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Next Generation Building Performance Metrics to Enable Energy Systems Integration

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Abstract

Traditional building performance metrics consider a building as a standalone and static utility consumer. Voluntary green building certifications of districts generally aggregate the metrics of standalone and consuming buildings. There is a lack of performance metrics concerning the integration of critical services to a building and the utility networks supplying these critical services of electricity, natural gas and water. In order to achieve integration of energy systems, including storage based demand side management and rain water harvesting, a methodology is modelled for a typical office. The methodology requires building parameters to be combined and manipulated in order to create the proposed performance metrics.

The building model is simulated for three periods of interest: a whole year, a winter design day, a summer design day. The proposed metrics enable operational management during peak and standard loads, as well as longer term analysis of the building performance. Operational management includes the role of storage and the responsiveness of a building during demand ramping or shedding. Over the longer term, the metrics indicate efficiency trends and guide design and investment decisions. It is found that electrical storage combined with demand side management reduces energy costs with no service disruptions. Rain water harvesting is also found to significantly reduce financial and energy costs, and given its current dearth of deployment, has high future potential.

Keywords – Building performance metrics, Demand side management, Energy storage, Rainwater harvesting, Smart metering

1. Introduction

The European Commission 2020 targets include a 20% improvement in energy efficiency [1] and 2050 targets include an 80% reduction in green house gas (GHG) compared to 1990 levels [2]. The energy efficiency of buildings is addressed by the Energy Performance of Buildings Directive (EPBD). The EPBD, recast in 2010, obliges member states to implement Energy Performance Certificates of buildings [3]. The certificate metrics vary by member state but most include energy performance information and GHG emissions, according to a report from the Building Performance Institute Europe [4]. The report states that the building metrics calculated in the energy performance certificates act as a marketing tool to create demand for building energy efficiency.

The National Renewable Energy Laboratory (NREL) take a user-orientated view of building metrics, as opposed to the market orientated approach of the aforementioned certificates. Metrics are tiered to by user type [5], providing them with specific performance metrics requiring different levels of analysis, Fig. 1. Tier 1 metrics provide a high level performance view and can be derived from monthly and annual utility bills. Tier 2 decomposes energy metrics to detailed hourly or sub-hourly metering. A *performance indicator* at the apex of Fig. 1 aggregates complex data to show planning level trends towards goals.

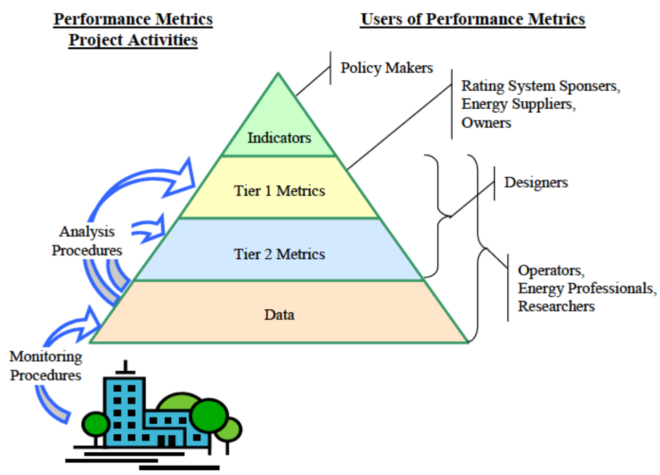

Fig. 1 Overview of building performance evaluation - differentiating metric types and indicators [5]

Ideally, building performance objectives are supported by performance metrics which define the building performance over the entire building lifecycle [6]. NREL conclude that performance objectives ultimately drive the design to obtain the desired results. One approach to achieving higher building performance objectives is voluntary building certificates that exceed the statutory ratings. The metrics contained in the voluntary certificates, such as LEED [7], BREEAM [8] and DGNB [9], consider the building as an isolated load and lose the diverse nature of the building performance in the context of annualised metrics. Annual calculations of energy metrics normalised by building area, kWh/m^2 or CO_2/m^2, are intuitive and easily comparable between standalone buildings [10]. Metric values may be obtained by measurement or energy modeling, known as operational rating or asset rating respectively [11]. Operationally however, these annual metrics do not enable control or effective interaction with the utilities. Building performance metrics are now required in order to exploit current communications technology and adapt to the diverse and dynamic nature of building energy demand. The new metrics will assist in decision-making and efficiency improvements by multiple stakeholders, particularly the building/energy manager(s) and their utility suppliers. One area that building/energy managers and the utility operators require shared building performance metrics is demand side management (DSM).

