An empirical methodology for rating building thermal mass as energy storage system

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ABSTRACT

Cities are facing unprecedented challenges as the pace of urbanization, the last decades, has faced a significant increase. These challenges appear in several fields, such as supply, exchange, and consumption of energy. At the same time, the increasing demand for electrification by end-use sectors can lead to higher power fluctuations across the daily demand profile. In fact, it is well documented that the building sector demands approximately 40% of primary energy used within the European borders. Managing energy consumption is a multifaceted challenge; introducing grid flexibility and offering various innovative approaches for optimal use in both building and district level are the keys for a sustainable urbanization in the upcoming years.

According to research, Decentralized Energy Systems (DES) using Renewable Energy Sources (RES) for energy production, offer an optimum solution for energy savings and grid flexibility, especially in stand-alone systems. However, due to the intermittent nature of RES and for meeting the load demand at any time, the need for energy storage systems is essential. Building thermal mass is a key parameter to mitigate inside temperature variations. Used with an optimized control strategy, a thermal mass increase is a solution to maintain a better thermal comfort, to stabilize heating and cooling loads and mitigate peak power demand. This study introduces both an efficient and flexible way to rate the thermal storage capability and through that the exploitation potential as a short-term energy storage system, by mainly using room temperature data as well as basic information of the building construction along with its Heating, Ventilation, and Air Conditioning (HVAC) equipment. So far, complex procedures are followed, which require extensive input of historical data, human efforts and time by developing theoretical models on simulation software, used by high experienced personnel. This study presents an empirical methodology for rating and exploiting the building thermal inertia in order to enhance RES penetration by evaluating its performance. The research is based on real data, harvested by an intelligent monitored building in Lavrion Technological and Cultural Park operated solely for research activities. The methodology will provide a tool for real time quantification and evaluation of building thermal mass, which could be integrated to intelligent control algorithms. The whole system through commercial monitoring technologies and Building Energy Management Systems (BEMS) will deliver to the market a low cost, reliable tool for efficient and precise control of the HVAC equipment aiming to maximize RES penetration without compromising occupants' comfort levels.

INTRODUCTION

Overwhelming evidence indicates that balancing energy's supply and demand is one of the main challenges humanity faces nowadays. According to research, 55 % of world's population in 2018 resided in urban areas and it is projected to reach 68 % by 2050. Taking into account the overall growth of world's population and the gradual shift in residence of the population from rural to urban areas, it is estimated that urban population will be increased by 2.5 billion people in the forthcoming decades (United Nations, 2018). According to Eurostat, the building sector in European Union demands approximately 40% of primary energy (around 23% of total energy consumed is electricity). Managing energy consumption at both building and district level in the optimum way is the key for accomplishing a sustainable urbanization the upcoming years. Therefore, improving energy performance of buildings as well as developing efficient energy storage systems is becoming vital in order to establish an economically efficient and sustainable power system that uses powerful renewable energy technologies.

Following this direction, European countries support the integration of RES as an effective decarbonisation measure along with covering the continuously increasing energy demand. According to Revised Renewable Energy Directive (2018/2001/EU) renewable energy target for the EU for 2030 is set to reach at least 32%. For that reason, there is a necessity for the use of alternative systems that will generate, distribute and store power. Decentralized Energy Systems are characterized by generating power mostly from RES near demand centers and operating at lower scales targeting the coverage of local energy needs. Simultaneously, they can both coexist with the grid, where the surplus generated power will be infused, and function independently with exclusive target to meet the demands of remote locations. Therefore, the successful integration of DES is considered a challenging task as it depends on the energy performance of buildings and it can be optimized by taking into account technologies for conversion, storage, and distribution of the generated energy. Nonetheless, standalone PV/wind systems are able to meet load demand only when sunshine/cut-in wind speeds are available. Despite that, the specific RES are available in abundance; they are intermittent in nature and site specific (Bajpai & Dash, 2012). To overcome this drawback, demand side flexibility is a promising factor to further increase the penetration of RES in the total energy consumption mix and manage local demands. Demand side flexibility is described as the ability of consumers to reduce their energy demand in times of the peak load, by potentially shift demand to other periods (Nordic Council of Ministers, Nordic Energy Research, 2017). It also contributes to the reduction of peak pressure on the grid. Considering the challenges associated with penetrating a renewable energy source into an electrical grid, the integration of smart grid technologies and the demand of side management is currently under investigation in order to increase the reliability of renewable and sustainable energy systems (Orehounig, Evins, & Dorer, 2015). More precisely, space heating offers the highest potential for demand side flexibility. Based on research conducted in Germany, Sweden and elsewhere in Europe, it is estimated that residential space heating contributes at least half of the total potential. To utilize demand side management at residential buildings, in terms of load shifting and peak reduction, one building will have to turn up HVAC system at night and turn down in the morning, or vice versa (Nordic Council of Ministers, Nordic Energy Research, 2017). Optimal performance of demand side management can lead to technical, economic, and environmental advantages, such as increased system reliability, reduced operating costs and emissions of the system. However, efficient performance of demand side flexibility requires an integrated management framework that can optimally manage the various components of the system including buildings, RES and energy storage systems.

