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Exploring Value and Performance Parameters for Thermal Energy Storage in Low Carbon Buildings and Districts.

P.G.Tuohy[1], N.Kelly[1], J.Allison[1], A.Cowie[1], A.Lyden[1], G.Flett[1].

1. ESRU, University of Strathclyde.

Abstract

There is much effort focussed on development and implementation of thermal energy storage (TES) for future energy systems. This paper explores the context within which TES has potential to provide benefits from a range of perspectives. First the wider role of storage and demand side flexibility is explored and then the potential roles of TES, both explicit TES (i.e. designed storage systems) and inherent TES (e.g. in standard building structure) are examined. The potential benefits of storage are categorised as: (i) short term supply side response, (ii) load shaping for supply side optimisation, (iii) local supply optimisation, (iv) capital investment and return on investment optimisation, (v) comfort and resilience. A set of potential downsides for TES systems is also given. For each category performance metrics are proposed which could be used to support the quantification of the benefits of TES in modelling and other assessments.

Keywords:

Energy Storage, KPIs, Quantification, Low Carbon Buildings, Low Carbon Districts, TES, Modelling, Grid, DSM

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1. Introduction

There is much work on development and integration of thermal energy storage (TES) aimed at future energy systems. In IEA ECES Annex 31 Task A the focus has been on modeling in support of effective integration of TES in low carbon buildings and districts.

A first step in this task was to establish a context for the modeling of TES and to establish the required outputs from the modeling. Modeling was viewed as a multi-level activity with system, building, district and national levels. At each level modeling should comprehend TES system behavior and provide outputs required to support design optimization plus provide the modeling outputs for higher level models.

For TES to be valued and successfully adopted in low energy buildings and districts it is critical that the value of TES is correctly quantified. To support this quantification it is essential to understand the potential services that TES can provide. It would be helpful if performance metrics were available to easily capture this performance and underpin assessments, design studies and future standards.

The aim here is to examine benefits of TES in future energy systems and suggest performance parameters to quantify these benefits.

The work of others was reviewed to identify energy services and other values of storage in future energy systems and how these are quantified. These were then categorized and a set of performance metrics proposed. Implementation of TES to provide these services is briefly discussed.

2. Benefits of Storage in Future Energy Systems

A variety of different views or perspectives on services associated with storage and demand response and the quantification of performance of these are found in literature. Here these are analyzed in top down sequence: first giving perspectives on regional or grid energy systems operation; then looking at district and building scale and considering explicit thermal storage systems and then inherent thermal storage.

2.1. Regional or Grid Perspectives on Storage and Demand Response

Many documents provide a perspective on the energy services that storage or demand side management can provide to electricity grids in future particularly in regards to the integration of stochastic renewable generation such as from wind and photovoltaic. Here a selection of these are reviewed.

In their 2017 update to the energy storage roadmap (EASE-EERA, 2017) the EASE and EERA describe 34 potential storage application services with direct relevance to TES in 5 categories: 1. Generation and bulk services including price arbitrage and curtailment minimization; 2. Ancillary services including black start support; 3. Transmission services including investment deferral; 4. Distribution services including investment deferral and local voltage and frequency control; and 5. Consumer services including peak load reduction, time-of-use cost management, maximizing self production and consumption, limitation of upstream disturbances.

Blanco and Faaij (2018) look at electricity services in future high penetrations of variable renewable energy and highlight the role of storage in providing security for such systems, defining security in terms of: stability, flexibility, resilience, adequacy and robustness. The suggested roles of conventional (electrical or thermal) storage including demand response are primarily in provision of short and medium term stability and flexibility. Power to gas or power to liquid fuel and associated fuel storage is seen as a solution for longer term storage and for greening in other energy sectors. Flexibility related parameters are identified as response time, ramp rate, power capacity, energy capacity, and round trip efficiency.

Staffell and Rustomji (2016) suggest that energy arbitrage based on intra-day electricity price differentials is not currently sufficient to make energy storage financially attractive and that provision of other grid support services can build a more attractive financial case for storage. They note the fact that negative pricing is occurring on occasional high wind days in UK and Germany but show that in Germany the average daily base to peak spread has reduced from 23% to 10% over the 2002 to 2014 period despite large increases in wind and PV generation over this time. They propose and demonstrate an algorithm to assess the maximum revenue available from a wider range of services. They use a technology neutral approach to modeling storage which considers charge and discharge power and efficiency and the energy capacity of the storage referencing Lund and Connolly and their ENERGYplan modeling tool (H. Lund et al. 2016). The financial costs are inputs and the outputs are CAPEX, OPEX, Profit and Rate of Return. Sensitivity analysis is conducted around reasonable parameter variations including variations in weather and renewable generation.

H. Lund et al. (2016) analyze the role of storage in future energy systems based on a number of their own studies based on the ENERGYplan calculation methods. Their analysis shows TES to be 100x cheaper in cost per kWh than electrical storage, and chemical storage through power to green fuel (methane, methanol, etc) processing to be 100x cheaper than TES largely due to the pre-existence of storage facilities for green fuels meaning zero capital investment. A further performance metric was applied to the cost per storage cycle which further illustrated the differentials between technologies with TES being increasingly cheaper as cycles increased. Other important parameters used to assess the performance of storage were: investment costs, O+M costs, lifetime (years, cycles), cycle efficiency and annual costs per MWh.

