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Thermal battery with CO₂ compression heat pump: Techno-economic optimization of a high-efficiency Smart Grid option for buildings

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ABSTRACT

Increasing penetration levels of wind and solar power in the energy system call for the development of Smart Grid enabling technologies. As an alternative to expensive electro-chemical and mechanical storage options, the thermal energy demand in buildings offers a cost-effective option for intermittency-friendly electricity consumption patterns.

Combining hot and cold thermal storages with new high-pressure compressor technology that allows for flexible and simultaneous production of useful heat and cooling, the paper introduces and investigates the high-efficiency thermal battery (TB) concept. In a proof-of-concept case study, the TB replaces an existing electric resistance heater used for hot water production and an electric compressor used for air refrigeration in a central air conditioning system. A mathematical model for least-cost unit dispatch is developed. Heat pump cycle components and thermal storages are designed and optimized. A general methodology is applied that allows for comparing the obtained results with other Smart Grid enabling options.

It is found that the TB concept leads to improvements in the intermittency-friendliness of operation Rc (improves from -0.11 to 0.46), lower CO₂ emissions (reduced to zero), and lower operational costs (reduced by 72%).

The results indicate that TB may be the most cost-effective Smart Grid enabling option for supporting higher penetration levels of intermittent renewables in the energy system.

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1. Introduction

Intermittent renewables are on the rise. For example, in April 2011, California's Governor signed an update to the Renewables Portfolio Standard Program now targeting 33% renewables by 2020, a majority of which will come from intermittent sources, like wind and solar. Similar high-spirited action plans are being formulated by major economies concerned with their dependency on risky fossil fuels.

As societies are pushing for higher penetration levels of wind and solar energy, the market for energy system intelligence and flexibility – vis-à-vis Smart Grid enabling technologies and services [1] – is projected to become one of the fastest growing markets within just a few years. In March 2011, one study projected that the global market for Smart Grid enabling technologies will reach USD 33 billion by 2016 [2]. Also in 2011, another study projected that Europe's Smart Grid market alone will reach USD 80 billion by 2020 [3]. Multiple studies have looked into markets for sub-categories of Smart Grid enabling technology. In 2011, a study projected that the global market for Smart Grid cyber security will reach USD 3.7 billion by 2015 [4], and in 2009, a study projected that the market for electro-chemical storage including advanced battery technologies and flow batteries could reach 1.3 billion by 2013 [5].

From an energy system perspective, the most critical Smart Grid technology area should be energy storage. Wind and solar energy is intermittent by nature and does not necessarily correlate with energy demand, whether electrical or thermal. While regions in Denmark, Germany, and Spain – constrained by limited transmission capacities to adjacent energy systems – have managed to reach penetration levels of intermittent renewables up to 25% without any major technical changes, it is generally recognized that Smart Grid enabling technologies – such as energy storage – are required to reach higher penetration levels. But what kind of energy storage should be considered for Smart Grids? Electricity storage? Well, not necessarily to begin with.

Many will appreciate the importance of considering the energy system in terms of end-use services, rather than in terms of fuels and electricity. Basically, no one needs oil, gas, and electricity. Rather, people demand space heating, refrigeration, and light. An end-use perspective has proven to be the best point of departure

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	M.D. Burke et al. / Energ
Nomenc	lature
κ	thermal conductivity
€1	=DKK 7.45 = USD 1.35
Α	surface area of storage tank
d	system electricity load minus intermittent renew-
	able energy production (positive for net demand,
	negative for excess supply)
r	thickness of the insulation material
d_m	mean of <i>d</i>
е	option's net electricity exchange (production - con-
	sumption)
e_m	mean of <i>e</i>
$f_{\rm CO_2}$	CO ₂ emission factor of marginal electricity producer
$M_{\rm CO_2}$	CO ₂ emissions
MILP	mixed-integer linear programming
Rc	intermittency-friendliness coefficient
TB	thermal battery
T _{in}	return water temperature
Tout	demand water temperature

- $T_{ambient}$ ambient temperature w electricity production of marginal electricity pro-
- ducer
- η thermal efficiency of marginal electricity producer

MILP parameters

$\overline{ph}/\overline{pc}$	heating/cooling production capacity
$\overline{sh}/\overline{sc}$	heating/cooling storage capacity
dh/dc	heating/cooling demand
l	electricity price
COPh/CC	<i>DPc</i> coefficient of performance heating/cooling
sldh/sldc	differential heating/cooling storage loss
sleh/slec	heating/cooling storage loss in empty state
MILP vai	riables
DumpPh	/DumpPc dumped heating/cooling
Fν	electricity consumption
Pe	electricity production
Ph/Pc	heating/cooling production
Sh/Sc	heating/cooling storage content
ShIn/ScIi	n heating/cooling production to storage (storage in)
ShOut/So	cOut heating/cooling storage to demand (storage
	out)
Slh/Slc	heating/cooling storage loss
U	binary variable
MILP ind	lices

k unit (e.g. electric heater – excluding thermal storages).
 t time interval

for identifying truly energy efficient and cost-effective alternatives. For example, society stands to benefit greatly from not focusing on supplying people with roads, when people really need mobility services.