Diverse back up energy storage systems can be utilized and that includes batteries, fuel cells (FC), diesel generators (DG) and ultra-capacitors (UC). The most commonly used energy storage system is batteries. However, they experience noteworthy energy losses and there are remarkable limitations in storage capacity, performance and lifetime. On the contrary, solutions based on coordinated and optimized overall systems that utilize buildings as energy storage and allow load shifting present a promising approach (Bajpai & Dash, 2012).

The portion of a building which separates the interior conditioned space from the exterior environment is called building envelope and it consists of building's walls, roof and ceiling, and floor (Childs, Courville, & Bales, 1983). The thermal activation of the building envelope introduces cost effective potential for short-term thermal energy storage. The activation is based upon the following heat transfer mechanism: heat is transferred through the building envelope primarily by conduction. When glazing voids or cavities are within the envelope, two other mechanisms may be involved including natural convection and radiation. The type of construction naturally determines the thermal storage capacity of a building and the order of magnitude for "one room" ranges from 2.7MJ/K to 42MJ/K (Reynders, Nuytten, & Saelens, 2013). This capacity range allows the "storage" of the energy in the building envelope by performing temperature variations of ±3°C (around the setpoint) in line with the current comfort norms. However, the quantification of the available thermal mass requires not only to have a perfect knowledge of the building structure (i.e. materials) but also to deploy massive numbers of sensors.

In this respect, the concept of exploiting buildings envelope for increasing RES penetration is introduced and evaluated in the framework of European research project. This work aims to develop new technology and financial models to connect, control and actively manage generation and storage assets to exploit synergies between electrical flexibility and the thermal inertia of buildings by maximizing the use of renewable energy sources and according to demand side flexibility management. This approach relies on three synergetic management schemes taking place at different time intervals:

1. aggregation and management of the electric and thermal flexibilities at district level (daily basis)
2. conversion and storage of the excess electrical energy to thermal energy into the freely available building inertia estimated with a groundbreaking, automatic method (daily basis)
3. optimization of control algorithms for renewable production inverters, based on automatic grid topology (impedance) mapping (second to minute timestep)

The proposed technology is not only applicable on new and existing buildings but also compatible with integrating additional energy storage systems, such as batteries, to increase the potential of renewable integration. This work targets at converting the excess electrical energy to heat or cold and storing it in freely available thermal inertia that is present in all buildings. The core of the concept relies on standard power to heat/cold (i.e. heat pump) systems with minimal sensing and algorithmic technical solutions. To conclude, there is an important potential of thermal inertia storage to increase the penetration of RES to cover the electricity use and at the same time to reduce the use of traditional power plants.

However, the integration of control and prediction algorithms in such systems may result in increased computational costs. In fact, these costs depend on the number of parameters, which are required to be introduced to a model as inputs and the complexity of the calculations of the selected models. Consequently, the more accurate the model we try to simulate, the more complex and costly the tools are.

Along these lines, this study aims to introduce a set of empirical factors aiming to assess the thermal energy profile of a building and rate its potential capability of storing energy on its envelope. The outcome key factors will allow an effective understanding of building's storage capabilities and an efficient treatment of the building so to decrease energy consumption and activate the thermal mass of the building. In fact, the major contribution of this paper, comparing to previous works, is that it is experimental rather than analytical: it seeks to define a metric for quantifying thermal mass rather than a parameter calculated through building energy models. Therefore, this paper investigates how new metrics can be derived from real measurements, which exhibit all the complexities that analytical models are forced to avoid for tractability. The current paper has two research contributions. Firstly, it introduces and analyzes an algorithm able to measure rating factors, which provide a quantification of building envelope storing capabilities. Secondly, it shows the potential use of these factors as a tool to improve efficiency in prediction algorithms and demand side flexibility systems. Hence, it is considered a valuable source of information regarding the improvement of a building's thermal performance.