Strbac et al. (2012) provide a strategic assessment of the role of storage from a UK electricity grid perspective. They highlight the ability of storage to: allow greater absorption of low cost renewable energy; and to reduce generation, transmission and distribution investment costs through smoothing of supply and demand profiles. These reductions in investment costs were quantified for each layer of grid and also generation. Overall benefits were quantified in terms of £bn/year and storage costs in £/kW.year for different scenarios. Market value associated with storage was evaluated with short term storage services up to an hour having highest commercial value at £30/kWh, while longer term storage over 5 hours had a market value of only £1/kWh. This again highlighted that short term balancing services had 2x higher value than inter-day price arbitrage. The modeling of storage was at a high level with generic technology representation of capacity (GW), duration (h), efficiency (%), lifetime and costs.

A further report from the UK Carbon Trust involving some of the same authors in 2015 (Carbon Trust, 2017) further elaborated the services storage can provide describing these as: capacity adequacy where the addition of storage allows time-shifting to provide capacity firming of intermittent renewables, improved system reliability services through provision of an operating reserve (UK market rewards 3MW 2h contributions), frequency control through fast response absorption or provision of power, black start support to energize the system, and deferral of the need for system capital investments.

Wegner et al (2017) carried out a value pool economic analysis of the UK electricity market and identified that up to 21bnGBP per year of new financial value is available by 2050 with carbon pricing identified as critical, and electrical vehicles as a key driver of growth in demand. They assumed that load shifting occurred for 5 peak hours per day (6-8am and 5-8pm) and that domestic and non domestic heat would be up to 100% shiftable but that the amount of heat load available to be shifted would vary with a 'seasonality factor'. It was estimated that power firms could potentially generate between 210 to 610mGBP in 2050 from balancing markets and avoid wholesale costs in the range 150-410mGBP but that these are relatively small amounts compared to other sources of revenue such as energy efficiency, low carbon generation, and carbon capture and storage.

P. Lund et al. (2015) carried out a comprehensive review of flexibility measures in an electricity / energy market or utility service context for both residential and service sectors in Germany. Loads with potential flexibility analyzed included space and hot water heating, ventilation, refrigeration and appliances. The capacity to reduce loads or increase loads was assessed and expressed relative to the current generation mix and loads. There was more capacity identified for load absorption than for load shedding with space heating having the largest potential contribution, night storage heaters and heat pumps with thermal stores were identified as having the smallest investment costs and being significantly cheaper than increasing flexible capacity with a gas turbine. The flexibility costs included the necessary control and communications infrastructure.

2.2. District or Building Scale Perspectives, Explicit Thermal Storage Systems

Ulbig and Andersson (2015) provide a more bottoms up approach in their framework for quantification of flexibility. They propose metrics for representing storage including power ramp rates, power capacity, energy capacity and duration (only one of these two is a requirement as the other can be calculated) within a 'power node network' modeling framework where each element of the system i.e. load, generation or storage is represented. They characterize storage state of charge as being between 0 and 1 and ascribe efficiencies to charge or discharge events, they consider a store to have losses due to leakage, and also for there to be losses due to curtailment. The storage state of charge is then modified based on energy balance.

Stinner et al. (2016) reference and build further on the work of Ulbig and Andersson in order to quantify operational flexibility potential of thermal storage. They focus on time, power and energy characteristics of storage systems and consider TES systems as multi-segmented systems with state of charge determined based on an energy balance with respect to a reference temperature representing the return water temperature from heating or the cold water feed temperature with seasonal variations. Beginning with the same storage representation as Ulbig and Andersson they add further parameters. Temporal flexibility for absorbing or shedding of load are captured through the time at maximum charge rate till full, and the time at maximum discharge rate until empty. Forced power absorptance and shedding are represented by the difference between forced and normal power which can be integrated over the period of interest to give average power, net energy effects and efficiencies etc. Modeling is carried out for two example systems. The output parameters used to describe the flexibility performance are: the thermal power generation or absorption capability of the store divided by the nominal heat loss for the building, the energy storage capacity divided by the heat demand for a single day, similar parameters are calculated for the electrical rather than thermal power capabilities. These outputs are plotted based on Modellica hourly calculations over a year for the example systems identifying the amount of load shift potential as it varies over the year for each system configuration.

