservation, and Operating Costs

"There are many different kinds of energy, all of which are measured in joules. Yet energy is always conserved and never destroyed: instead it is transformed."

— William F. Pickard [6]

1 Energy Efficiency

Energy efficiency (EE) in general is about getting *more* output or benefits for *less* input or costs. To make sure you're comfortable with the engineering terminology and variables I'll be using here, see the thermodynamics review (Lecture 2) or your textbook as needed. Unless otherwise noted, assume that we are talking about a First Law efficiency.

1.1 Economic benefits from EE

There's no clear-cut way to say whether a given energy efficiency measure (EEM) is economically beneficial–it depends on the payback period (PBP) that the financing person or entity expects to receive, and there is always some uncertainty in whether the EEM performs exactly as expected (including uncertainty in external factors like weather), although engineering judgment and wise use of modeling and calculation tools can help to reduce that. A simple payback period just indicates the amount of time required to recover an investment. We'll discuss more complicated methods of calculating economic metrics in Lecture 17.

$$PBP = \frac{CC}{AR} \tag{1}$$

where CC represents the capital cost outlay [$] and AR represents the annual return [$/yr]. You can see from the units that the payback period will conventionally be described in years (although we might be lucky enough to find a project with a PBP of only a few months).

Efficiency is a description of what we *get* versus what it *costs* us, i.e. Energy in/Energy out. By convention, the numerator and denominator should be in the same unit system so that we come up with a fractional number between 0 and 1.

1.2 Device efficiency

When we think of efficiency, we are most often thinking of it at the device level. This is also the most straightforward type of efficiency to quantify: we consider one control volume and we measure the fuel (for example) that goes in and the mechanical work (for example) that comes out.

1.2.1 Heating (combustion) devices

If we're using fuel to provide heat, then we want a description of how much thermal output we have for each unit of fuel input. Fuel energy is described by its heating value:

> The **heating value** of the fuel...is defined as the amount of heat released when a fuel is burned completely in a steady-flow process and the products are returned to the state of the reactants. [4]

Note that this definition emphasizes the state of the products of the chemical reaction. It's important to differentiate between higher and lower heating values because they will different for the same fuel, and therefore you'll get different efficiency results for a fuel-burning device when you use one or the other. The **higher heating value (HHV)** means that the water in the products is in a liquid phase (e.g. condensing boiler), and the **lower heating value (LHV)** means that the water in the products is in a gaseous phase (e.g. water vapor exiting with combustion exhaust).

1.2.2 Cooling (or heat pump) devices

Devices that use energy (usually electrical) to move heat are described in terms of their **coefficient of performance (COP)** rather than using the term 'efficiency.' It still tells us the same type of information: What we *get* versus what it *costs* us, only what we get is the movement of heat and what it costs us is electricity. By convention, the numerator and denominator should be in the same unit system so that we come up with a dimensionless number, but we are not limited to a number between 0 and 1 (and in fact, a COP below 1 would be quite bad for, say, a vapor compression refrigeration cooling device).

In practice, COPs for cooling devices (or heat pumps) are often discussed using metrics with units:

Energy efficiency ratio (EER) is a COP given in units of $\frac{BTU}{Wh}$. Note this is a watt-hour and not a kilowatt-hour; this is a conventional unit for this particular metric. One way to think of it is that you're moving X BTUs per hour using Y amount of electrical power.

Seasonal energy efficiency ratio (SEER) is an EER that is taken over an entire year, or over a cooling season. This metric tries to capture the fact that a given cooling unit will not be operating at steady state in the real world, and its performance will be affected by changing conditions. Details on how this is calculated can be found in the ANSI/AHRI Standard 210/240 [3].

1.3 System efficiency

When we combine devices into systems, it becomes even more important to clearly state the method used for calculating efficiencies. For example, you have options [9] in describing the efficiency of a combined heat and power system, which provides both electrical energy and thermal energy, based on whether you're trying to capture the thermal efficiency as described using the first law in our engineering thermo courses or whether you're trying to compare a CHP system against a conventional power generation system (Lecture 3).

2 Energy Productivity

Energy productivity is another term you may see that is similar to efficiency, although it's usually much broader than the tightly defined types of efficiency we tend to think of when we hear energy efficiency. In general, we can say that this represents the services or benefits that we receive from each unit of energy used in a certain way. The U.S. Department of Energy defines energy productivity on a national scale as "the ratio of economic output (gross domestic product (GDP)) to primary energy use." [1]

3 EUI for buildings

The energy performance of a building as a whole is often described in a rough sense as its **energy use intensity (EUI)**, which normalizes site energy use with the building's floor area. It's common to use the total site energy consumed (of whatever type) divided by the total gross floor area [10], but could be done on a source energy basis [7] or per unit area of conditioned space basis, depending on what you're concerned with.

It's a classic way to benchmark a building, either to gauge its overall efficiency or to set a baseline before some EEM takes place. It's common to compare against buildings of similar use types (see Lecture 9 for general categories):

> Generally, a low EUI signifies good energy performance. However, certain property types will always use more energy than others. For example, an elementary school uses relatively little energy compared to a hospital. [10]

When benchmarking and comparing, it's important to specify clearly how the EUI is defined, and to consider the effects of weather on building energy use. If you want to get a sense of the range of EUI values for different types of buildings, Energy Star Portfolio Manager provides some national guidelines [8]. They also provide free online tools that can help you benchmark an existing building [2].