PREDICTION ALGORITHMS BASED ON MODELLING TOOLS

To begin with, it is essential to distinguish the words "simulation" and "modeling". Becker and Parker defined simulation as "an act of imitating the behavior of a physical or abstract system, such as an event, situation or process that does or could exist." On the contrary, modeling is the representation of a system that contains objects that interact with each other. A model in most cases is mathematical and aims to present a system, which will be simulated at a certain level of abstraction. Prediction building models are widespread and promise to represent not only the accurate energy profiles of a building but also its inner conditions. Such models utilize simulation tools, which take into account reasonable inputs from public databases. In fact, building energy models have been developed in order to predict building energy profiles such as electricity demand, since the 1970s. They are based on physical models (e.g. EnergyPlus, and TRNSYS) and on data-driven models (Black-box models such as Regression models), thus they simulate the energy profile and the thermal performance of single buildings. However, increasing the accuracy of the predictions for a building energy model demands vast input information regarding building’s structure characteristics, location, climate data, installed equipment operation HVAC and occupancy patterns. In addition, several assumptions, approximations and compromises need to be made in order to simulate the energy profile and possible energy interactions between the building and its environment (Irving, 1988). This fact leads to complex models, which highly depend on the consistency and accuracy of the input information and the skills of the energy modeler as it is shown in previous researches (Prada et al., 2014; Mantesi et al., 2015; Burman et al., 2012; Irving, 1982). On the other hand, estimating the behavior and demands of a building provides the basis for the development of energy district models. Principally these models aim to predict, analyze and optimize energy profiles of building stocks, in accordance with available RES. These modeling tools integrate building energy models and associate software tools addressing district-level interactions in energy systems such as district energy system and renewable energy generation. The predictions of a district model focus on both the energy sector and other variables such as econometric and technological factors. Nonetheless, the outcome results are not an exact replication of the real energy demands and they may be inconsistent and unreliable. In addition, there are often discrepancies in the outcome results in cases where different models are applied to the same case (Hopfe & Hensen, 2011). These aspects conclude to the necessity of developing empirical methodology able to represent a real building case by utilizing a minimum set of parameters to perform calculations and without including uncertain factors, such as assumptions.

EMPIRICAL FACTORS INTEGRATED IN THE METHODOLOGY PRESENTED

In the following section, the Variable-Base Degree Days (VBDD) method and the Empirical factors identified is presented. While there are several energy analysis methods with varying levels of complexity, the degree-day methods are able to provide simple and prompt estimations of heating and cooling requirements, on a monthly or seasonal basis, mainly in buildings of residential and light commercial use. Furthermore, degree-days are useful for studying the optimal design of a building and comparing energy requirements from one location to another. Thus, it is obvious that degree-day methods are of high significance and can offer multiple and useful parameters for further evaluation and research.

In addition, a set of empirical factors is introduced aiming to rank the capability of building’s thermal mass to store thermal energy in relation with its installed HVAC equipment. The proposed factors have been formed by combining real measurements derived from smart power meters and commercial temperature sensors. Consequently, this configuration allows the application of the methodology in every case without taking into account its specific characteristics (e.g. location, construction, equipment). Additionally, the availability of excess renewable energy to be stored is assessed, but it is not considered mandatory for building case to owe to its own RES system.

Variable Base Degree Days

The balance-point temperature is calculated by taking into account the indoor design air temperature of the building, the total heat gains (occupants, lights, equipment and sun) and the total heat-loss coefficient of the building. For heating purposes, the method recognizes that the total heat gains provide heat down to the balance-point temperature, which may vary from one building to another as well as from one location to another. Below the specific temperature, the energy consumption for heating is proportional to the heating degree-days with a base equal to the balance-point temperature. Thus, the balance-point temperature in ^{o}C is given by the function (ASHRAE 2009 Handbook–Fundamentals- chapter 19):

$$T_{bal} = Setpoint - \frac{\dot{Q}_{occ} + \dot{Q}_{lit} + \dot{Q}_{equ} + \dot{Q}_{sol}}{K_{tot}} \tag{1}$$