Tuohy et al (2016) describe an orchestration scheme for the use of storage to support load shifting with the aim of increasing local consumption of renewables. The context is a Scottish Community where renewable generation by wind and solar is currently supported by feed in tariffs, the project looked beyond feed in tariffs to maximizing local self consumption as an alternate financial paradigm. They forecast ahead 48hrs based on a model of the thermal storage system which projects storage node temperatures over time based on current timestep storage temperatures, including the effects of: losses, destratification, solar thermal inputs, required flow temperatures for comfort, costs, and user behaviors. The forward projection informs a load flexibility vector capturing load absorbing or load avoiding opportunities and costs for potential load shift for each timestep over the future 24hour period. The load flexibility vector is of the following form: [timestamp (48hrs @30min steps): F_Q_load, F_Qprecharge, F_Qcoast, F_h_coast, F_h_prech_coast, F_Cost] where F_Q_load is the forecast load were the load to occur at the standard time, F_Qprecharge is the forecast capacity for absorbing surplus and reducing the standard load by pre-charging, F_Qcoast is the energy that would be required to charge the load if it were to be coasted, F_h_coast is the predicted hours that a load can be coasted for and still meet the comfort requirements, F_h_prech_coast is the hours that the load could be coasted if it were to be charged at this timestep, F_cost is the cost factor taking account of the extra energy that may be used due to increased losses or lower efficiencies if a load is pre-charged or coasted.The vectors for each available load shift opportunity are aggregated and a decision made on the optimal action to take to meet a load shaping objective function (matching with local renewable generation in this case).

Palmer (2017, 2011) has investigated the benefits of storage in the context of plant design for servicing districts or commercial buildings with biomass systems and has produced industry guidance and a free tool for optimizing the plant and storage size for such systems. Storage is shown to be beneficial in reducing capital costs and allowing the biomass heat generator to run in its most efficient manner. Historical industry sizing had been to size the generation plant for peak load which occurs typically for a few hours of the day a few times during the year. The system sizing tool analyses generation with thermal storage and identifies the optimum overall system in which storage allows a smaller generator to be specified with associated capital cost savings and improved operational characteristics. The calculations are based on a simple 2 node energy balance model of thermal storage. Palmer highlights that many pre-existing installations without storage have potential to serve higher loads if storage is added, avoiding capital expenditure on heat producing plant and providing improved economics for the existing plant.

2.3 Building Level, Inherent Thermal Storage

Multiple authors have focused on building level and in particular at the use of inherent energy storage to provide energy services. The inherent storage is a function of the thermal capacity of exposed construction elements and the buildings heat loss characteristics. Several authors have also looked at the potential for grid services from aggregation.

Oldewurtel et al. (2013) looked at using an aggregation of office buildings to provide grid services by flexing the heating and cooling loads within the allowed thermal comfort bands. The power shift potentials and power shift efficiency were evaluated over a 48 hour look ahead period and an optimal control infrastructure proposed based on a future price signal.

Hurtado et al. (2017) provide a framework for quantifying demand flexibility due to structural storage. Demand flexibility parameters are: reaction time; ramping rate; power capacity; energy capacity; comfort capacity (time to drift from nominal to maximum thermostat setting); comfort recovery (time to get from minimum back to nominal). In assessing these performance parameters simple building energy models are used.

Le Dreau and Heiselberg (2016) provide an assessment of the potential of buildings to modulate heating power. Thermostatic setpoints of 22+/-2C are considered for charge and discharge operations with durations between 2 and 24hrs. The impact on overall energy use of a charge operation is quantified by integrating the power used over an extended time period during and after the charge period. The thermal response efficiency is defined as the energy saving in a discharge operation divided by the energy cost of a charge operation. A flexibility factor F is defined to capture the load shift capability for load shifting between 2 time periods, F = (Qh-Ql)/(Qh+Ql) where Q is cumulative energy delivered and h and l refer to high and low tariff periods respectively. It was recognized that this flexibility factor and the other performance parameters have high dependence on climatic and building user conditions and need to be evaluated over a range of conditions.

Reynders et al. (2017) also provide a characterization method for quantification of energy flexibility of buildings and their ability to respond in an active demand response

(ADR) mode under rule based control. The demand responses involve changes in thermostatic settings and control of delivered power to absorb energy when required. Parameters are defined for the energy capacity available for absorption, the power shift capability and efficiency. Power shift capability is expressed as a timespan over which a set load can be supplied without compromising the comfort limit, the time duration to be quantified for different loads. The efficiency for the load shift event is a measure of the usefulness of the forced energy in meeting overall heating demands and is calculated by integrating over a longer period the cumulative energy used under the ADR case and the standard no-ADR case, if the integral shows that there is no difference in energy use e.g. increased losses, then efficiency is 1, if the energy injected is all lost and doesn't offset heating demand after injection then efficiency is 0. A simple case study is used for illustration which shows that higher thermal capacity and higher insulation levels improve efficiency and extend the power shift capability.

Inherent thermal storage is captured to some extent in current regulations but only indirectly as a means of mitigating overheating in buildings. The thermal capacity and heat loss parameters included in ISO13790 (ISO 2008) which are used in calculating gain utilization factors and in overheating calculations could potentially also be used to represent inherent thermal storage. As an example, thermal capacity numbers in the ISO13790 based Passivhaus design software range from 60Wh/m^{2}K (low thermal capacity) to 204Wh/m^{2}K (high thermal capacity) which for a 100m^2 dwelling gives 6kWh/K and 20kWh/K respectively. If we consider a 2K change in temperature acceptable then this gives 12kWh and 40kWh thermal capacity respectively. With Passivhaus levels of insulation the design day heat loss will be around 10W/m^2 or 1kW total giving around 12 hours duration before the 2 degree comfort budget is used up in the low thermal capacity building if the heat supply were to be interrupted, and 40 hours in the high thermal capacity building. Lower levels of insulation would have correspondingly shorter durations e.g. 3 and 16 hours respectively for a 4kW heat loss (around 2007 UK building regulations) and 1 and 3 hours for an 11kW heat loss (typical UK building).