Management of energy demand is implemented by control or rescheduling of end use devices, or use of demand side storage. One driver for DSM is the trend of market based operation, which has been forecast [12] to increase the influence of consumers in decision-making over the operation and future of the electricity system. In this case of a commercial building, the agent of the consumers is the building/energy manager. Market information pertinent to the building/energy manager is Time of Use (ToU) tariffs, which reflect the utility's cost structure by higher energy prices during peak periods. The building/energy manager is hence informed of when energy costs can be reduced. From a utility's perspective, DSM allows access to end user storage or the similar effect by controlled demand respomse. The storage is capable of acting as operating reserve to support the utility's system. These examples of DSM benefits are most effectively implemented by a combination of both ToU tariffs and smart meter information to consumers [13].

A "smart meter" is considered in this paper as an electronic device that accurately measures the consumption of a utility (electricity, gas or water), records and stores data, while providing real-time consumption information to the consumer. Note the unidirectional data flow to the consumer. Many DSM operations require *bidirectional* communications between the consumer and the grid. Real time pricing and demand response signals would transmit over the low latency smart grid to buildings. Demand response is a DSM application that time shifts demand by controlling thermostats or building functions such as cooling without availing of conventional energy storage. DSM with energy storage is capable of time shifting demand from the utility system during peak periods, but with the advantage of not affecting cooling systems and end use devices such as computers.

This paper is organised as follows. The methodology follows this introduction; describing how new metrics are identified for a modern building integrated with its utility suppliers. Subsequently the proposed metrics for each critical utility service are detailed in Section 2, accompanied by simulation results presented in Section 3. The final Section 4 comprises conclusions and future work.

2. Methodology

This analysis is limited to network delivered utilities of a commercial building. The critical services that allow a building to function for users are identified. These are electricity for HVAC and appliances, natural gas for space and water heating, and water for hygiene and health. The metrics are grouped by critical service, to filter metric views for particular users [5], or allow future development of scenario model views [6]. Based on the existing context and literature described in the introduction, metrics are formulated to measure the performance of a modern commercial building.

Since a building integrates with the utility systems, the diversity of the building demand is compared with the diversity of the utility's generation and supply. The concepts of daily ramping and shedding and seasonal variations of energy demand are well known in traditional electricity utilities [14]. Metrics for ramping and shedding are now defined for a building's demand of both electricity and heating by natural gas. The ramping and shedding utility supplied water is not a critical metric due to water storage already located in buildings. Water distribution losses however, do affect water utilities that are obliged to supply excess treated water to meet the sum of demand *and* distribution losses. Building/energy managers also have an opportunity to reduce total demand of treated utility water by harvesting non-potable water.

Natural gas typically provides space and water heating in modern European buildings. In one European country, natural gas is calculated to be 52% of the primary energy consumed by buildings [15]. Although currently less popular than natural gas heating, the use of electric heating is worth measuring due to its operation with ToU pricing in one form of DSM [12]. The DSM selected for this analysis is based on electrical storage and a peak period determined by demand levels, not pre-defined times of the day. A model of a typical commercial building and climate are simulated for annual results, and results for a winter design day and a summer design day. The results demonstrate energy and financial savings, in addition to building performance in terms of DSM peak shaving and thermal comfort.

2.1. Electricity Metrics

Electricity is the second largest form of energy consumed in a typical residential building which is heated by combustible fuels and located in a north European climate [16]. In comparison to other energy forms, electricity is more versatile, more expensive per unit energy but potentially exportable. A building's capability to consume, generate and store electrical charge will be key factors in the development of the new metrics in this paper.

The first metric, Elc1, is the total electrical energy demand by building during a given time step (TS). A time step of 1 minute resembles real-time, while an annual time period replicates building certifications discussed in Section 1. Real-time values of the total electrical demand indicate the likelihood of an increase or decrease in power demand to a building/energy manager and the utility. Useful benchmarks to real-time demand values are Elc2 (standard demand) and Elc3 (maximum power demand). In a real electricity market, price changes by a utility signal the peak demand period. The simplification for this study is application of the Pareto principle [17]. Peak demand and its associated increase in costs occur when demand is above the 80th percentile (1).

$$Elec_{peak} \geq 80^{th} percentile\ of\ maximum\ power\ demand\ measurements \quad (1)$$