Setpoint refers to the temperature setpoint of the HVAC system, Q_{occ} refers to internal sensible heat generation rate per unit floor area due to occupancy, given in W, Q_{lit} refers to internal heat generation rate per unit floor area due to electric lighting, given in W, Q_{equ} refers to internal heat generation rate per unit floor area due to mechanical equipment, given in

W, Q_{sol} refers to the building heat gain per unit floor area due to solar radiation, given in W and K_{tot} refers to the total heat transfer coefficient, given in W/K. For this case, Q_{occ}, Q_{lit} and Q_{equ} will be neglected. Moreover, the solar radiation heat gain was estimated (ASHRAE 2017 Handbook–Fundamentals- chapter 18). By definition, the solar radiation passing through a transparent surface can be written as:

$$\dot{Q}_{sol} = A_{glass} * I_t * (\tau + N * \alpha) * SC \tag{2}$$

A_{glass} refers to the surface of fenestration exposed to radiation, given in m^2, I_t refers to total radiation incident on the surface, given in W/m^2, τ refers to transmissivity of glass and α refers to absorptivity of glass, assuming the transmittivity and absorptivity of the surface are same for direct, diffuse and reflected components of solar radiation. SC refers to Shading Coefficient and N refers to fraction of absorbed radiation transferred to the indoors by conduction, convection, and reflected radiation, which under steady state conditions is equal to:

$$N = \frac{U_{glass}}{h_o} \tag{3}$$

U_{glass} is the overall heat transfer coefficient of fenestration, given in W/m^2K and ho is the external heat transfer coefficient given in W/m^2K. In addition, the total heat transfer coefficient K_{tot} is given by the following function:

$$K_{tot} = d_{air} C_p \dot{V} + U_{gnd} A_{gnd} + \sum_k U_k A_k \tag{4}$$

d_{air} refers to density of air given in kg/m^3, C_p refers to specific heat capacity of air given in KJ/KgK, V refers to wind driven infiltration airflow rate given in m^3/sec, A_k and A_{gnd} refer to the areas of building envelope and floor respectively given in m^2, U_k and U_{gnd} refer to heat transfer coefficient of building envelope and floor respectively given in W/m^2K. Afterwards, Heating Degree Days (HDD) are estimated in accordance with the estimated balance-point temperature, which is hourly variable. The HDD are given by the following function:

$$HDD_h(t_{bal}) = \frac{\sum_{hours}(T_{bal} - T_o)}{24h} \tag{5}$$

T_o refers to ambient temperature. The HDD were calculated for the selected period including only four out of five weekdays for ensuring similarity among processed data.

Factors defined for thermal mass rating

Cooling-Heating-Rate (CHR) is an empirical factor, which aims to assess the thermal capability of the building. This factor calculates the duration (in hours), which is required, for increasing the inner temperature of the building 1°C (loading building). It represents the cooling or heating (degree Celsius) rate at the unit time (hour). CHR [°C/h] is calculated by the following function:

$$CHR = \frac{T_{setpoint} - T_{i_{start}}}{|t_{setpoint} - t_{start}|} \tag{6}$$

$T_{setpoint}$ refers to the temperature setpoint of the available HVAC system, $T_{i,\ start}$ refers to the average inner temperature when the HVAC starts to operate and $t_{setpoint}$ and t_{start} refer to the time the HVAC reached the selected set point and start its operation respectively.

Equipment Response Rate (ERR) is the second identified indicator, which aims to assess the effectiveness of the available HVAC system. In specific, it allows the assessment of the required electrical energy consumption needed to reach the selected setpoints. ERR [kWh/m^2] is calculated by the following function:

$$ERR = \frac{\int_{start}^{setpoint} C_{HVAC}(t)dt}{A_{gnd}} \tag{7}$$

Start refers to start time of the available HVAC system operation, setpoint refers to the time of the available HVAC system operation where it reaches the selected set point and C_{HVAC} refers to the average power consumption of the HVAC, which is measured in a 15min interval.

Building Ranking Coefficient (BRC) aims to rank the building by its capabilities to reach a selected set point and store excess energy produced by RES on each envelope. BRC is calculated by the following function:

$$BRC = \frac{CHR}{ERR} \tag{8}$$

BRC presents a correlation between the existing building thermal mass and the installed heating/cooling infrastructure. It eliminates the impact of the dimensioning of the building as well as the type and specifications of each HVAC system. Accordingly, the introduction of VBDD method contributes to the exclusion of the location and the climate conditions.