2.4 Summary of literature

Fast load response can have a high value in electricity service markets. Storage for load shift has a value based on grid price spread. Local optimization at community or building level to optimize for self consumption of local renewable generation, or to take advantage of supply price opportunities can have significant value particularly in a future post renewable generation subsidy era.

Avoidance of capital investment and the opportunity to increasing revenue from existing generation assets (heat and electricity) can provide significant value at both grid and local system scales.

The ability of buildings and systems to provide flexibility support in future energy systems can come from both explicit and also inherent storage capacity.

Building and system characteristics which support flexibility can also support enhanced thermal comfort and improve resilience to loss of supply.

Various performance parameters and models have been put forward in literature but there is a lack of a set covering all of the potential energy services storage can provide. In the next section such an overall set is proposed.

3. Proposed Performance Metrics for TES Services.

The intent here is synthesize from prior work a useful list of metrics capturing the broad scope of potential benefits (and negatives) of storage. Energy Storage consists of both explicitly designed systems for storing thermal or electrical energy such as hot water tanks, phase change materials, batteries etc. and inherent storage incorporated in buildings and district systems due to their normal functional characteristics such as buildings, district heating distribution systems. In order that the value associated with storage is properly captured in the design and operation of low carbon buildings and districts it is important to be able to clearly define and quantify these values, and have these values incorporated in the assessment of different design options so that an optimal system is achieved. Modeling tools must support quantification of the key performance metrics associated with explicit and inherent storage so that storage is correctly comprehended in modeling tools that support policy formulation, design, and regulatory processes. From the literature potential benefits from storage can be categorized into:

- Load shedding or grid surplus absorption for short term supply response (<15mins).
- Load shaping for grid supply / demand system balancing optimization (> 15mins).
- Local building or district supply optimization (Cost, CO_2, Renewable Energy etc.).
- Plant optimization (e.g. smaller generator if storage etc). applies at all levels.
- Enhanced service in terms of reduced fluctuations e.g. thermal comfort.
- Enhanced resilience to loss of service.

There are however potential negatives associated with storage to be considered:

- Losses in storage cycle lead to increased energy use.
- Losses in storage lead to discomfort e.g. due to lack of service or parasitic losses).
- Lifecycle (costs, risks, embodied energy, carbon, environmental impacts).

Energy systems are dynamic and subject to stochastic and seasonal variations in demands and supply characteristics. Performance metrics should therefore be quantified for appropriate periods, e.g. time of day, intra-day, typical summer period, typical winter period, annualized, and the quantification should consider statistical uncertainties.

Potential performance metrics are discussed at high level in the following sections, it is important to note that in practice detailed models are expected to be used to quantify these metrics across a range of timescales, and ideally for an appropriate range of weather, building operations, and user behaviors.