However, when dealing with intermittent renewables, many policy analysts and utility planners continue to have a narrow focus on the supply and distribution of electricity. As a result, appropriate options for Smart Grid enabling technologies in heating and cooling services for buildings are overlooked. From a socio-economic system perspective, such ignorance is costly.

In fact, from simply considering the specific capital costs of establishing energy storage, we find that the specific cost of thermal storage is easily 1% or less of the costs of electro-chemical or

Table 1

Characteristics of Li-ion battery and sensible water storage.

	Li-ion battery	Sensible water storage
Specific energy costs	200–850 USD/kWh	1–5 USD/kWh
Charge-discharge efficiency	80-90%	95%
Lifetime	Perhaps 1000 cycles	30 years+
Capacity affected by cycles	Significantly	No
Monthly self-discharge rate	8% (21 °C), 15% (40 °C)	25% (1000 m ³)
Energy density	250–620 kWh/m ³	$65 \text{ kWh/m3} (\Delta T = 50 \circ \text{C})$
Specific energy	100–250 kWh/ton	65 kWh/ton (ΔT = 50 °C)

Li-ion battery data from [23].

mechanical storage. Furthermore, thermal storage offers advantageous characteristics, including longer life time, no degradation in capacity, and higher charge–discharge efficiency (Table 1).

This should be a sufficient point of departure for our basic hypothesis: if energy (both electrical and thermal) generated by intermittent sources is destined for thermal end-uses, then technologies allowing for immediate conversion to thermal energy and thermal storage close to these end-uses, will be more costeffective in meeting Smart Grid enabling objectives than any electro-chemical or mechanical storage option. While thermal storage is not the only energy storage option required in the making of Smart Grids towards extreme penetration levels, our investigation will provide an indication of what should be the priority focus of Smart Grid efforts towards reaching higher penetration levels in a cost-effective way.

In exploring this hypothesis, the paper presents a concept – the thermal battery (TB) – that effectively couples the supply of electricity with the provision of heating and cooling services, utilizing both hot and cold thermal storages, thereby allowing for the intermittency-friendly provision of heating and cooling services for buildings. The paper investigates how the TB may be designed, modeled, and operated as a Smart Grid enabling technology, and by which degree it may support increasing penetration levels of intermittent renewables. Furthermore, the paper assesses the marginal economic and environmental consequences of introducing the TB.

2. Thermal battery concept

The TB concept takes advantage of the pressure and temperature difference across evaporator and gas cooler (or condenser) that can be obtained with new high-pressure compressor technology. The TB converts electricity simultaneously to hot and cold reservoirs at useful temperature levels using a high-pressure CO₂ compression heat pump in combination with an auxiliary electric resistance heater (Fig. 1). With the integration of thermal storage reservoirs and intelligent control systems, the TB may take advantage of real-time or time-of-use electricity pricing markets as well as automatic or manual downwards auxiliary/balancing/curtailment markets to provide heating and cooling services at lowest possible costs and/or carbon emissions. While latent and chemical thermal storage mediums are possible, and possibly favorable in certain applications, this study focuses on sensible water-based storages.

The TB represents a general principle that may be utilized for a wide range of applications ranging from distributed generation to industry and buildings. Blarke [6] provides an analysis of the concept for large-scale applications in distributed co-generation and tri-generation. In fact, the TB concept is widely applicable for replacing or supporting systems which are currently providing heating and cooling separately. In buildings, TB may replace water heaters and central A/C systems, which is also the application analyzed here. The provision of refrigeration services may also be integrated. On a more speculative note, the TB concept – possibly using thermo-electric devices rather than CO₂



Fig. 1. The thermal battery concept.

compressors – may also apply to for small-scale site-specific distributed cooling and heating or low quality waste recovery.

The idea of using CO_2 heat pumps for simultaneously producing useful heat and cooling has been dealt with by Adriansyah [7], Stene [8], and more recently by Byrne [9], Sarkar et al. [10] and Chen and Lee [11]. Considering CO_2 (R744) rather than HFCs (hydrofluorocarbon, such as R134A) or HCs (hydrocarbon, such as propane R600A), for refrigerant is relevant for a number of reasons:

Thermodynamically, CO_2 allows achieving higher temperature levels on the warm side without compromising the COP. For the TB concept, the higher temperature levels on the warm side are particularly important as the TB rely on thermal storage for which we need to account for resulting heat losses, while maintaining useful temperature levels. Using HFCs or HCs may rather provide what is sometimes referred to as "free" heating from cooling appliances, but this low-temperature heat is useful mainly for pre-heating purposes, not for meeting final requirements. Significant auxiliary heating (electric resistance heater) is required, which reduces the COP. In fact, Byrne compares the use of HFC and CO_2 for simultaneous heating and cooling applications and concludes that "the replacement of a standard heat pump [..] leads to a higher increase in performance with carbon dioxide than with an HFC" [9].

