Predicting Thermal Load Profiles for Integration of Renewable Energy in Islanded Microgrids

Research Component Objective
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Abstract
In Alaska, temporal data on thermal energy use are not collected in most buildings. This is partly due to the decentralized nature of predominantly fuel-oil heating and a lack of available and affordable sensors. Without data required for energy modeling, it is difficult to estimate the true benefit that energy efficiency retrofits or renewable energy integration with heating may have on a building or community. This paper highlights research related to predict thermal load profiles, the results of which will be incorporated into an energy optimization tool in order to simulate the effect of using different energy strategies on building heating applications. The thermal load calculation can be performed with two different methods of determining building insulation values (UA values) in a community and both static and dynamic modules for determining diurnal and seasonal temperature variations.

Introduction and Literature Review

Remote communities often lack metering and sensing data to record energy use, despite extensive existing microgrid infrastructure to generate electrical and thermal energy locally. The absence of data inhibits the ability to study building energy systems efficiently and to incorporate new design strategies or technologies that promote more affordable, reliable, and cleaner delivery of energy. Thus, it is critical to create an intuitive and scalable approach for modeling thermal energy use in buildings in a manner specifically tailored toward specific applications, in rural Alaska villages.

Understanding thermal loads better could allow for better integration of demand with energy supply, specifically by allowing for the use of demand response. For example, some thermal loads, like hot water tanks, can be met on a schedule amenable to intermittent renewable energy generation while maintaining specific bounds on hot water availability for domestic use. While electric metering for remote areas has recently become more available to a certain extent, thermal metering and recorded data is virtually non-existent for measuring space heating and cooling, as well as domestic hot water use.

In cold climates, space heating can constitute a majority of energy use. Specifically in Alaskan villages, space heating constitutes 57% of total fuel consumption [1]. On average, the retail price of heating fuel is $4.49 per gallon throughout rural Alaska; thus, community members spend a significant fraction of their limited income on energy [2]. The US Arctic Research Commission identified the need for “basic, fine temporal scale data on energy and fuel type use for residential heat” as the most pressing data gap for rural energy use [2]. However, very few sensors have been deployed to measure heating fuel use in rural areas of Alaska or the Arctic in general. Operating sensor networks in remote, harsh climates can be difficult, as can monitoring fuel usage on a finite temporal resolution. Currently, the University of Alaska-Fairbanks is developing one of the first sensors for determining high-frequency fuel oil usage in residences, called PuMA (Pumping Metering Apparatus).

Given the distributed nature and complex method of measuring thermal energy consumption and building performance for numerous buildings in remote areas, modeling is required to estimate thermal energy use if no sensors are available. Whereas building models, such as eQUEST or EnergyPlus, can perform thermal simulations for a building at the hourly time resolution required for most microgrid energy modeling applications, such simulations are not tailored to the unique conditions of remote Alaskan and Arctic buildings that may dictate additional modeling knowledge. For example, domestic fuel oil heaters or thermal storage in water or ceramic brick are generally not available to be modeled in commercial building software. Also, buildings in rural Alaska are different from those in warmer climates and vary dramatically in terms of construction, making the use of commercial building simulation tools difficult and often inaccurate. In contrast, an open-source thermal energy modeling program called AKWarm has been created for modeling Alaskan buildings. However, its output simulation is only in monthly time resolution, not fine enough for modeling energy dispatch schedules. Therefore, a new engineering modeling approach is required that accounts for the physics of heating use and the nature of Arctic construction. While statistical models for building thermal modeling have been created [3], given the limited amount of data, an engineering model approach is required to suit the application until more data is collected.

Methodology

The goal of this research is to develop an engineering modeling approach for thermal load profile prediction in the context of an entire remote Alaska community at every hour of a typical year. The thermal load for a given building, at its simplest, can be summarized by a heat loss equation (Equation 1), which outlines the key parameters that need to be simulated for determining an accurate profile.

$$Q_{del}\,[\tfrac{Btu}{hr}] = UA\,[\tfrac{Btu}{hr * {}^oF}] * (T_{set} - T_{amb})\,[{}^oF] \qquad (1)$$

In Equation 1, Q_{del} is the heating rate that must be delivered equal to the thermal losses of a building, which are characterized by: $U\,[\frac{Btu}{hr\,ft^2\,{}^oF}]$, the value for estimating the thermal losses through a building envelope and thus its insulating properties; $A\,[ft^2]$, the floor area of the building; and their product comprise the UA-value, $UA\,[\frac{Btu}{hr * {}^oF}]$. The thermal losses are proportional to the difference between the interior building temperature set point, T_{set}, and the outdoor ambient temperature, T_{amb}, both in units of $[{}^oF]$.

The methodology for modeling thermal loads depends on multiple approaches that this research has hypothesized for obtaining satisfactory UA-values and temperature differences. The user has the option of selecting one of two methods for determining UA values (*Top-Down* or *Bottom-Up*) and temperature set points (*Static* or *Dynamic*).