4 Energy Return on Energy Invested

Pickard [6] provides a brief introduction to, and thoughtful critique of, the use of the EROI concept. Here is the basic explanation:

> The concept of **energy return on energy invested (EROI)** is related to the familiar economic observation that a wise investor does not expend more money on a project than, in aggregate, he expects to get back. Therefore, it is commonly defined as EROI = (energy output)/(energy input) = (energy returned)/(energy invested); and one desires it to be greater than one: much greater. [6]

This opinion article [6] provides some thoughtful questions and recommendations about how EROI is used for policymaking, and how the implications of this concept change when energy sources are renewable versus conventional.

Hall et al. [5] explain that a reduction on EROI (meaning it takes more energy input to produce a certain amount of energy output) is also tied into our economic development:

> Declining EROI means that an increasing proportion of energy output and economic activity must be diverted to attaining the energy needed to run an economy, leaving less discretionary funds available for "non-essential" purchases which often drive growth. [5]

5 Energy Conservation

It's important to note that energy conservation refers to a reduction in energy expenditures, so while it is often related to energy efficiency, they are not the same thing. We can conserve energy by simply building a smaller building, by turning a device off entirely (mathematically, making its efficiency ∞ if our needs are still met), or perhaps even by replacing a system with a less efficient system (from a First Law perspective) that has to run much less often (thereby using less input overall).

6 Operating Costs

We can broadly divide the energy and water-related operating costs for a typical building into the types of resources used:

- Purchased electricity (kWh)
- Fuel used on-site (BTU)
- Water used on-site (gal)
- District energy purchases, e.g.
  - Steam
  - Hot water
  - Chilled water

Remember that simple payback is defined as the cost to implement divided by the savings per year. For projects that save energy, the annual savings are often described in units like MMBtu or MWh, and these must be converted to a dollar amount to get a value for PBP. If the facility does not pay a flat rate like most of us do for kWh consumed in our homes (e.g. they are a on a rate schedule that charges for energy in blocks and/or they have demand charges to content with), this could be a tediously detailed undertaking to accurately quantify.

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Lecture 16. BEM: Parametric Analysis

> "Computerized searching has the potential to automate the input and output, evaluate many options, and perform enough simulations to account for the complex interactions among combinations of options."
> — Ellis, Griffith, Long, Torcellini, and Crawley [2]

1 Parametric analysis for modelers

We will use the term **parameter** here in one of its broadest senses, that is, "any of a set of physical properties whose values determine the characteristics or behavior of something." [1]

The term **parametric analysis** encompasses methods for varying model parameters (e.g. through building energy simulation) and, hopefully, learning from the changes in model outputs. Samuelson et al. [7] provide a brief description of the advantages of performing parametric analysis with your simulations during a design process:

> By utilizing parametric simulation techniques with today's computing power, a modeler can evaluate numerous potential designs to produce guidance that design teams can use as an informed starting point in the design process. [7]

Parametric analysis is a closely related concept to *sensitivity analysis*, which we will study more formally in the latter half of this course. A parametric analysis varying one particular variable over a range of values would be the simplest form of a sensitivity analysis, but there are much more complex methods, and the phrase sensitivity analysis usually implies a more formal mathematical quantification of how changes to the input(s) affect the output(s).

Within the discipline of statistics, 'parameter' and 'parameter statistics' have narrowly defined meanings, so be careful using terms in that context.

2 Parametric analysis and the built environment

There are often a number of parameters that can be changed in building energy analysis, both those relating to the design and operation of the building and those related to the conditions it experiences. Here are some examples of parameters related to energy performance [8]:

- Geometry
- Materials
- Glazing system (fenestration/windows)
- HVAC (system or schedule)
- Lighting (system or schedule)
- Plug loads (system or schedule)
- Occupancy (system or schedule)
- Adjacent site conditions
- Weather conditions

Running simulations for a parametric analysis can allow us to investigate the range of effects of a given change on the outputs we are most interested in (e.g. overall energy use, fuel and electricity costs, carbon emissions). Samuelson et al. [7] describe one of the difficulties with taking advantage of parametric analysis tools during a building design process:

> Simulations traditionally used in the building industry require detailed inputs and, therefore, are difficult to employ in early design stages when the pace of design iteration is fast and the simulation inputs include many unknown variables. [7]

In this quote, they are summarizing the work of Ochoa et al. [4], who describe specific hurdles for using thermal models for building performance early in the design process:

> "They require exact data in a stage when designers consider conceptual ideas from a range of options rather than precise details and numbers... The number of possible configurations can be overwhelming and decisions made in early stages have profound effects on energy and comfort performance.
>
> It would be desirable to include an accurate energy evaluation system for the first design stages that is capable of modelling the complexity of these systems... [But] most tools are dedicated to evaluate and model a certain finished alternative, not to suggest and evaluate different design options and directions." [4]

This is particularly difficult early in the design process, when the most opportunities exist for affecting the ultimate performance of the building. However, in all phases of the design process (including retrofit design for existing buildings), we will benefit from:

- Flexibility in the level of detail included in the model
- Narrowing down the number of design parameters to those that can have the most impact on performance [7]
- Ability to run many simulations when the range of potential parameter values is large
- Easy to use interface for the modeling tool [4]
- Visualization tools that clearly illustrate the differences resulting from varying parameters or design choices
- Rapid elimination of options that are not feasible or "dead-ends" [4]
- Changing modeling tools to become more detailed as the design evolves [7]
- Integrating expert knowledge and engineering judgement based on experience as model results are evaluated

3 Parametric analysis with OpenStudio

OpenStudio provides support for parametric analysis through a specially designed interface. This program also has support for running multiple models on the cloud through AWS. The basic steps to use the tool (on your desktop computer) are [5]:

1. Open the Parametric Analysis program — This is a separate application that was installed in your OpenStudio directly with the OpenStudio interface application.
2. Name your project — This will be the name of the directory where your parametric analysis is stored.
3. Provide a default seed model — This is the OSM model that will provide a baseline for the parametric analysis.
4. Provide a default weather file — This is the EPW file that will provide a baseline for the parametric analysis.
5. Add measures to your project — These can be OpenStudio, EnergyPlus, or Reporting measures.
6. Select measures and create design alternatives — These are the changes that will be made when the simulations are run.
7. Run simulations — Select the design alternatives you want to run and click the simulate button, just like in the OpenStudio interface.
8. View results — "You can open htm report files in your browser. EnergyPlus and standard and calibration OpenStudio reports can be found by right clicking on a design alternative, on the Results tab, and selecting the results you want to view." [6]

4 Presenting parametric analysis results

We often have multiple things that could potentially be varied in our analysis, and we want to be able to present the results in a way that captures more than the variation in a single parameter. For example, Szabo et al [3] analytically calculated the maximum 'heat load' (that is the rate of heat removal that would be necessary for air conditioning, or what we would think of as 'cooling load') for a simple reference room. One of the conclusions of their paper was that "The sensitivity of the heat load depends on the orientation and chosen summer day," which isn't something we can directly put into practice without more details. Figure 1 show the results obtained for a *glazing ratio* (think window-to-wall ratio) of 20–80%. Note that in their presentation of these results they are also capturing important differences that are relevant to the design process, and their parametric results between 20% and 80% glazing look slightly different depending on these other factors:

- The room's orientation was tested in all four cardinal directions.
- They considered cooling the room's surfaces and tested the need for cooling on a wall versus on the ceiling.
- Symmetric weather days assume that east and west orientations receive the same amount of solar radiation (which was an assumption made in the standard they were using), while asymmetric weather days represent that in their location it is actually the case that "solar energy yield for East orientation exceeds the data registered for West orientation." [3]

They have aligned all the wall cooling results on the left and ceiling cooling results on the right, as well as providing one cardinal direction in each row of Figure 1. It would have been almost impossible for us to compare across these factors by looking at this figure if the graphs had not been ordered in a logical manner.

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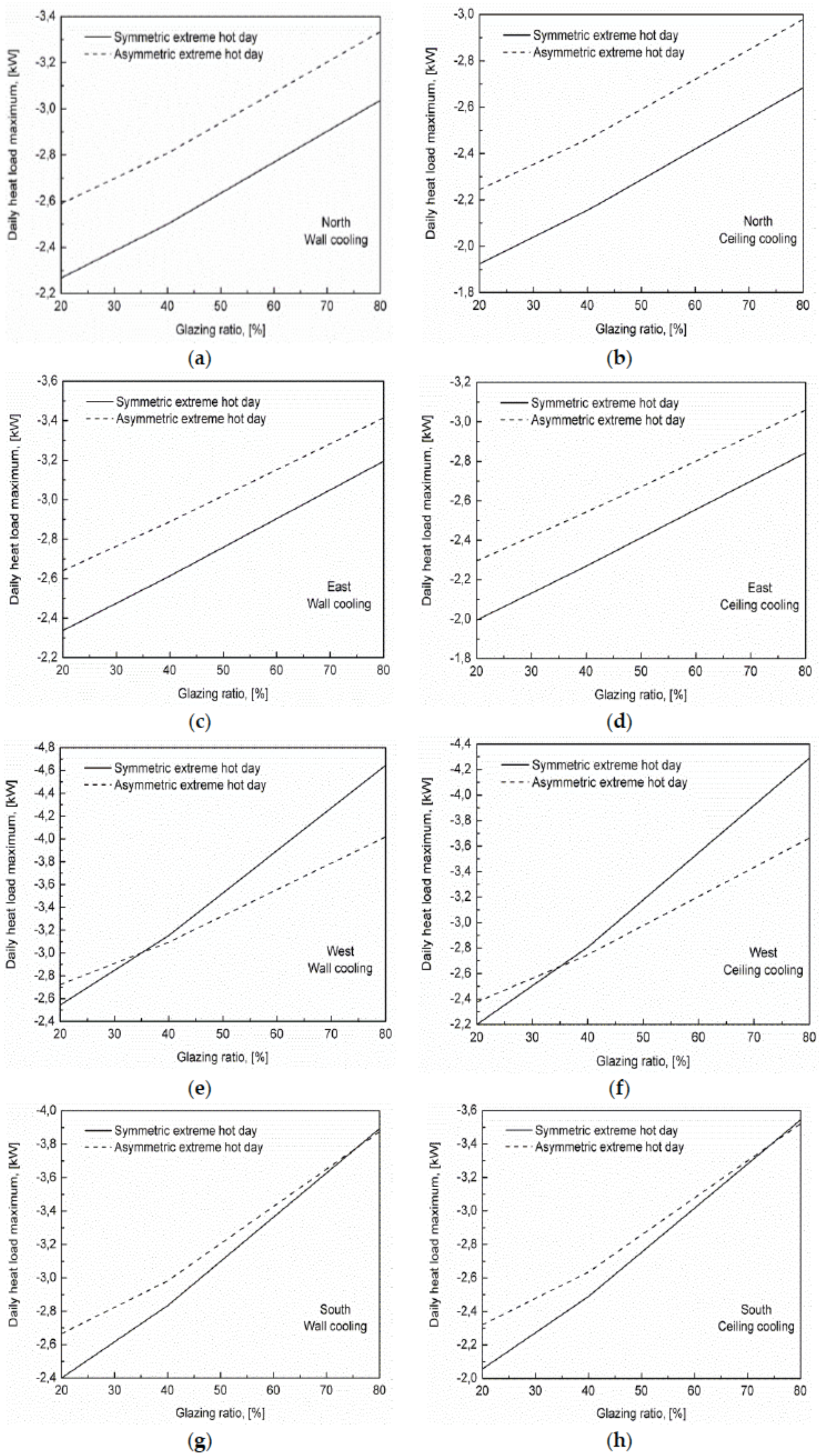