3.1 Capturing positive benefits from thermal storage

3.1.1 Load shedding or absorption for short term response (<15mins).

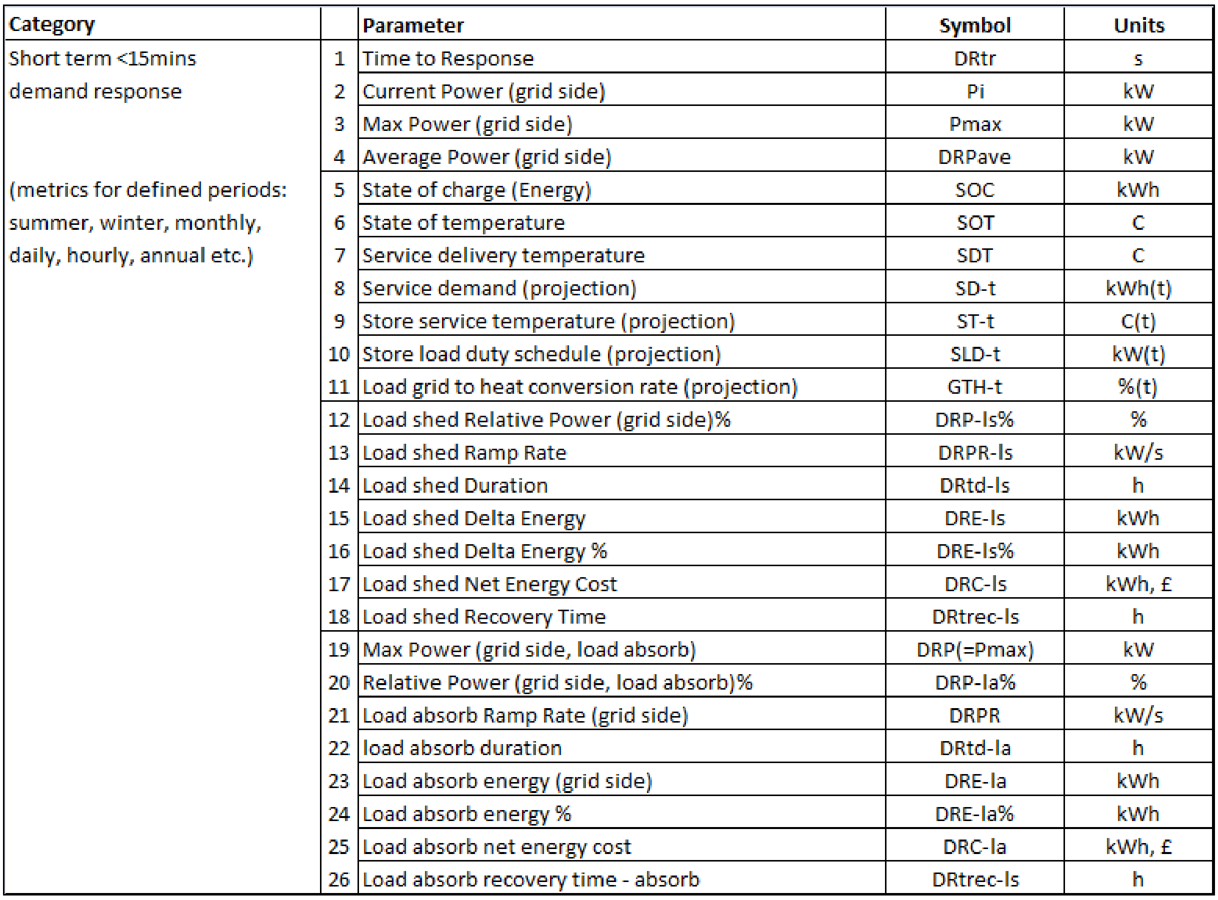
Storage, whether explicit or inherent, allows the possibility that it can be used to provide short term response services to the grid through reduction or increase in load based on a signal from the grid operator or local measurements of frequency or voltage condition. This functionality is often termed 'demand or frequency response' and typically requires the system to respond with an ON (load absorb) or OFF (load shed) within a time of the order of seconds (depends on the size of the network and its reactance). This type of demand response is currently deployed for curtailment of a renewable generator such as local PV when there is an oversupply or to start up fossil fuel backups if there is a renewable shortfall, in future demand response actions associated with storage would be used in order to minimize CO_2 emissions. Infrastructure similar to that used for 'smart meters' or 'storage heaters' on 'white meter' tariffs could potentially be used to aggregate consumers to provide this service in future. Local intelligence (or in the cloud) would in principle allow individual systems to provide a response if capacity was available without compromising delivery of services to the customer. The aggregator would require some assessment of the likely response at any particular time to quantify the service they could provide to the grid. Performance metrics important for this short term response service are given in figure 1.

Available response is primarily characterized from the grid side by the time to respond, the current power consumption (or the average power for aggregated loads), the maximum power consumption, the power ramp rates, the available durations (and associated energy) for power absorb or load shed operations, the energy and financial costs associated with these response events, and the recovery time required before a repeat response is available. The response available as a fraction of the total load may also be a useful parameter.

The duration of the required absorb or shed response is a key parameter. Very short responses of the order of seconds or a few minutes would in many circumstances be invisible to the end user due to the large time constant of the system or building.

Longer responses would require the available durations to be assessed, by 'local' intelligence i.e. the storage or enhanced heating/cooling system controls, based on individual system parameters such as the current stored energy, current store temperature, service demands and store temperature projections including system losses, store normal duty cycle and grid to heat conversion rate (e.g. for a heat pump) etc. (parameters 5 to 11 in figure 1). The individual system would then only provide a response if there was no impact on comfort.

The view is taken here that the storage parameters should directly consider temperature outputs from storage systems and compare the storage temperature to the required temperature to operate the service, in the literature this is normal in the studies for building level inherent storage, but was generally neglected in the Community and Grid level studies which generally consider only the energy balance.



Category		Parameter	Symbol	Units
Short term <15mins demand response	1	Time to Response	DRtr	s
	2	Current Power (grid side)	Pi	kW
	3	Max Power (grid side)	Pmax	kW
	4	Average Power (grid side)	DRPave	kW
(metrics for defined periods: summer, winter, monthly, daily, hourly, annual etc.)	5	State of charge (Energy)	SOC	kWh
	6	State of temperature	SOT	C
	7	Service delivery temperature	SDT	C
	8	Service demand (projection)	SD-t	kWh(t)
	9	Store service temperature (projection)	ST-t	C(t)
	10	Store load duty schedule (projection)	SLD-t	kW(t)
	11	Load grid to heat conversion rate (projection)	GTH-t	%(t)
	12	Load shed Relative Power (grid side)%	DRP-ls%	%
	13	Load shed Ramp Rate	DRPR-ls	kW/s
	14	Load shed Duration	DRtd-ls	h
	15	Load shed Delta Energy	DRE-ls	kWh
	16	Load shed Delta Energy %	DRE-ls%	kWh
	17	Load shed Net Energy Cost	DRC-ls	kWh, £
	18	Load shed Recovery Time	DRtrec-ls	h
	19	Max Power (grid side, load absorb)	DRP(=Pmax)	kW
	20	Relative Power (grid side, load absorb)%	DRP-la%	%
	21	Load absorb Ramp Rate (grid side)	DRPR	kW/s
	22	load absorb duration	DRtd-la	h
	23	Load absorb energy (grid side)	DRE-la	kWh
	24	Load absorb energy %	DRE-la%	kWh
	25	Load absorb net energy cost	DRC-la	kWh, £
	26	Load absorb recovery time - absorb	DRtrec-ls	h