Table 1. Developed building electrical metrics displaying descriptions and units

Metric ID	Performance Metric	Metric Description	Unit
Elc1	Building electrical energy demand	Total building electrical energy demand	kWh per TS
Elc2	Standard electrical energy demand	Average electrical energy demand during occupied hours	kWh per TS
Elc3	Maximum power demand	Maximum electrical power demand during peak	kW
Elc4	Duration of peak demand	Duration where demand exceeds standard demand	hours
Elc5	Electrical storage	Electrical storage availability	yes | no
Elc6	Building Capacitance	Thermal mass of building construction	kWh/°K
Elc7	Electrical quality	Electricity meets grid quality	yes | no
Elc8	Required storage discharge	Storage discharge required to shave peak demand to 80% of maximum demand	kWh
Elc9	Percentage of demand shifted	Percentage of electricity demand time shifted	%
Elc10	Total available storage	Total available charged storage	kWh
Elc11	Percentage of storage used	Percentage of potential discharge in available storage	%
Elc12	Building ramping rate	Rate of power increase from base load to standard load	kWh per TS
Elc13	Storage ramping rate	Rate of power increase by storage charging	kWh per TS
Elc14	Building shedding rate	Rate of power decrease from standard load to base load	kWh per TS
Elc15	Storage shedding rate	Rate of power increase by storage discharging	kWh per TS
Elc16	Total electricity cost – without storage	Summed products of dynamic tariff by demand, without storage	€ per TS
Elc17	Total electricity cost – with storage	Summed products of dynamic tariff by demand, with electrical storage	€ per TS
Elc18	Percentage financial saving by storage	Reduction in utility electricity costs by storage	%
Elc19	Cooling demand	Plant supply side cooling demand	kWh per TS
Elc20	HVAC demand	Total facility HVAC electrical demand	kWh per TS
Elc21	Percentage of active zones	Percentage of HVAC zones actively in use	%
Elc22	Total electricity for heating	Total electricity used in space heating	kWh per TS
Elc23	Percentage of total demand for heating	Percentage of total demand for heating	%

Metrics Elc3 and Elc4 are the magnitude and duration of peak electrical demand and along with metric Elc5, are control inputs to storage based DSM. Available storage, identified by a positive "yes" Elc5 value, allows time shifting of demand. Storage discharge requires electrical quality as indicated by metric Elc7. Design and sizing of the storage is determined by metric Elc8, which requires the identification of the periods of peak demand above the 80th percentile. Implementation of Elc8, regulates demand on the grid by the use of building storage during peak demand periods. This is a process of demand shifting because the storage is charged during off-peak period. Time shifting of demand flattens the building demand profile, reduces peak grid demand and abates GHG emissions. Metric Elc9 represents shifted demand as a percentage of total demand (2).

$$\% \, Demand \, shifted_{storage} = \frac{Shifted \, demand}{Total \, demand} \times 100\% \quad (2)$$

The total available charged storage expressed in metric Elc10 limits the shifted demand. From a utility perspective, electrical storage consumes surplus wind energy generated overnight, thus facilitating renewable energy penetration. The time shifted demand by storage on a particular day is the product of two metrics: total available storage (Elc10) and percentage storage used (Elc11). The resulting storage discharge limit is critical to the design of effective DSM.

The next metrics quantify the dynamics of the charge and discharge rates for both the building and any electrical storage. Critically they quantify the building responsiveness to grid imports or exports. Elc12 is the building ramping rate that describes the rate of increase in electrical energy demand as it rises from an unoccupied building base load to an occupied building standard load. The reverse process is quantified in Elc14, the building shedding rate. Similarly metrics Elc13 and Elc15 describe to the utility the ramping and shedding rates of electrical storage.

A building's export to the grid depends on the export price and the following building metrics; current electricity demand (Elc1), stored electrical energy (Elec10 and Elc11) and any local generation such as solar energy. The electrical utility may view the building storage as a means to shave peak demand, relying on an additional metric (Elc8). The building energy manager and especially the grid operator require the storage ramping and shedding metrics (Elc13 and Elc15).

The financial case for electrical storage requires building energy metrics to compute periodic cost savings (Elc16 and Elc17). Generally, electrical wholesale tariffs are dynamic, calculated in time steps of 30 minutes labeled j. Both metrics Elc16 and Elc17 are calculated (3), but Elc17 employs a smoother demand profile. Metric Elc18 is a percentage measure of financial savings due to time shifting demand to lower tariff periods, which indicates energy performance and enables comparisons between buildings.

$$Electricity \, financial \, cost = \sum_{j \, start}^{j \, end} (Demand_j \times Tariff_j) \quad (3)$$

Many commercial buildings consume electricity to cool and condition air, which is quantified in metrics Elc19, Elc20 and natural gas metric NG13. The summation of Elc19 and Elc20 is the total building energy allocated to facilities cooling. Cooling energy can now be normalised by floor area, occupant numbers or expressed as a percentage of total building energy consumption. These indicate to an energy manager a building's efficiency or its optimal occupancy and should be considered alongside metric Elc21 (% active HVAC zones) that should statistically correlate with occupancy level.

Building capacitance or thermal mass affects the energy required to control indoor temperature. This metric is the product of the specific heat capacities of the construction material and the material masses (4). Where the heating energy source is electricity, the metric name is Elc6. More often a building is natural gas heated, meaning the same metric is named NG6, obviating Elc6 as described in Section 2.2.

$$Building \, capacitance = \sum (Specific \, heat \, capacity_{mat} \times Mass_{mat}) \quad (4)$$

The final two metrics of electrical heating exist due to the extra losses and GHG emissions caused by conversion of thermally generated electricity back to heat. As already mentioned in the introduction, electrical heating also has an application in DSM, specifically responding to ToU tariffs.