Figure 1: Interrelation between glazing ratio and the maximum of the daily heat load. (a) North orientation and wall cooling; (b) North orientation and ceiling cooling; (c) East orientation and wall cooling; (d) East orientation and ceiling cooling; (e) West orientation and wall cooling; (f) West orientation and ceiling cooling; (g) South orientation and wall cooling; (h) South orientation and ceiling cooling. [3]

Lecture 17. Building Energy Use and the Energy Sector: Basic Engineering Economics

"All market-based economies operate against a background of laws and regulations, including laws about enforcing contracts, collecting taxes, and protecting health and the environment."
— Steven A. Greenlaw et al. [2]

1 Time value of money

"The ability to make personal choices about buying, working, and saving is an important personal freedom."
— Steven A. Greenlaw et al. [2]

The phrase **time value of money** refers to the fact that it's preferable to have money *now* rather than an equivalent sum at a later time. If I offered you $20 right now, you'd take it. If I offered you $20 at the end of the semester as an alternative, you'd turn it down and take the first option. But there's some larger amount of money you'd be willing to wait for, and pass on the $20 now (assuming you believed I would deliver at the agreed-upon date).

1.1 Interest rate

The term **interest rate** can refer to either the cost of borrowing in a financial market (e.g. interest rate on a mortgage) or to the benefit reaped from an investment (e.g. rate of return based on an energy conserving upgrade).

1.2 Discount rate

The **discount rate** is the interest rate that banks pay to receive loans. It has become a major lever of monetary policy: "If the central bank raises the discount rate, then commercial banks will reduce their borrowing of reserves from the [Federal Reserve], and instead call in loans to replace those reserves. Since fewer loans are available, the money supply falls and market interest rates rise. If the central bank lowers the discount rate it charges to banks, the process works in reverse." [2] This means that even if you have zero debt and pay for everything in cash, the prices you pay (and your own net wealth) result from a combined "interlocking system of money, loans, and banks." [2] Talk about complex systems!

If you're not familiar at all with U.S. financial history, check out Ch. 28 of the open textbook *Principles of Economics 2e* [2] —the financial news will make a lot more sense in context. And who would have thought that the interest rate we get when purchasing a house here in Salt Lake City in 2019 results from the operations of a system whose purpose and structure were a reaction to bank runs circa 1907? (Full disclosure: I learned about bank runs from the movie *Mary Poppins*.)

2 Economic metrics for energy systems and energy-related investments

"The ability to make personal choices about buying, working, and saving is an important personal freedom."
— Steven A. Greenlaw et al. [2]

We discussed the simple payback period in Lecture 15 as our most simple and straightforward way to quantify the potential benefit of an investment. Larger and more complex investments may require other metrics that capture more information about the potential benefit of the investment. It is particularly valuable when we can capture the time value of money because a company that is considering making an investment will want to compare the potential investment against all the other options they have for making money in the same time period.

Long-term financial projections are also a great place to apply uncertainty analysis, which we will learn about in more detail in the second half of the course, because a relatively small amount of uncertainty in one of the inputs to a financial model could lead to dramatic differences in the outputs in terms of expected revenue or payback period.

2.1 Discounted payback period

The term **discounting** refers to "a technique for converting cash flows that occur over time to equivalent amounts at a common point in time using the opportunity cost for capital." [1] If you had a specific number in mind for the example described in Section 1 like, say, \$30, then you are *discounting* that \$30 a few months from now into an equivalent \$20 now. That is some steep discounting!

You may also see the term 'discount rate' used in a microeconomic sense to describe a more personal discounting that incorporates the time value of money to that individual: "The rate of interest for which an investor feels adequately compensated for trading money now for money in the future is the appropriate rate to use for converting present sums to future equivalent sums and future sums to present equivalent sums. ... This rate is often called the *discount rate*." [1]

The discounted payback period of an investment is the number of years N where:

$$DPBP : CC = \sum_{t=0}^{N} \frac{AR}{(1+d)^t}$$

where CC = capital costs, d = discount rate (in the sense described here in Section 2.1), t = time in number of years, and N = number of years in the analysis period (Section 3).

Annual return can also be expressed as:

$$AR = B_t - C_t$$

where B_t = benefits in year t and C_t = costs in year t. [1]

2.2 Life cycle cost

The life cycle cost of an investment is:

$$LCC = I + E + O\&M + R - S$$

where, for the alternative being considered, I = present-value investment costs , E = present-value energy costs, $O\&M$ = present-value (non-fuel) operating and maintenance costs, R = present-value repair and replacement costs, and S = present-value salvage or resale value. Note that if disposal costs exceed the salvage value of an investment, the S term would be negative, and when multiplied by the negative sign in front of the term, would add to the overall LCC value.

2.3 Net present value or present discounted value

You may also see this called present discounted value [2] or present value (PV), but we'll reserve the acronym PV for photovoltaics in here.

Net present value of an investment is:

$$NPV = \sum_{t=0}^{N} \frac{FV}{(1+i)^t}$$

where FV = future value (received years in the future), i = annual interest rate, t = time in number of years, and N = number of years in the analysis period (Section 3). [2]

Future value can also be expressed as:

$$FV = B_t - C_t$$

where B_t = benefits in year t and C_t = costs in year t. [1]

2.4 Levelized cost

The **levelized cost of energy (LCOE)** is a common metric used to express cost for an energy supply system. It's important to note that this metric was designed for comparing alternatives, particularly comparing between two electric generation technology types.