Figure 1: Demand Response Metrics

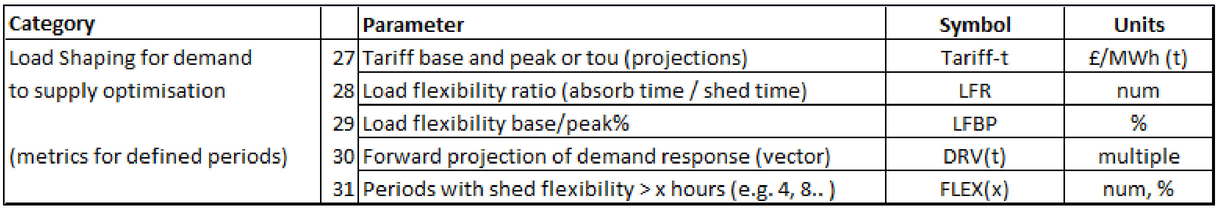
3.1.2 Load shaping for supply to demand optimization.

The load shaping functionality is similar to the short term demand response but acts over longer periods of the order of 2 to 48 hours ahead based on forecast grid conditions. Pricing signals are applied, either standard schedules for peak and base tariffs, or increasingly, time of use (tou) hourly or half-hourly electricity cost schedules. The intent of these is to reduce peak demands and provide less variation in demands in order to reduce the need to for investment for peak capacity and to increase the utilization factors and return on investment for the existing capacity. There has historically been a need to move demand to night time to fill in the overnight demand gap and reduce morning and evening peaks which has been enabled by technologies such as the system of 'storage heaters' and thermal stores on 'white meter' tariffs in the UK. In future there is likely to be increasing availability of 'time of use' tariffs where each 30 minute timeslot in a 24 or 48 hour period is given an independent price, re-forecast periodically, allowing for storage to enable load shifting to low tariff periods. Storage used in this way can also enable surplus grid scale renewable energy to supply the grid that would otherwise be curtailed. Most of the performance parameters that were important for short term demand response are also important for load shaping however some further metrics are also useful (figure 2).

The load flexibility in support of demand optimization has 2 dimensions, the first is the ability to absorb cheap electricity during periods of availability and to this end the time to charge (DRtd-la, parameter 22 in figure 1) is important as if it is too slow then opportunities will be missed, the second is the ability to coast through periods of high cost ((DRtd-ls, parameter 14 in figure 1) as if this is too short then high cost electricity cannot be avoided. A load flexibility ratio is defined as the ratio of charge time to coast time to help characterize storage flexibility.

The percentage of the load that can be shifted to periods of low tariff for defined high and low period situations would provide a useful but tariff specific output so tariff used must be clearly stated. The load shed duration could be used to provide alternative tariff independent metrics derived simply from an analysis of load shed durations for a range of potential flexibility periods.

The current logic applied to tariff periods is generally a simplistic switch on of off-peak charging when low tariff periods commence and off when the off-peak period ends with charging maximum controlled thermostatically. If the storage reaches its lower control limit during peak times then peak electricity is used to boost. In future, time of use tariffs will potentially support more sophisticated local optimization through some forward projection of performance (e.g. a multi-parameter vector) and option selection.



Category		Parameter	Symbol	Units
Load Shaping for demand to supply optimisation (metrics for defined periods)	27	Tariff base and peak or tou (projections)	Tariff-t	£/MWh (t)
	28	Load flexibility ratio (absorb time / shed time)	LFR	num
	29	Load flexibility base/peak%	LFBP	%
	30	Forward projection of demand response (vector)	DRV(t)	multiple
	31	Periods with shed flexibility > x hours (e.g. 4, 8..)	FLEX(x)	num, %