Chemically, CO_2 has a Global Warming Potential (GWP) of 1, while HFC R134A has a GWP of 1300. In fact, some EU regulators are even considering phasing out the use of HFCs due to leakages contributing increasingly to greenhouse gas emissions. For HC refrigerants, these may be problematic for residential applications due to risks associated with high flammability.

The paper's novel focus is the integration of both hot and cold thermal storages in combination with the simultaneous production principle, while considering its application and operational optimization in a Smart Grid context. The TB's double storage system allows for meeting non-concurrent thermal requirements and for optimizing and analyzing TB in an energy system perspective, where flexible operation utilizing thermal storages – thereby un-coupling demand and supply – is crucial towards supporting intermittent renewables.

Furthermore, within the perspective of Smart Grid metering and electricity markets, we will develop and present a mathematical model for optimal economic scheduling of the TB's thermal services. For a proof-of-concept case-study, we will apply the model for evaluating the marginal economic and system-wide consequences of the TB concept. In a proof-of-concept case study, we apply the TB for simultaneous, yet flexible supply of hot tap water heating and space cooling for a residential building in a warm continental climate zone, where the majority of buildings are supplied with space cooling (San Jose, California). Our hypothesis is that a particular market potential exists for the hot tap water heating and space cooling application in this climate zone and energy market. California's energy system is characterized by modern electricity markets and high penetration levels of intermittent renewables (wind and solar power). While space cooling is not relevant in all climates, the TB may be also be designed for space heating and/or hot tap water on the warm side, and refrigeration and/or process cooling on the cold side. Such TB applications would be relevant for markets in Northern Europe and Scandinavia.

3. Techno-economic approach and methodology

A techno-economic analysis is performed for a TB replacing a hot tap water heater and central A/C system providing heat and cooling services in an existing residential building. The focus of the analysis will be on comparing parameters that are particularly important to Smart Grid developments: intermittency-friendliness of operation, system-wide CO₂ emissions, and economic costs of operation.

The analysis is performed for a proof-of-concept case study comparing TB with an existing conventional option for a single summer day of operation (July 19, 2011) for a specific location in California, USA: San Jose in PG&E's service area. The location is selected due to its closeness to major Smart Grid research programs, and due to the climatic conditions in San Jose due to which typically generate a demand for space cooling. The case study is a proof-of-concept in the sense that it is expected to represent ideal conditions under which the TB may replace conventional separate heating and cooling technologies. As such, the case study is not suggested to be representative for every possible TB end-use reference situation or location, but will primarily help to identify a best practice potential for TB.

In fact, our hypothesis is that the cost-effective use of CO_2 compressors – at least in the medium term – will be limited to situations allowing for simultaneous production of heating and cooling. If a significant share of the cooling or heating production is not utilized, the return on investment for integrating



Fig. 2. PG&E load, intermittent renewables production, and net requirements on July 19, 2011 (MWh/h).

the thermal supply using costly compressor technology is likely to be low.

Only operational aspects are considered. No attempt is made to establish the feasibility of operating the system over any longer planning period. Investment costs, including the costs of replacing existing equipment, are not considered. Fixed operational costs are assumed to be similar for TB and the existing conventional option and are thus excluded from the analysis. Furthermore, no mechanical considerations are offered with respect to the physical integration of the TB. However, the existing conventional technology chosen for analysis is expected to make the replacement relatively straightforward while maintaining central elements of the existing heating and cooling distribution systems, thus, keeping investment costs relatively low.

3.1. COMPOSE: Software for comparing energy options in a system perspective

The analysis is performed using the COMPOSE software [12,13] that combines detailed operational simulation under the deterministic techno-economic constraints of the TB and the existing appliances with a least-cost marginal-dispatch model for the energy system in which the TB is analyzed. The energy system model allows for an identification of the marginal system-wide consequences with respect to the intermittency-friendliness of operation and CO_2 emissions. These particular system analysis methodologies are described in further detail below.

In COMPOSE, the user defines an energy option in terms of enduse requirements, storages, and conversion processes (e.g. heat pump). Options may be designed from scratch or based on build-in libraries. Furthermore, the user defines an energy system in terms of spot markets, candidate marginal power producers, electricity demands, and intermittent production. For both option and system, parameters are specified on an hourly basis for each year of analysis. System specific parameters may be imported from utility databases, or adapted from COMPOSE's build-in libraries.