2.2. Natural Gas Metrics

Natural gas typically provides space and water heating in modern European buildings as discussed in the introduction. Existing metrics associated with natural gas are boiler efficiency (%), normalised primary energy (MJ/m^2) and normalised CO_2 emissions ($kgCO_2/m^2$). This paper proposes more holistic metrics of building heating.

Similar to the electricity metrics of section 2.1, the initial natural gas metrics (NG1 - NG4) illustrate the total, standard and peak demand of natural gas over a user defined time step (TS), Table 2. The application of a small time step causes metric NG1 to be almost real-time. Comparison of the real-time demand to historical demand enables short-term forecasting of the demand movements. The threshold for peak natural gas demand is again the 80th percentile of the demand profile, consistent with the definition of peak electricity demand (1). The duration of peak demand (NG4) and presence of local gas storage (NG5) could inform a gas supplier's storage management. Local gas storage would simplify the gas transportation and pumping. An example is Ireland's central gas storage where Bord Gáis, the largest supplier, pumps cheaper summer gas into a remote offshore gas field for subsequent winter supply.

Metric NG6 is the building capacitance and equals metric Elc6 (4); the choice of either metric is determined by the source of heating energy. This paper assumes that natural gas is the source of heating energy, thus building capacitance is discussed in this section.

Table 2. Developed building gas metrics displaying descriptions and units

Metric ID	Performance Metric	Metric Description	Unit
NG1	Building gas demand	Total building gas demand	kWh per TS
NG2	Standard demand	Average natural gas demand during occupied hours	kWh per TS
NG3	Daily peak demand	Expected peak daily gas demand	kWh per TS
NG4	Duration of peak demand	Duration where demand exceeds standard demand	kWh per TS
NG5	Natural gas storage	Natural gas storage availability	yes | no
NG6	Building thermal capacitance	Thermal mass of building construction	kWh/°K
NG7	Building ramping duration	Time to reach full occupied thermal conditions once occupancy commences	hours
NG8	Building temperature ramping time	Time to increase building temperature 1°K	hours
NG9	Building temperature shedding time	Time to decrease building temperature 1°K	hours
NG10	Total cost	Total cost of natural gas by time period	€
NG11	Percentage active heating zones	Percentage of heating zones actively in use	%
NG12	Heating set point not met	Heating set point not met while occupied	hours
NG13	Cooling set point not met	Cooling set point not met while occupied	hours

Building capacitance or thermal mass correlates inversely with a building's responsiveness to heating and cooling. Since the building's materials effectively store energy this characteristic is called building *capacitance*.

Building ramping duration (NG7) measures the time for an unoccupied building's temperature to increase to a fully occupied building's temperature. Ramping rate is a function of a building's capacitance and its heating system, and measures the building's responsiveness to occupant heating demands. Note that in humid climates, certain variable speed systems ramp up blowers slowly for energy saving and dehumidification purposes [18]. A development of metric NG7 is to specify ramping and shedding rates per ºK. This useful metric enables quantification of the time required to condition an occupied building. Due to the range of outdoor and indoor conditions that affect indoor temperature metrics NG8 and NG9, they may be calculated by more sophisticated methods than a single equation. Such methods include regression of historical data or computer simulations. The temperature ramping and shedding rates allow time programming of the heating system in order to cost effectively fulfill occupant thermal comfort. The total financial cost of natural gas during a time period appears in metric NG10. The tariff is fixed throughout the day; hence the lack of time step simplifies the calculation (5).

$$Gas\ financial\ cost = \sum Demand \times Tariff \tag{5}$$

Zoning refers to space subdivision of large buildings based on their purpose and location, which is typically reflected in the HVAC controls. Heating demand and duration will vary by zone, hence metric NG11 identifies the proportion of zones that currently require heating. NG11 is expected to correlate positively with NG1 (natural gas demand) and NG10 (total cost of natural gas). The final two metrics, NG12 & NG13, indicate thermal comfort by identifying occupied hours when the heating or cooling set points are not met, as defined by ASHRAE [19]**.** Ideally both metric values are low, because higher values flag the need for system maintenance.

2.3. Water Metrics

Water consumption traditionally attracts less attention to its financial and energy costs than other building utilities. The embodied energy, however, in treated water ranges from 0.77 – 1.02 kWh/m^3 [20], depending on treatment and distribution distance. If used, reverse osmosis desalination consumes up to 2-6 kWh/m^3 [21]. An embodied energy in treated water of 1.02 kWh/m^3 is accounted for in the building water metrics, Table 3.