> The LCOE is the value that must be received for each unit of energy produced to ensure that all costs and a reasonable profit are made. [1]

In its simplest form, LCOE is expressed as:

$$LCOE = \sum_{t=0}^{N} \frac{C_t}{Q_t}$$

where C_t = costs incurred in year t, Q_t = energy produced in year t, and N = analysis period (Section 3). [2]

Lazard, a financial advising firm who regularly release thorough analyses of LCOEs for the U.S., cautions with their own Levelized Cost of Energy Analysis [3]:

> Other factors would also have a potentially significant effect on the results contained herein, but have not been examined in the scope of this current analysis. ...This analysis also does not address potential social and environmental externalities, including, for example, the social costs and rate consequences for those who cannot afford distribution generation solutions, as well as the long-term residual and societal consequences of various conventional generation technologies that are difficult to measure (e.g., nuclear waste disposal, airborne pollutants, greenhouse gases, etc.). [3]

3 Analysis

"Economists believe that we can analyze individuals' decisions, such as what goods and services to buy, as choices we make within certain budget constraints."

— Steven A. Greenlaw et al. [2]

We, as engineering analysts, are dealing with a certain time frame over which the economic analysis is relevant. Selecting this time period is related to the technology of interest, the financial details, and the reason(s) for performing the analysis.

Useful life the period over which the investment has some value; i.e., the investment continues to conserve or provide energy during this period. [1]

Economic life the period during which the investment in question is the least-cost way of meeting the requirement. [1]

Analysis period need not be the same as either the "useful life" or the "economic life," ...The selection of an analysis period will depend on the objectives and perspective of the decision maker. [1]

3.1 Taxes and incentives

Taxes and incentives are important to consider within an economic evaluation, including: income taxes, sales taxes, property taxes, capital gain taxes, tax deductions, tax credits, energy incentives, subsidy grants, government cost sharing, loan interest reductions, tax subsidies, and income tax credits [1].

These may make a formerly promising investment less economically viable, or may take an investment that didn't look promising into the realm of economic viability.

The North Carolina Clean Energy Technology Center sponsors a public database (formerly Department of Energy-funded) that helps people find state-level incentives for renewables and energy efficiency projects in the U.S.: http://www.dsireusa.org/

3.2 Uncertainty and risk assessment

A simple sensitivity analysis, or parametric study on variables that may change throughout the lifetime of the project, allows us to understand how economic performance (in the form of whatever metrics are most relevant to the decision maker) will change as these variables take on different values.

> Although sensitivity analysis does not provide a a single answer in economic terms, it does show decision makers how the economic viability of a renewable energy or efficiency project changes as fuel prices, discount rates, time horizons, and other critical factors vary. [1]

When we are able to quantify the probability of obtaining certain values (i.e. assign statistical distributions to the variables), a formal uncertainty analysis can be used to incorporate the effects of these uncertainties into the predicted economic performance values.

Additional economic metrics and economic analysis methods exist that allow us to better capture the effects of uncertainties, including modified versions of some of the metrics shown in Section 2: expected value analysis, risk-adjusted discount rate (i.e. discounting values based on the decision maker's acceptable or typical level of risk), certainty equivalent (a version of NPV that accounts for uncertain outcomes), and others.

4 Economic performance and sustainability

> "Some academic disputes over environmental policies, like how much to reduce carbon dioxide emissions because of the risk that they will lead to a warming of global temperatures several decades in the future, turn on how one compares present costs of pollution control with long-run future benefits."
>
> — Steven A. Greenlaw et al. [2]

Economic performance is itself a pillar of sustainability (Lecture 1, 'prosperity') and affects whether the project itself will be sustainable as well as how the project will affect larger systems within the other two pillars of sustainability. Because there are inherent trade-offs and interconnections between ecological, social, and economic systems, methods like carbon tax accounting have been created to allow us to discuss environmental impacts in the language of finance.

In my own work, we prefer to look for opportunities to positively affect multiple sustainability pillars at the same time. For instance, where can we save emissions *and* reduce cost? How can we improve someone's experience in the built environment *and* use less water? I hope you will look for these potential bright spots in your work and that by the end of this course, you have a set of tools and ideas that allow you to quantify your analysis in a way that resonates with decision makers.

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Lecture 18. Building Energy Use: Quantifying Emissions and Water Use

"Given the increased urgency in curbing global greenhouse gas emissions, reducing the carbon footprint of new and existing buildings has become a priority in many jurisdictions."
— Brackney, Parker, Macumber, and Benne [2]

1 Emissions reduction

When discussing emissions reductions, it's important to clarify what exactly you are interested in reducing and why. A building may be responsible for emissions of CO_2, N_2O, or $PM_{2.5}$, but cutting CO_2 emissions in half is not the same thing as cutting $PM_{2.5}$ emissions in half. It's also not necessarily going to halve the building's carbon footprint.

Greenhouse gases (GHGs) contribute to global climate change, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (e.g. Freon) and hydrochlorofluorocarbons [14]. Their relative impact on global warming can be gauged with their **global warming potential** (GWP), which "is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2)." [17]

Local air quality is affected by a number of substances, including some emitted due to human activity in the built environment. Notably, **criteria pollutants** are those that the U.S. Environmental Protection Agency (EPA) uses to set quantitative standards for air quality: ground-level ozone (O_3), particulate matter (PM), carbon monoxide (CO), lead, sulfur dioxide (SO_2), nitrogen dioxide (NO_2) [4].