UA-Value Calculations

This research has developed two approaches for determining the UA-value for an entire community's building stock: a Top-Down approach that aggregates all community values without detailing each building specifically, and a Bottom-Up method that determines the UA-value for each building in a community and sums them all. There are advantages and disadvantages to both as detailed below.

1) Top-Down Approach to UA-Value Calculation

The Top-Down approach hypothesizes that a community's thermal load profile can be determined based on the total amount of fuel oil delivered. The advantage here is that only obtaining one fuel bill would be required and typically, for a remote village, shipments of fuel are imported a few times a year allowing for rather simple determination. However, obtaining this information may be difficult in some villages, as currently some data is available through the Alaska Affordable Energy Model. This assumes that all fuel oil delivered is consumed in buildings for heating (all building energy efficiency characteristics are averaged) and does not account for other methods of heating such as wood.

The UA-value can then be calculated by solving Equation 2 below:

$$UA\,[\tfrac{Btu}{hr * {}^oF}] = 24\,[\tfrac{hr}{day}] * HDD\,[\tfrac{{}^oF - day}{yr}] * [\tfrac{gal\,fuel}{138{,}000\,Btu}] * [\tfrac{\$}{gal\,fuel}] * [\tfrac{1}{\eta_f * \eta_d}]\,/\,Fuel\ Cost\,[\tfrac{\$}{yr}] \qquad (2)$$

Either the total fuel cost divided by the price per gallon of fuel, or the total amount of fuel in gallons, can be obtained. The heat rate of the fuel (138,000Btu per gallon of fuel oil) and the efficiency with which it's burned ($\acute{\eta}_f$) and distributed ($\acute{\eta}_d$) within each building and averaged within the community are also inputted. Finally, the heating degree days (HDD) for the community are found, which is a value readily available for any community based on historical weather conditions. The total heating degree days is the sum of the temperature difference between the interior set point and external temperature for every hour of the year. Thus, solving this equation provides the total UA value for the community, without necessarily knowing the details of building area or construction.

2) Bottom-Up Approach to UA-Value Calculation
An alternative approach is to determine the UA-value for each building in the community. This approach can be more accurate but requires a complete building inventory for the village, including sizes, construction, and insulation characteristics (preferably energy audit data). If these characteristics are known for some but not all buildings, there are Cold Climate Housing Research Center (CCHRC) and Alaska Housing Finance Corporation (AHFC) estimates of typical construction techniques in given census areas or communities for residential and non-residential buildings respectively. Using this data, a UA-value for each structure and customer class (residential, commercial, community, etc) can be calculated based on a spreadsheet model (shown in Appendix). This method allows for enhanced granularity if thermal load profiles for specific buildings are desired.

Temperature Calculations
The other major parameter is the temperature set point inside the buildings. This can either be fixed (static) at constant temperature or regular schedule, or flexible (dynamic) within a certain range to better integrate renewable energy. The static module is a simplified version and offers an approximate thermal load profile, whereas the dynamic module can also account for the thermal capacitance and heat storage in a building on an hourly basis using a finite difference method. In either case, an hourly ambient temperature profile must be obtained, from a historical weather station like an airport.

Static Temperature Module
Most buildings in Alaska operate at a fixed temperature set point at all times. For example, most residents set their fuel oil stove to a constant temperature, say 70°F (although some residential users may implement temperature setbacks). In this case, most of the heating use occurs during the coldest part of the day, typically early morning before dawn.

However, some buildings in a community may implement flexible temperature set points based on occupancy. This is typically the case for the school building, which may reduce temperature set points and thermal energy use at night. On the other hand, ventilation requirements and thus thermal energy use may increase during occupied hours (9am - 5pm); this may be incorporated in the UA value of the building through the *Bottom-Up* UA-value calculation above. Some heat in community buildings may be provided through district heating with the diesel powerhouse and will be addressed in the renewable energy optimization of the research.

Dynamic Temperature Module

The dynamic temperature module allows the optimization model to choose the appropriate temperature within a specific comfort range in order to build the thermal load profile model as an integrated component of a renewable energy microgrid optimization model (a separate body of research). In this way, the thermal load model can develop hourly profiles that can be exported on their own for other uses or inputted into the energy optimization model. Thus, the energy optimization model could also be used to determine the optimal building retrofits and behavior to manipulate the thermal load profile in order to reduce capital cost of additional energy infrastructure. The modeling steps to complete this research task are outlined below.

The temperature in the next hour can be calculated from the temperature in the previous hour, the thermal capacitance *C*, and the difference between the amount of heat delivered and the heat lost in the previous time step, as shown in Equation 3.

$$T_{n+1}\,[{}^{o}F\,] = T_n\,[{}^{o}F\,] + (\tfrac{\Delta t}{C})\,[\tfrac{hr}{Btu/{}^{o}F}\,] * (\,Q_{del}\,[\tfrac{Btu}{hr}\,] - UA\,[\tfrac{Btu}{hr*{}^{o}F}] * (\,T_n - T_{amb})\,[{}^{o}F\,]\,) \quad (3)$$

Where *T* is the temperature at hour *n*; *t* is the time step (1 hour), and *C* is the thermal capacitance defined by Equation 4.

$$C\,[\tfrac{Btu}{{}^{o}F}] = \rho\,[\tfrac{lb}{ft^3}] * c\,[\tfrac{Btu}{lb*{}^{o}F}] * V\,[ft^3\,] \quad (4)$$

Where ρ is density of material, *c* is the specific heat capacity of material, and V is the volume of the conditioned building space. A typical value of *C* is 3 $\frac{Btu}{{}^{o}F}$ and a building with high thermal mass can be upwards of C=30 $\frac{Btu}{{}^{o}F}$ [4].