The first metric, Wtr1, quantifies the water consumed by the building over a user defined time step. Wtr2 is the total cost of water and the product of Wtr1 and water tariffs, which vary by building purpose and inclusion of wastewater services. The proportion of building water consumption substitutable by non-potable water varies by building type. A Japanese study quantifies potential proportions of lower quality water use in buildings: 29% for a residential home (without garden irrigation) and up to 52% for a commercial building [22]. In a north European climate, a source of non-potable water is rainwater harvesting (RWH). RWH is possible on paved areas or more likely from rooftops, and is quantified in metric Wtr6 (6).

$$RWH_{potential} = Roof\ area \times Rainfall\ depth \tag{6}$$

Table 3. Developed building water metrics displaying descriptions and units

Metric ID	Performance Metric	Metric Description	Unit
Wtr1	Total water consumed	Total building treated water consumption	m^3 per TS
Wtr2	Total water cost – no RWH	Total cost of water supplied by utility – without RWH	€ per TS
Wtr3	RWH storage available	RWH storage is available and operational	yes | no
Wtr4	Non-potable water used	Quantity of non-potable water used	m^3 per TS
Wtr5	Total water cost – with RWH	Total cost of water supplied by utility – with RWH	€ per TS
Wtr6	Potential rainwater harvest	Quantity of potential roof rainwater harvest	m^3 per TS
Wtr7	Embodied energy in water – no RWH	Normalised treatment and distribution energy of utility supplied water – no RWH	kWh/m^3
Wtr8	Embodied energy in water – with RWH	Normalised treatment and distribution energy of utility supplied water – with RWH	kWh/m^3
Wtr9	Cost of embodied energy in water – no RWH	Normalised costs of treatment and distribution energy of utility supplied water – no RWH	€/m^3
Wtr10	Cost of embodied energy in water – with RWH	Normalised costs of treatment and distribution energy of utility supplied water – with RWH	€/m^3
Wtr11	Energy saving by RWH system	Normalised energy saving due to non-portable water provided by RWH system	kWh/m^3

An operational RWH has the potential to make significant savings for a building manager, and hence its operational status appears in metric Wtr3. The quantity of non-potable water used in practice by the building is identified in metric Wtr4. The lower cost of water consumption due to the RWH volume measured in Wtr4, is computed in Wtr5. The difference between Wtr2 and Wtr5 is the financial saving derived by RWH. Assuming a flat rate tariff on utility supplied water, the maximum percentage cost reduction matches the maximum non-potable use already referred to as 52%.

Building water use correlates with the embodied energy consumed by the water supply utility (E_{util}). The higher level of embodied energy in supplied water is 1.02 kWh/m^3, as already mentioned [20]. Where the utility supplies all building water (W_{tot}), metric Wtr7 measures the normalised embodied energy of utility supplied water $E_{util,all}$ (7). Alternatively, where RWH substitutes a quantity of supplied water (W_{RWH}), Wtr8 quantifies the normalised embodied energy of the reduced utility supplied water $E_{util,RWH}$ (8). Water utility energy consumption escalates due to distribution losses of treated water, reported in Ireland as a whole at 49% [23]. As expected the urban distribution losses of treated water are reported as less severe, recently reduced to 29% in Dublin, Ireland [24]. Both these loss figures are inside the international range of 25-50% [20].

$$\mathrm{E_{util,all}} = 1.02 \times \frac{\mathrm{W_{tot}}}{(1-0.49)} = 2.00 \times \mathrm{W_{tot}} \qquad (kWh/m^3) \tag{7}$$

$$\mathrm{E_{util,RWH}} = 1.02 \times \frac{\mathrm{W_{tot}} - \mathrm{W_{RWH}}}{(1-0.49)} = 2.00 \times (\mathrm{W_{tot}} - \mathrm{W_{RWH}}) \qquad (kWh/m^3) \tag{8}$$

Cost metrics Wtr9 and Wtr10 build on the embodied energy metrics of Wtr7 and Wtr8. Their calculations require information on the energy tariffs payable by the water utility that may vary by time of day, location and energy supplier. Finally Wtr11 measures the energy savings of a RWH system ($E_{saved,\ RWH}$), normalised by RWH system size (RWH_{size}). The size of a RWH system is determined by local climate, building rooftop size and water consumed. These factors are incorporated in metric Wtr11 (9), which assists decisions on RWH sizing, regulations and incentives to promote suitable RWH.

$$\mathrm{E_{saved,RWH}} = \frac{\mathrm{E_{util,all}} - \mathrm{E_{util,\ RWH}}}{\mathrm{RWH_{size}}} \tag{9}$$

3. Case Study Simulations

The metrics are tested by an EnergyPlus model of a two storey office building located in northern Europe. The building comprises 10 zones; four on the ground floor and six on the 1st floor. The simulation calculates results every 10 minute time step. The results are subsequently aggregated over three periods of interest: a whole entire year, a winter design day (January 30th) and a summer design day (June 3rd).

3.1. Electricity Metric Results from Case Study

Metrics that varied during simulation appear in Table 4, while three metrics are assumed constant. Electrical storage (Elc5) and electrical quality (Elc7) are in continuous positive status and the building capacitance (Elc6) caused mainly by concrete floors, is calculated as 93.5 kWh/°K.