1.1 Direct

Direct emissions are those that occur at the site. These are probably the first emissions you think of when imagining a given building, and they may be prioritized (e.g. reducing the amount of combustion or increasing combustion efficiency) if the building's impact on local air quality is a driving concern.

These are also called **Scope 1** emissions within the Greenhouse Gas Protocol framework published by the World Resources Institute: "GHG emissions from sources located within the [site] boundary." [7]

1.2 Indirect

Indirect, or off-site, emissions are those that occur elsewhere but are caused or impacted by a building's operation. An example would be emissions occurring at a power plant that is burning fuel miles away while providing grid electricity that's purchased to provide services at a building site. They may be prioritized if the building's impact on greenhouse gas emissions is a significant concern.

These are also called **Scope 2** emissions within the Greenhouse Gas Protocol framework: "GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the [site] boundary." [7]

For a quick estimate of the indirect emissions associated with electricity purchases in a U.S. location, visit Power Profiler at `https://www.epa.gov/energy/power-profiler` and enter your zip code.

1.2.1 Flat rate emission factors

The most straightforward option for calculating indirect emissions to due electricity purchases is to use a simple flat rate emissions factor that gives one number for the amount of emissions per unit of electrical energy (e.g. lb/MWh). Power Profiler will show these numbers for CO_2, SO_2, and NO_x, and you can simply multiply by each MWh of electricity used to get an estimate for indirect emissions based on the region they've aggregated. Our eGRID subregion is WECC Northwest [1], abbreviated NWPP (for Northwest Power Pool), as shown in Figure 2. You may recall from Lecture 3 that this larger region is not necessarily representative of Utah's power generation mix; for instance, it includes a significant portion of hydropower generation. You could also make your own estimate based on Utah's fuel mix (see Figure 1); while there's no guarantee that electricity produced within the state will be consumed within the state (we are a net power exporter), this would be a little more representative of the fuel mix contributing to power purchased here compared with using the fuel mix for NWPP as a whole.

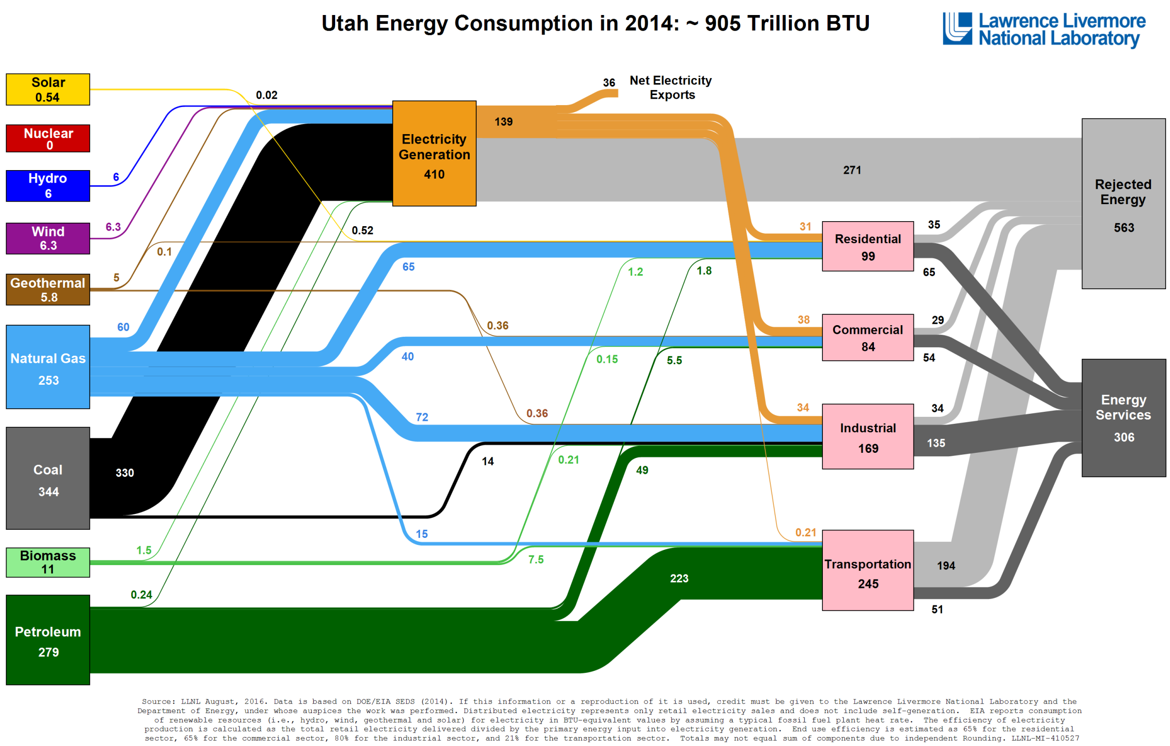

Figure 1: Utah energy flow chart for 2014 from LLNL [11]

This is quick and easy to implement, but doesn't capture anything about how emissions vary with time of use or location of use. If you use power disproportionately at peak or off-peak hours, or if you happen to be located in an area within the grid topology where electricity tends to be mostly generated by coal or mostly generated by renewables, this may give you an inaccurate picture of your "actual" emissions. It's not possible to account for your true emissions with certainty because it's not possible to physically trace a quantity of electrical energy to exact generators—we make a statistical best estimate.

1.2.2 Time-varying, regionally aggregated emission factors

Another option that's fairly straightforward to implement, but begins to capture some of the temporal variability in emissions from grid generators, is to use the Hourly Energy Emission Factors for Electricity Generation in the United States published by the National Renewable Energy Laboratory (NREL) and based on Environmental Protection Agency (EPA) data [9]. You may also recall these from Lecture 5. The emissions are based on changes to which generators are producing power at a given time of day and a given time of year, based on previously recorded data [5] and economic models run using GridView software [8].