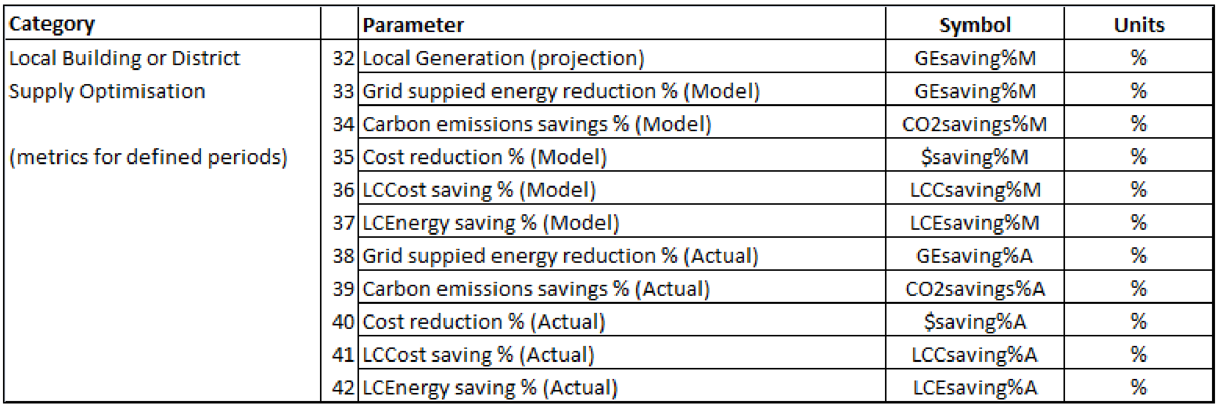
Figure 2: Load Shaping Metrics

3.1.3. Local building or district supply optimization (Cost, CO_2, Renewable Energy etc.).

Local supply optimization would take information on future renewable energy availability, grid energy tariff pricing, grid associated carbon emissions, weather and end user demand forecasts over a future time horizon as inputs, and optimize the use of the thermal energy storage to achieve the best possible performance for a selected objective function. The required functionality for this service could potentially be built upon smart meter platforms or similar infrastructure. The parameters described in the previous sections should provide inputs to the optimization.

A set of performance metrics quantifying the benefits of the storage can be envisaged (figure 3) such as: saving in grid supplied energy (GEsaving%), reduction in carbon emissions (CO_2saving%), reduction in total energy cost ($saving%), reduction in lifecycle cost (LCCsaving%), reduction in lifecycle energy (LCEsaving%). In reality the objective function for the optimization is likely to be some combination of these.

Design estimations of performance should be clearly differentiated from actual measured performance to allow insight into performance gaps that may exist due to practical problems. Based on evidence from the building industry there is large scope for such performance gaps unless the prevalent industry issues are addressed (Tuohy and Murphy 2015). Actual verification of system performance would appear to be essential to provide validation (Tuohy and Murphy 2015a).



Category		Parameter	Symbol	Units
Local Building or District Supply Optimisation (metrics for defined periods)	32	Local Generation (projection)	GEsaving%M	%
	33	Grid suppied energy reduction % (Model)	GEsaving%M	%
	34	Carbon emissions savings % (Model)	CO2savings%M	%
	35	Cost reduction % (Model)	$saving%M	%
	36	LCCost saving % (Model)	LCCsaving%M	%
	37	LCEnergy saving % (Model)	LCEsaving%M	%
	38	Grid suppied energy reduction % (Actual)	GEsaving%A	%
	39	Carbon emissions savings % (Actual)	CO2savings%A	%
	40	Cost reduction % (Actual)	$saving%A	%
	41	LCCost saving % (Actual)	LCCsaving%A	%
	42	LCEnergy saving % (Actual)	LCEsaving%A	%

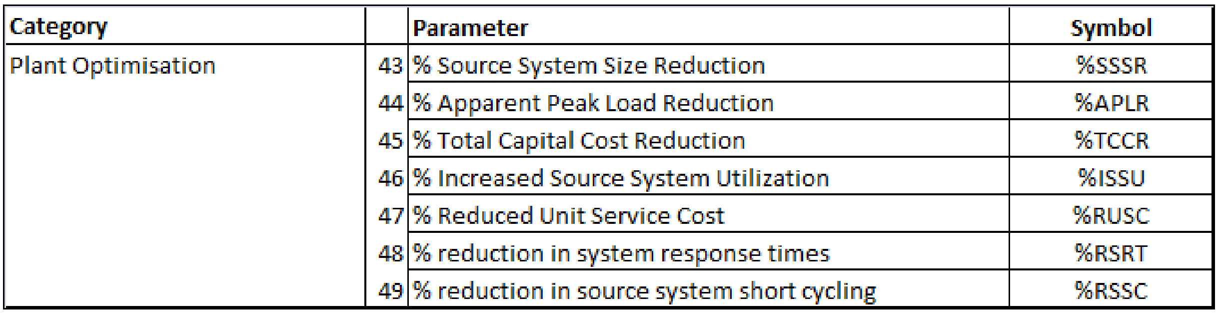
Figure 3: Local Performance Optimization Metrics (Modeled and Actual)

3.1.4. Capital and return on investment optimization.

Storage has significant capital cost reduction and revenue enhancing benefits at both large and smaller scale. At large scale the savings in capital cost required for generation, transmission and distribution expansions associated with increased electrification of heat and transport and increased implementation of variable renewable generation technologies is substantial. Storage can also enable increased revenue from renewable generation through avoidance of curtailment. The need for flexible backup generation to accommodate variable renewables can potentially be avoided through thermal storage.