Table 4. Simulation results of electricity metrics over three durations of interest

Metric ID	Performance Metric	Unit	Annual	Winter Design Day	Summer Design Day
Elc1	Building electrical energy demand	kWh	48,289	137.47	147.96
Elc2	Standard electrical energy demand	kWh	2.93	2.24	2.74
Elc3	Maximum power demand	kW	23.03	17.01	22.26
Elc4	Duration of peak demand	Hours	1,216.17	4.67	5.00
Elc8	Required storage discharge	kWh	4,183.75	16.22	18.23
Elc9	Percentage of demand shifted	%	8.66	11.80	12.32
Elc10	Total available storage	kWh	4547.75	21.50	21.53
Elc11	Percentage of storage used	%	91.97	75.43	84.67
Elc16	Total electricity cost – no storage	€	3,127.78	9.59	10.20
Elc17	Total electricity cost – with storage	€	2,940.14	8.72	9.43
Elc18	Percentage financial saving by storage	%	6.00	9.1	7.5
Elc19	Cooling demand	kWh	17,625.84	4.50	172.24
Elc20	HVAC demand	kWh	7,687.44	34.32	21.36

Elc1 is the building electrical energy demand, which can be met with or without storage discharge (Elc8), Fig. 2. As expected, the maximum peak power demand Elc3, has a higher coefficient of variation than standard energy demand Elc2. Elc3 has two consecutive outliers above 34 kW in February worthy of further investigation. The annual peak demand duration (Elc4) is 1,216.17 hours; a 3.33 hours daily average which both design days exceed.

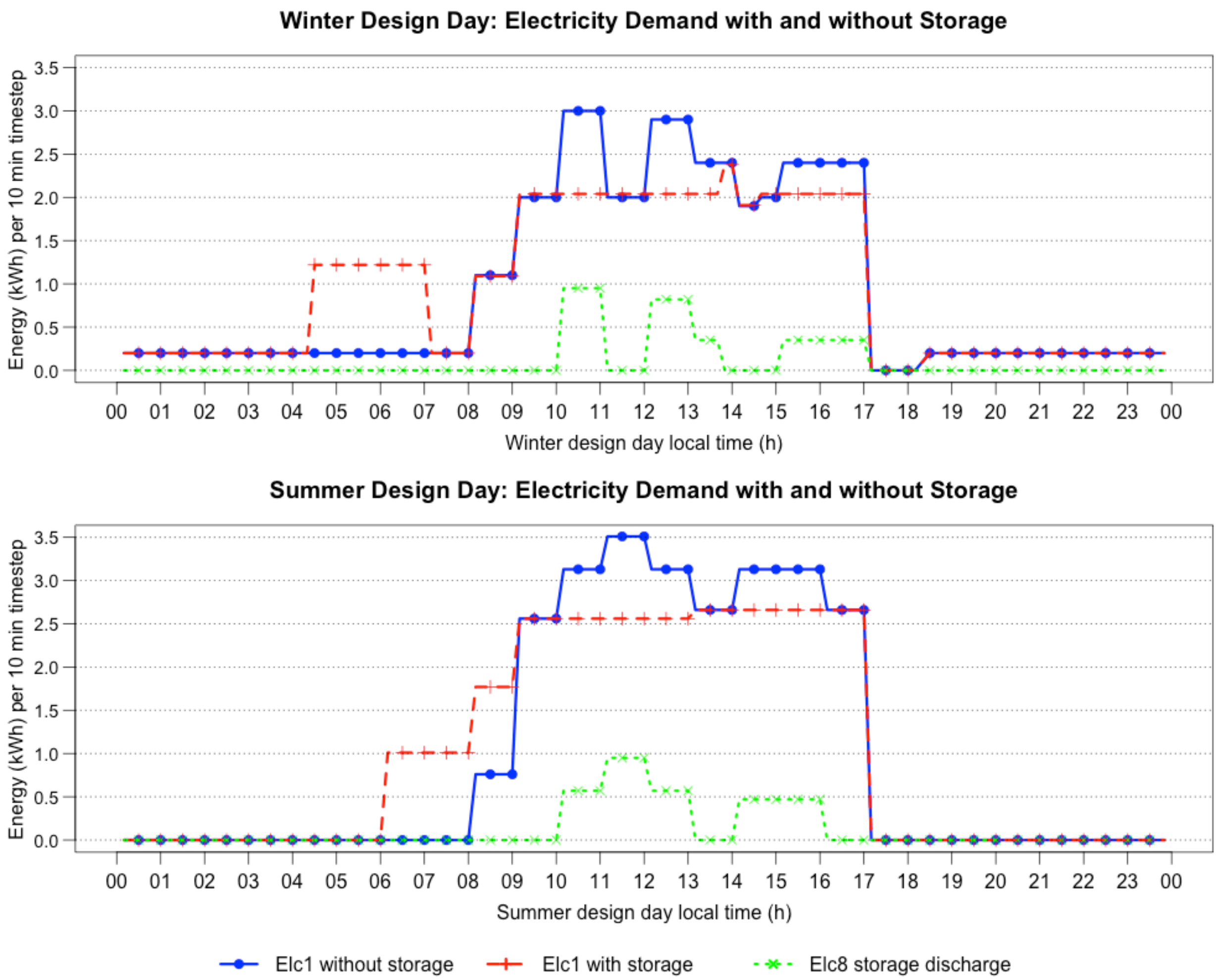

Fig. 2 Electricity demand on simulated design days showing peak shaving implemented by storage - winter (top) and summer (bottom)