Therefore, the optimization can determine when to add heat to the building depending on how much is lost in the previous hour and how well the building passively stores heat in its inherent thermal capacitance. For example, if there is a significant amount of excess renewable energy available in one hour, the building can be heated to the high end of the temperature comfort range constrained by the model (~75^{o}F); if there is no excess renewable energy available in the next hour then the building temperature may coast down to the lower temperature range (~65^{o}F), depending on how well the building stores heat through its thermal capacitance. Thus, the building may not need to heat every hour and can optimize excess renewable-to-electric-heating delivery as well as reduce overall fuel oil consumption.

Model Synthesis and Validation

Choosing and combining the appropriate UA-value calculation and temperature set point module will result in a modeled thermal load profile for a community that can be integrated with a renewable energy optimization model. The resulting microgrid power profile may look like Figure 1, with appropriate dispatch strategies of diesel and renewables to dispatchable loads and thermal energy storage, either actively in a Steffes-type unit or passively in building thermal capacitance. In this case, excess renewable energy in the form of solar or wind is first used to power dispatchable loads and any excess is delivered to building space heating through electric resistance heating or Steffes thermal stoves.

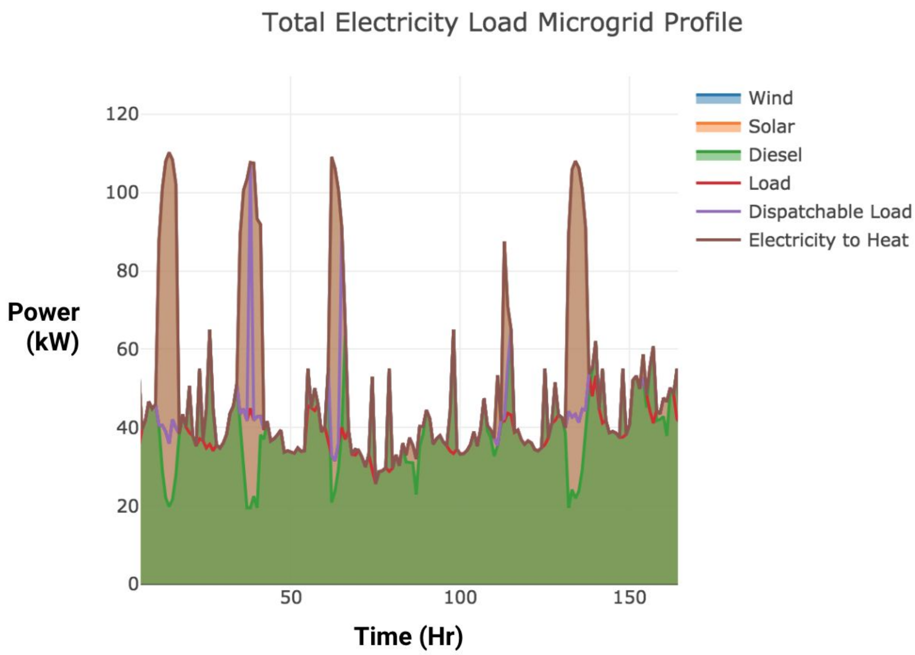

Figure 1: Sample Result demonstrating Renewable Energy Optimization with Diesel and Renewable Dispatch to Loads and Thermal Energy Use

This model for thermal energy use can also be evaluated by comparing to commercial building models. Initial community building models have been created in eQUEST and EnergyPlus building programs to output thermal energy demand per hour over a year. The *Bottom-Up* UA-value calculation method above can also be compared to the outputs of the AKWarm building modeling software, for which several sample rural community building models have been obtained.

Conclusion and Future Work

Ultimately, this combined thermal load profile model will enable the understanding thermal energy use in remote villages, which until now has not previously been quantified or predicted in a formal study. The integration of this model within a microgrid energy optimization tool (as a separate chapter of the PhD work) will determine the ability for various energy systems to meet this thermal load in ways that can benefit the larger microgrid and allow for quantifying otherwise unknown value in terms of resilience that energy technologies can simultaneously provide. The merits of this research include a scalable platform for heating prediction that can be used by community leaders, tailored to local applications, and integrated with renewable energy modeling, aspects currently lacking in commercial building models.

The process will be validated upon additional data collection in a remote Alaska village setting, with thermal data collection to commence in January 2020 in Galena, AK. Additional data will also enable the development of an integrated statistical modeling approach. Future work will also incorporate domestic hot water requirements.

References

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