At the smaller scale, for new installations thermal storage can allow peak loads to be satisfied by a significantly less expensive smaller thermal or electrical generator (e.g. with a heat pump) running for longer hours achieving better asset utilization. Where heat or electrical generation capacity is already installed, storage can allow larger loads to be served and longer run hours increasing asset utilization and maximizing revenues. The thermal storage allows the system to run in a more continuous mode rather than short cycling which improves operational efficiency and can reduce maintenance requirements and extend the asset lifetime. Thermal storage allows demands to be served immediately from store rather than waiting for the heat generation system to come up to operating speed which often requires significant time.

To capture these benefits in generic terms the following metrics are proposed (figure 4): % Source System Size Reduction (%SSSR); % Apparent Peak Load Reduction (%APLR); % Total Capital Cost Reduction (%TCCR); % Increased Source System Utilization; % Increased Rate or Return or % Reduced Unit Service Cost; % Reduction in System Response Times; % Reduction in System Cycling.



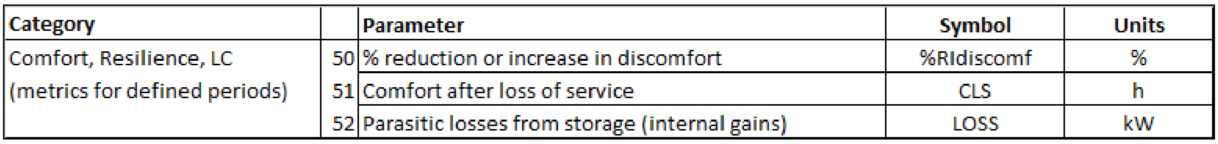
Category		Parameter	Symbol
Plant Optimisation	43	% Source System Size Reduction	%SSSR
	44	% Apparent Peak Load Reduction	%APLR
	45	% Total Capital Cost Reduction	%TCCR
	46	% Increased Source System Utilization	%ISSU
	47	% Reduced Unit Service Cost	%RUSC
	48	% reduction in system response times	%RSRT
	49	% reduction in source system short cycling	%RSSC

Figure 4: Plant Optimization Metrics

3.2.5 Enhanced thermal comfort, and resilience to loss of service.

Storage has the potential to provide capacity within a system which reduces the fluctuations that would otherwise be seen by building occupants, potentially providing a comfort benefit, or extends the period that the system can withstand a loss of service improving resilience.

These properties are captured in several the demand response and load shifting metrics provided earlier, however there remains a potential to express these more directly in thermal comfort and resilience metrics including: % reduction in discomfort events (%RIdiscomf), hours of comfort after loss of service (CLS) etc.



Category		Parameter	Symbol	Units
Comfort, Resilience, LC (metrics for defined periods)	50	% reduction or increase in discomfort	%RIdiscomf	%
	51	Comfort after loss of service	CLS	h
	52	Parasitic losses from storage (internal gains)	LOSS	kW

Figure 5: Comfort and Resilience Metrics

3.2 Capturing potential negative impacts from storage

Negative aspects of storage need to be explicitly captured in performance metrics and considered in design. These include the potential for increased energy use through the incorporation of storage systems which have an energy penalty due to charging, discharging and standby losses, these losses need to be closely scrutinized at the design and also post design stages. This increase in energy use is captured in parameters 25 and 17 but experience from the buildings domain suggests that often these parameters are underestimated as parasitic losses due to pipe connection points, pumps and other service connections are often neglected from calculations. Underestimating these energy costs could significantly undermine the benefits and must be avoided.

Parasitic losses also have the potential to cause discomfort and further unintended secondary energy use e.g. parasitic losses from thermal stores in summer can cause overheating which stimulates the use of cooling systems etc. Experience from implementation of solar thermal systems in Passivhaus dwellings in the UK has been that gains associated with the thermal storage systems cause overheating particularly due to poor insulation on connecting pipework rather than the store itself (Tuohy and Murphy 2015).

The manufacture of the storage systems and the infrastructure required for their implementation should be carefully considered as part of a comprehensive lifecycle analysis including production, disposal and recycling etc.

These considerations are covered by the performance metrics described above but need to be managed throughout the design and post design phases to ensure positive intended outcomes from storage are achieved.

4. Discussion and Conclusions

This paper has explored where TES can provide benefits in future energy systems from a range of different perspectives, and put forward 5 categories for potential services: (i) short term demand response, (ii) load shaping for demand to supply optimization, (iii) local supply optimization, (iv) reduced capital investment and increased return on investment, (v) enhanced comfort and resilience. A set of potential downsides for TES systems is also given which need to be managed.

For each category of potential benefit performance metrics are proposed to support the quantification of the benefits of TES in modeling and other assessments.

The building time constant in standard regulatory calculation methods is illustrated as having potential use to include inherent thermal storage in standards promoting thermal resilience and load flexibility. Similar parameters representing explicit storage systems could also be developed.

There are many valuable benefits that can arise from the utilization of TES in future energy systems. Arbitrage has been a primary focus of many studies from the building engineering community however other benefits of thermal storage when taken into account could give a more compelling case for future adoption.

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