DSM employs electrical storage to time shift demand during the periods of peak demand (Elc4). The excess demand during the peak demand periods sums to the required storage discharge, measured as Elc8, which is 16.22 kWh and 18.23 kWh on the design days. With both the total demand (Elc1) and demand met by storage (Elc8) now known, percentage time shifted demand is calculated as metric Elc9. The total charged storage, tracked in metric Elc10, meets the required storage to time shift peak demand (Elc8). Metrics Elc10 and Elc11 quantify to the grid operator the remaining storage capacity capable of balancing excess (and potentially cheaper) grid connected wind energy. One both design days the stored charge (Elc10) is 21.5 kWh, compared to rated storage capacity of 23 kWh. Metrics of the cost savings enabled by the storage appear in Elc16, Elc17 & Elc18. The annual average financial saving is 6%, with both winter and summer design days being above average at 9.1% and 7.5% respectively.

The penultimate metric Elc19 reflects the fact that the building cooling is electrically powered. Potential exists to time shift this cooling demand by the use of thermal energy storage. The more important metric, Elc20, quantifies the total HVAC demand for the entire building which in the simulation amounted to 15.9% of the total electrical demand.

3.2. Natural Gas Metric Results from Case Study

The natural gas metrics that vary during the simulation appear in Table 5. Two metrics are assumed constant; gas storage (NG4) is not available and the constant building capacitance (NG6) is identical to Elc6, at 93.5 kWh/°K.

Table 5. Simulation results of natural gas metrics over three durations of interest

Metric ID	Performance Metric	Unit	Annual	Winter Design Day	Summer Design Day
NG1	Building gas demand	kWh	160,505	1,171	0.00
NG3	Daily peak demand	kWh	22	18	0.00
NG4	Duration of peak demand	Hours	N/A	4.50	0.00
NG7	Building ramping duration	Hours	4.33	4.33	N/A
NG8	Building temperature ramping time	Hours	N/A	0.33	0.66
NG9	Building temperature shedding time	Hours	N/A	0.33	1.00
NG10	Total cost	€	6,078.31	44.36	0.00
NG12	Heating set point not met while occupied	Hours	75.8	4.17	0.00
NG13	Cooling set point not met while occupied	Hours	86.4	0.00	6.50

Similar to electricity, the initial metrics quantify the energy supply cost and durations of daily peak demand. Metric NG4 quantifies the duration of peak demand and its variations inform the building or energy manager of possible faults or changes in heating efficiency.

The critical metric NG7 measures the effectiveness of the building heating system, which is determined by the quality of construction, outdoor conditions and boiler efficiency. The NG7 metric of 4.33 hours on the winter design day means that building thermal comfort lags the boiler start time by several hours. NG8 and NG9 are developments of NG7; showing that on the winter design day that the building requires 20 minutes to rise or drop its temperature by 1°K, but is slower to warm or cool during the summer design day.

Metric NG10 sums the natural gas cost based on a static tariff of 0.03787 €/kWh. The annual cost of gas is greater than twice the annual cost of electricity with storage (Elc17). Latent potential exists for a dynamically priced gas for the small number of locations that can store natural gas during the summer.

The final natural gas metrics applied to the case study are N12 and NG13, which apply ASHRAE measurement of number of occupied hours where heating or cooling set points are not met. The annual results are 75.8 and 86.4 hours respectively, indicating poor management or methods of cooling. Simultaneous operation of both heating and cooling occurred in a small number of hours caused by temperature overcorrections. This value should be minimized, consequently preventing over-heating and over-cooling.

3.3. Water Metric Results from Case Study

The water metrics that vary during the previously described simulation appear in Table 6. Metric Wtr3, the availability of RWH, is set as a constant yes. This study assumes all potential rainwater is captured without storage constraint. The remaining metrics are based on 9 l/h (0.009 m^3/h) water usage by an office worker [25], neglecting the small consumption by services such as boiler and heating. The proportion of non-potable water, possibly supplied by RWH is assumed at 52%, as discussed in section 2.3.