There are two major concerns with the accuracy of this method: (1) The data are still aggregated, which means the building is treated the same no matter where it is located physically and within the grid network; and (2) The factors are the result of modeling performed with proprietary software, using data collected from 2005–2008 [9].

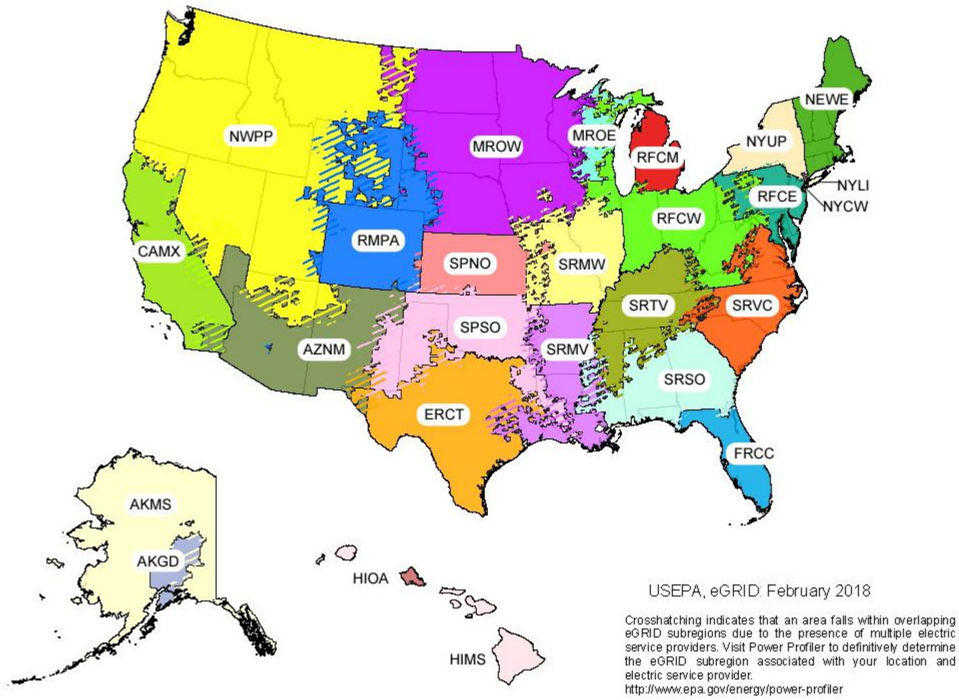

Figure 2: Representational map of the boundaries of eGRID subregions [1]

1.2.3 Temporally and spatially resolved emission factors

Finally, a technically preferred option, but one that's difficult to implement in practice, is to use real-time data about what generators are serving the load on the grid at a given time (or, in a simulation model, which generators would be expected to serve a given load at a given time). This requires data that often is not publicly available as well as computational resources. Please refer to the Lecture 5 slides and our related publication [6] for more about some of the methods that can be used to make this type of emissions quantification.

1.3 Embodied emissions

There are many reasons that emissions may be produced in conjunction with the manufacture and transportation of building components and with items we purchase and use day-to-day. These are called **Scope 3** emissions within the GHG Protocol: "All other GHG emissions that occur outside the [site] boundary as a result of activities taking place within the [site] boundary." [7]

As you can imagine, this is a difficult category to capture. The carbon footprinting exercise you did in Homework 1 was an attempt to look at CO_2 emissions holistically, including Scope 3 or 'embodied' emissions. Embodied (or you may also see the word 'embedded') indicates that the emissions are not readily apparent but that they should be accounted for within the environmental analysis of some product or service. We'll talk more about this idea in Lecture 19.

2 Water conservation

Water use due to human activity can affect ecosystems, weather and climate, food production, and the ability of other humans to have enough fresh water now and in the future to meet their basic needs. However, the use of potable, or treated, water is a small portion of overall water use. Most water used worldwide [18] and in the U.S. [10] is due to agriculture or power generation. If we continue to use water at current rates, we will face a water crisis—a severe deficit of available water to serve the world's population.