THE DEMONSTRATION SITE – LAVRION TECHNOLOGICAL AND CULTURAL PARK

Lavrion Technological and Cultural Park (LTCP) is located in Lavrion, in South-eastern Attica in Greece and specializes in key areas of modern applied technology, such as information technology, electronics technology, telecommunications, robotics, laser technology, environmental technology and energy management. Inside the park, there are 48 fully renovated buildings, which host mainly Research and Development (R&D) activities and they have been equipped with advanced energy monitoring and management system infrastructure for the efficient management and control of their loads therefore providing a suitable basis for any deployment of R&D activities.

The selected building for is study, named as H2Susbuild, is a nearly zero CO_2 emissions building (525 m^2) which is operated through an intelligent algorithm. It is able to harvest energy from RES and cover its demand. It is a two-storey conventional building (133kWh/m^2 annually electrical energy consumption) with an envelope, which consists of a concrete structure with double brick walls and non-insulated single-glazed windows with aluminum frames. It also has an external masonry consisting of double brick walls with EPS insulation and cement based plaster on both sides. The roof consists of metallic panels with 1" polyurethane insulation layer in the middle. The building has recently been equipped with an advanced Building Management System that monitors, stores and controls all building's electrical loads and with diverse sensors (temp/hum). The H2Susbuild uses two separate HVAC systems; the first one is based on two exterior Variable Refrigerant Flow (VRF) units and 13 floor mounted fan-coil units (maximum electrical load is approximately 25 kW). The two VRF units may operate simultaneously or individually according to the requested load and with a view to maximize their lifetime. The second system is a combination of an Air Handling Unit (AHU) and a closed-loop air/water Heat Pump

(HP) that provides the heating/cooling needs of half of the building. The AHU performs the recirculation of air through air ducts inside the building, with a maximum air supply of 10,000 m^3/h. The total maximum electrical load of the AHU and the HP is approximately 32 kW.

Inside the park, there are also different RES equipment that can be utilized for this test case. In specific, six downwind three-bladed wind turbines with a nominal power of 6kW each and photovoltaic panels (46.8 kWp) of thin film technology are available. The panels are divided in 6 main circuits powering 6 inverters, connected in pairs. The efficiency of the inverters is close to 98%. Currently this system is malfunctioning and the PVs will be replaced. Additionally, photovoltaic panels (15.1 kWp) of monocrystalline cell technology with an efficiency ratio of almost 16% are included in the LTCP premises. Moreover, an online weather station is installed in the perimeter of the park. It provides measurements with a 15 minutes interval on ambient temperature, humidity, solar irradiance, wind speed and direction and rainfall. The collected weather data are crucial for the development and validation of suggested empirical methodology.

For the above-mentioned infrastructure, the monitoring of production and consumption is performed by 54 smart power meters installed in the LTCP premises, evaluating energy flow and quality at building and district level. In fact, there are more than 480 measuring points gathered to one single data storage system; synchronizing district and buildings data can be used for further processing and analysis. Consequently, H2Susbuild represents an excellent test case for experimenting on building's energy profile and rating its thermal storage capability.

CASE STUDY

In the framework of this study, the building described is utilized for developing, validating and establishing the set of rating factors. Regarding this test case, the building operates as offices and thus the HVAC systems are scheduled to operate for twelve hours (06:00 – 18:00) on weekdays with a fixed setpoint of 22^oC. For this purpose, selected data has been evaluated from the test site from November 1st 2018 to March 31st 2019, namely the heating period for Greece (Assimakopoulos et al., 2014). The collected data include:

- temperature in ^oC harvested from 25 temperature sensors located inside the building with an 15min interval;
- temperature in ^oC, global irradiance in W/m^2 and wind speed in m/s measurements collected from the weather station with an 15min interval;
- energy consumed by HVAC system in kW from 3 power meters with 15min interval;
- energy generated by both wind turbines and photovoltaic panels in kW from 3 power meters with 15min interval.