Metric Wtr1 is the total water consumed which is multiplied by the Dublin commercial tariff of €1.99/m^3 producing water cost metric Wtr2. The cost includes both freshwater and wastewater services. As a result of the assumed parameters, the non-potable water consumed (Wtr4) is 52% of the total water consumed, and the resulting total cost with RWH (Wtr5) is 48% of the total cost without RWH (Wtr2).

Table 6. Simulation results of water metrics over three durations of interest

Metric ID	Performance Metric	Unit	Annual	Winter Design Day	Summer Design Day
Wtr1	Total water consumed	m^3	3,520.3	12.66	12.66
Wtr2	Total water cost – no RWH	€	7,005.40	25.20	25.20
Wtr4	Non-potable water consumed	m^3	1,830.56	6.59	6.59
Wtr5	Total water cost - with RWH	€	3,362.60	12.10	12.10
Wtr6	Potential rainwater harvest	m^3	7,668.05	42.4	0
Wtr7	Embodied energy of utility water – no RWH	kWh	7,040.63	25.3	25.3
Wtr8	Embodied energy of utility water – with RWH	kWh	3,379.50	12.16	12.16
Wtr9	Cost of embodied energy in water – no RWH	€	774.5	2.79	2.79
Wtr10	Cost of embodied energy in water – with RWH	€	371.75	1.34	1.34

The next metric, Wtr6, is the potential rainwater harvest that is a function of: catchment (roof) area, site perception depth and storage capacity. Wtr6 indicates if the RWH system is capable of supplying all the potential non-potable water. In the simulation the annual value of over 7,600 m^3 is over double the total of all water consumed.

As discussed in Section 2.3, the treatment and distribution of water incurs energy demand by the utility. The embodied energy of total treated utility water to provide the consumed water is calculated to be 2 kWh/m^3 (8). Thus each m^3 of consumed rainwater avoids 2 kWh of water utility energy demand. The overall effect of RWH is shown by the differing embodied energies (Wtr7 & Wtr8) and differing financial costs (Wtr9 & Wtr10) where the tariff is 0.11 €/kWh for industrial electricity [26]. RWH reduces the water demand and costs upon the building manager and reduces energy demands by the utility. The proportion of these reductions is identical to the proportion of treated utility water replaced by non-potable harvested rainwater. It is assumed that the RWH and its storage are sufficiently large. Wtr11 cannot be calculated in this study because the size of the modelled RWH system (9) is unconstrained by storage or other system limitations.

4. Conclusions and Future Work

The application of DSM by electrical storage results in peak shaving of electrical demand metric Elc1, during the building occupation period of both the winter and summer design days. The peak plateaus of both design days are not perfectly flat; both plateaus experience disturbance during the mid-period of building occupation. On both design days metric Elc8, the storage discharge, dips to zero simultaneously with the disturbance in Elc1, Fig. 2. These metrics indicate the source of the disturbance in peak shaving, and more generally display the metrics value to the building/energy manager and utility in control of DSM.

Total electrical energy consumption is unchanged but time shifted by storage. The metrics Elc16, Elc17 & Elc18 display the time shifting and the reduced costs due to dynamic pricing. Application of the proposed metrics with electrical storage would transform the utility perspective of the building from a traditional static load, to a dynamic node capable of bi-directional control signals. The control functionality depends on advanced metering infrastructure (AMI), but the potential benefits include: storage for excess wind energy, lower energy costs and reduced GHG emissions.

Natural gas metrics quantify the building thermal performance and improve occupant comfort. The control of heating, including the ideal boiler start time, is achievable by application of the proposed building capacitance metrics. Gas storage would reduce the supply chain complexity, but is more difficult to install at building level. In addition the market incentive of dynamic gas tariffs is absent.

The proposed water metrics demonstrate the possible energy savings of rainwater harvesting as 2 kWh/m^3 of replaced potable water. This metric and the associated energy costs (Wtr9) vary by local distribution losses incurred by the water utility. Locations for rainwater harvesting and remediation of distribution losses can be prioritized by this metric. The metrics of rainwater harvesting can be applied to both domestic and commercial buildings.

Future work includes application of real-time control and communication protocols to the electrical storage, and quantifying their effect on the metric performance. The electric battery or fuel cell has yet to be selected and tested for repeated charging and discharging. The impact of electric storage degradation on building performance metrics is useful for electrical storage sizing.

In terms of natural gas, the heating and cooling rates of a building could be analyzed and optimized to be climate specific. The objective is use of building heat capacitance to minimize fossil fuels heating over the long term. The role of thermal storage in meeting this objective could be assessed by metrics.

The key specifications of the RWH, such as storage capacity, should be defined and tested in an updated model. The metric Wtr11 can then be calculated to measure the performance of specific RWH systems. The use of RWH is applicable to other building types, and worth simulating the results of these proposed metrics.

Finally, the inclusion of solar energy on different building types merits validation by performance metrics. Metrics on solar energy allow comparison of overall cost savings and GHG reductions of different solar panel designs. Building managers would be equipped to make informed decisions on solar energy proposals.

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