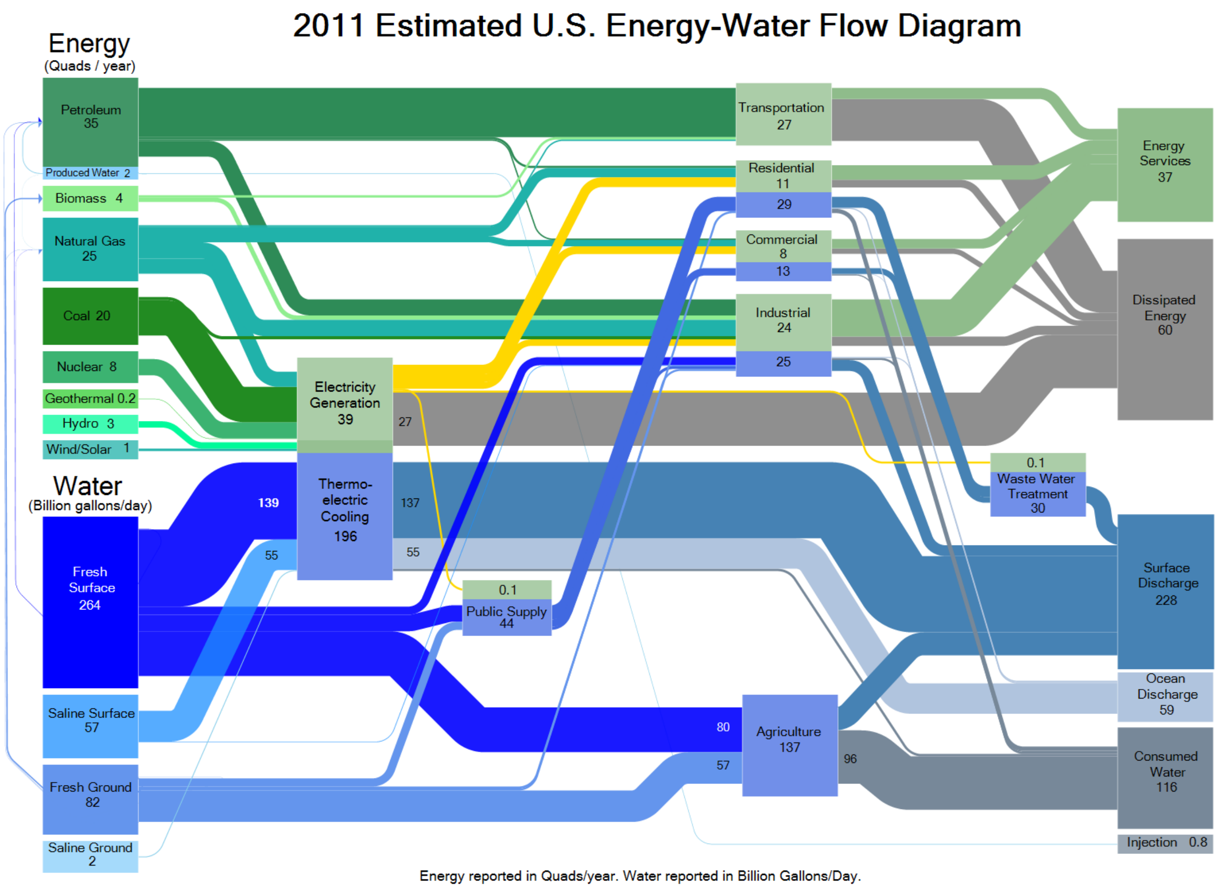

Figure 3: U.S. water-energy flow chart for 2011 [16]

2.1 Direct

Water conservation at the level of a building or energy system is straightforward—we want to use as little as possible to provide the services that we need. Direct water use is typically metered in gallons. Reducing direct water use in the built environment (Figure 4) usually involves conservation in restrooms or shower facilities, in water used for heating or cooling (evaporative cooling can be a significant water consumer in commercial buildings here in the West), and in outdoor landscaping [15]. The EPA provides resources for choosing water-efficient fixtures for buildings at `https://www.epa.gov/watersense`.

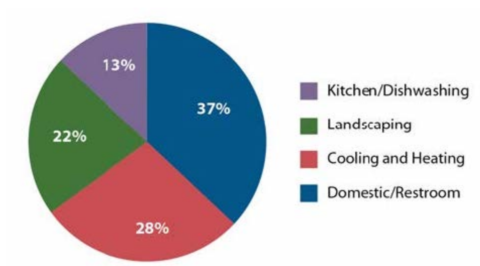

Figure 4: End uses of water in office buildings in the U.S. [1]

2.2 Indirect

A large portion of the water use that occurs due to human activity is hidden from our sight on a day-to-day basis. Indirect water use is also called 'virtual water.'

> Water **withdrawal** describes the total amount of water withdrawn from a surface water or groundwater source. Measurements of this withdrawn water help evaluate demands from domestic, industrial and agricultural users. [19]

> Water **consumption** is the portion of the withdrawn water permanently lost from its source. This water is no longer available because it evaporated, got transpired or used by plants, or was consumed by people or livestock. [19]

Some forms of power generation cooling systems might be extremely high in water withdrawn, with less being consumed (e.g. 'once-through' cooling systems); other forms have very high consumption rates but much less water withdrawn (e.g. cooling towers).

2.3 Water factors

As with emission factors, we can multiply out the quantity of electricity used by a water factor that gives one number for the amount of water *consumed* per unit of electrical energy (e.g. gal/MWh) and another number for the amount of water *withdrawn* per unit of electrical energy (e.g. gal/MWh). There are a limited number of comprehensive studies that have considered the available data and existing studies on water use for electricity generation to come up with water withdrawal factors and water consumption factors, and there is significant variance in the actual possible values for those factors, so as we saw with emission factors, this type of analysis has inherent uncertainty. There are two very nice U.S.-focused reviews that provide estimates for both withdrawal and consumption factors: one published in 2012 comes from NREL researchers and focuses more on cooling system technologies [12]; one published in 2013 comes from Western Water Assessment and NREL researchers and takes a life cycle perspective on electricity generation [13].

2.4 Embodied water

Embodied (or you may also see the word 'embedded') water indicates that the water use is not readily apparent but that it should be accounted for within the environmental analysis of some product or service. Water used to generate purchased power could be considered embedded water, as could water that was used to produce building components and items we purchase and use day-to-day.

3 Nexus view

The term **water-energy nexus** (or energy-water nexus) refers to the fact that energy and water systems are inextricably connected—water is used to generate electricity and provide energy services, and energy is used to extract, treat, and transport water. Constraints in water can lead to constraints in energy production, and vice versa [16].

Similarly, the climate is also affected by emissions and water use, so these interconnected systems are sometimes referred to together as the **water-energy-climate nexus** (or energy-water-climate nexus). Food production is critical to human health (and is also a contributor to many violent conflicts in the world), so the **food-energy-water nexus** (or water-food-energy; choose your preferred permutation) is an important area for interdisciplinary research [3].

Overall, any of these "nexus" terms indicate that the person or organization is taking a systems-thinking perspective when talking about or analyzing the sectors that precede the word 'nexus.'

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