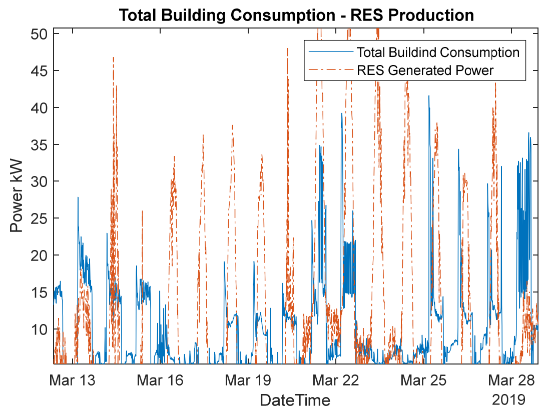
Dataset processing

The analysis of the collected data was performed utilizing a developed Matlab computer code. Regarding the interior conditions of the building, a mean value of all temperature sensors was calculated to represent building's inner temperature. It was assumed that each sensor contributes equally to the main temperature; the location and technology of sensors was not taken into account. This calculation not only simplifies the procedure but also decreases the impact of missing data. In addition, it was decided to take into account four days out of five to assess the HVAC effectiveness and the storage capability of the building in order to enhance similarity among data. The specific decision was taken because during weekends, the building was in free oscillation and as a result, the energy consumption would appear increased during Mondays.

In line with this notion, the energy production of the available renewables was calculated for the same period so to reliably identify the availability of excess RES energy production. Since, the aforementioned thin film technology PVs (46.8 kWp nominal power) currently present a malfunction, an upscaling of the measured generated power was performed. In specific, the PV power production was replaced by the power, which will have been produced if the system was operating properly. The estimated power was given by the following formula:

$$PV_{upscale} = \left(\frac{PV_{Power} - PV_{power}^{min}}{PV_{power}^{max} - PV_{power}^{min}}\right) * PV_{power}^{peak} \quad (9)$$

PV_{peak} power is equal to 46.8 kW, PV_{power} refers to the measured generated power, PV_{min} power refers to the minimum measured value and PV_{max} power refers to the maximum measured value.



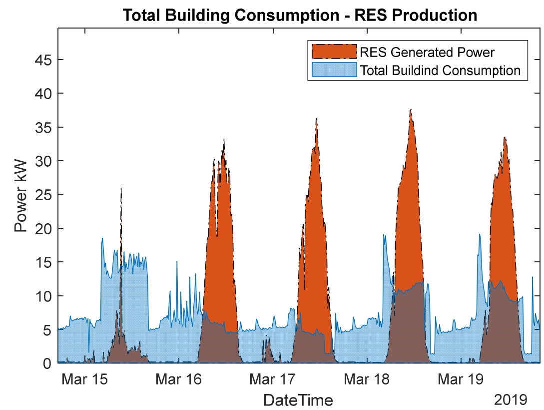


Figure 1. a) Overall energy balance of LTCP site for March 2019. b) Overall energy balance of LTCP site for a specific week

Figure 2 represents the energy flow pathways of generated and consumed energy. As it was observed, the RES production was unable to cover building's energy demands in its whole and on a monthly basis. Exclusively, March presented surplus energy available to be stored to the building's envelope as it is shown at Figure 2. Furthermore, there were days (Figure 1), in which energy production exceeded the building demand after inner temperature reached the selected setpoint. Thus, this energy was available to be stored to the thermal mass of the building as thermal energy.

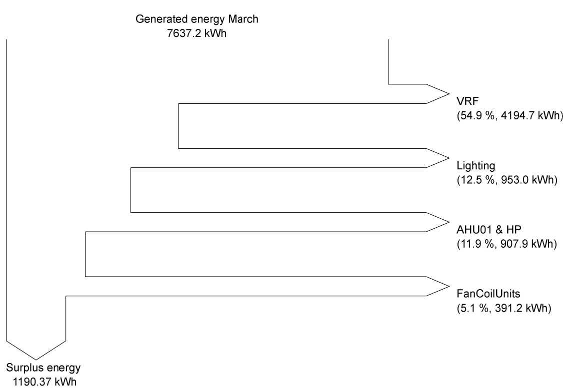


Figure 2. Energy flow path for March 2019.

Likewise, the weather has a significant impact on thermal performance of buildings, as well as on renewables. Therefore, it is essential to understand, quantify and exclude this effect of the measured data. In this line, degree-day methodology is a simple and proper procedure for energy analysis of buildings, especially in cases where the building use and the efficiency of the HVAC can be assumed as relatively constant.

In addition, Table 1 summarizes the input, which were used in the equations (2) to (4).

Table 1. Building Characteristics

Total heat transfer coefficient		Solar radiation heat gain	
Parameter	**Value**	**Parameter**	**Value**
U_k (W/m²K)	1.01	h_o (W/m² K)	22.70
U_{gnd} (W/m²K)	0.94	U_{glass} (W/m²K)	5.16
A_k (m²) - Total	919.30	α	0.12
A_{gnd} (m²) - Total	315.60	τ	0.77
d_{air} (kg/m³)	1.20	A_{glass} (m²)-Total	94.60

C_p (kJ/kgK)	1.00	SC	0.59
V (m^3/sec)	0.32		

ANALYSIS OF THE RESULTS

A regression analysis was performed in order to obtain a preliminary evaluation of the results. The local regression smoothing method is used by Curve Fitting Toolbox software by Matlab software. The smoothing process is considered local because, like the moving average method, each smoothed value is determined by neighboring data points defined within a span. The process is weighted as a regression weight function is defined for the data points contained within the span. In addition, there are two available methods, which are differentiated by the model used in the regression: lowess uses a linear polynomial, while loess uses a quadratic polynomial. The span is specified as a percentage of the total number of data points in the data set. For example, a span of 0.1 uses 10% of the data points. For this case, the smoothing method to smooth the response data was specified as 'loess' Local regression using a 2^{nd} degree polynomial model with a span of 0.99. It is noted that not enough data were collected for marginal conditions (HDD>13) and thus the error is higher in this area.

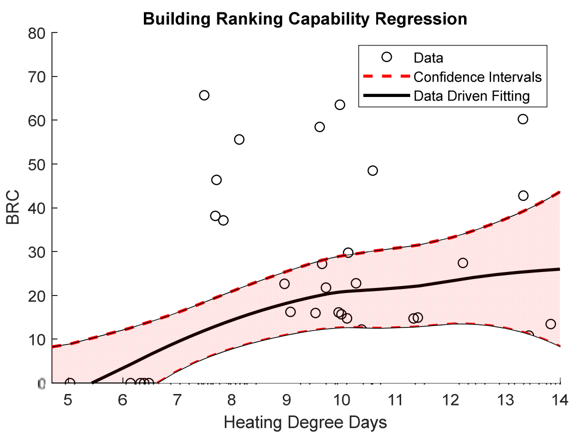


Figure 3. Preliminary Results - BRC.

In Figure 3, the results of the regression analysis with a confidence level of 95% are presented. These results lead to two major observations. Firstly, BRC indicator is increased while the difference between the balance-point temperature and the temperature setpoint is increased (HDD). Secondly, the fitting curve indicates that the impact of climate conditions on building's performance is decreased as the weather conditions become more intensive. Therefore, the gradient of a curve in relation with the BRC level can provide valuable information about the storage capability of the building and the effectiveness of the thermal mass. In specific, as the gradient of the curve approaches zero, the impact of the HDD approaches zero as well. Consequently, building envelope is well insulated so to maintain internal condition without increasing the energy consumption. Thus, the lower the BRC is, the less energy the HVAC systems consume.

CONCLUSION

The thermal mass of a building is considered an efficient and cost-effective energy storage system. With the utilization of thermal mass, the buildings can moderate the discrepancy of supply and demand, by storing the surplus energy generated by RES and consume it later when the demand overcomes the supply. Moreover, thermal mass in buildings can be used as energy storage components, which will allow the utilization of DES management at residential buildings, in terms of load shifting and peak reduction and will increase the penetration of RES in the total energy consumption mix. However, the quantification of the available thermal mass is proved complex and expensive, as it requires not only having perfect knowledge of the building structure (i.e. materials) but also deploying massive numbers of sensors. Due to recent interest in both urbanization and building energy consumption, the research of developing methodology able to assess thermal inertia of buildings is expanded. This paper examines a set of empirical factors aiming to assess the effectiveness of building envelope on an existing nearly zero CO_2 emissions building. This approach provides the following competitive advantages:

- It requires a minimum set of parameters to perform calculations
- The measuring equipment may vary in number and accuracy without affecting the results of the analysis
- Interrupted and inconsistent data can be neglected without affecting the results of the analysis

For further investigation, it is essential to quantify the building thermal storage capabilities by expressing BRC in a unified scale. As a result, the above-mentioned factor will be normalized in accordance to the weather conditions and the installed HVAC equipment. The outcomes will make available an evaluation procedure, requiring minimum efforts and sensor infrastructure, which can empirically rank a building capability to store energy to its thermal mass.

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The views expressed here are solely the authors' and are not those of the organizations where they work. All remaining errors are ours.

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