COMPOSE then identifies the option's optimal operational strategy by mixed-integer linear programming under the objective function of minimizing the economic cost of meeting heating and cooling demands for the period of simulation under given techno-economic constraints and boundaries, including hourly values for end-use requirements, capacities and efficiencies, market prices, variable O&M costs. The resulting detailed energy balance includes e.g. fuel and electricity consumption, storage states, energy losses, energy costs. For TB, based on the identified least-cost operational strategy, COMPOSE uses the resulting net electricity profile – the TB's hourly electricity consumption profile – as a basis for calculating the resulting energy system impacts, including intermittency-friendliness Rc and marginal CO₂ emissions. Several other COMPOSE results are available from such analysis, but are not considered here.

3.2. The intermittency-friendliness coefficient Rc

An intermittency-friendliness coefficient Rc has been introduced as a means of measuring how well an electricity demand (or supply) support the integration of intermittent renewables, thus enabling Smart Grid. Rc is defined as the statistical correlation between the net electricity exchange end-user and grid, and the energy system's net electricity requirements, as stated in Eq. (1) [14].

$$Rc = \frac{\sum (e - e_m)(d - d_m)}{\sqrt{\sum (e - e_m)^2 \sum (d - d_m)^2}}$$
(1)

where e is the net electricity exchange between end-user and system, d is the net electricity requirements vis-à-vis the system's electricity load minus intermittent electricity production, and m-subscript refers to mean values.

Eq. (1) is based on the Pearson correlation, which is a dimensionless index obtained by dividing the covariance of two variables by the product of their standard deviations. By definition, the index ranges from -1 to 1, where -1 expresses that two variables have an extreme negative association, while 1 expresses that the two variables have an extreme positive association. For the variables in the intermittency-friendliness coefficient *Rc*, net electricity exchange (using negative values for consumption) and net grid requirements (electricity demand minus intermittent supply), a coefficient of 1 identifies an electricity consumption pattern that perfectly support the system's balancing challenges by using more electricity when net requirements are low (high wind/PV periods), and



Fig. 3. PG&E spot day-ahead market on July 19, 2011 (USD/MWh).

avoiding using electricity when net requirements are high (low wind/PV and/or peak demand periods).

For individual options, extreme values are rarely achieved. But comparing options in terms of *Rc* allows maximizing the design and operational strategy of individual options towards supporting intermittent renewables in the energy system.

3.3. System-wide CO₂ emissions

COMPOSE applies a least-cost marginal dispatch energy system model for identifying marginal CO_2 emissions for each hour of operation. The marginal electricity producer is identified by comparing the short-term marginal cost of operation for dispatchable producers' with the day-ahead spot market price. For each hour of operation, the marginal electricity producer is identified as the producer with the lowest marginal cost of operation that is higher than the day-ahead spot market price. Subsequently, the emissions M [kg] are found as stated in Eq. (2).

$$M_{\rm CO_2} = \sum_{t=1}^{l} w_t \frac{f_{\rm CO_2, t}}{\eta_t}$$
(2)

where *t* is the hour of operation, *w* [kWh] is the electricity production, η is the thermal efficiency of the identified marginal electricity producer, and *f* [kg/kWh] is the emission factor of the fuel used by the marginal electricity producer.

3.4. Mathematical economic dispatch model for the TB

The TB and the reference option are modeled according to leastcost principles. Thus, the objective function f(x) in the mathematical unit commitment model is to minimize the costs of operation. Let Fv be the electricity consumption [kWh], l the electricity price, and k the units (e.g. the resistance heater, but excluding storages), then f(x) is determined by Eq. (3):

$$f(x) = \sum_{k=1}^{K} \sum_{t=1}^{T} F \nu_{k,t} \times l_{k,t}, \quad \text{where } t \in \{1 \dots 24\}$$
(3)

where *x* is the specified set of variables. In actual model implementation, the objective function includes proxy cost elements related to dumped thermal production, which is excluded here for the purpose of clarity.

The heating and cooling balance is given by Eq. (4):

$$dh_t = \sum_{\substack{k=1 \ K}}^{K} Ph_{k,t} - ShIn_t + ShOut_t$$

$$dc_t = \sum_{\substack{k=1 \ K}}^{K} Pc_{k,t} - ScIn_t + ScOut_t$$
(4)

where the heat/cooling demand *dh/dc* [kWh] is equal to the heat/cooling production *Ph/Pc* minus net production to the thermal storage (storage in (*ShIn/ScIn*) minus storage out (*ShOut/ScOut*)).

The heat/cooling production *Ph/Pc* is the product of the electricity consumption *Fv* and the *COPh/COPc*. Furthermore, as the TB's thermal production may not always be utilized, variables for dumped heating/cooling *DumpPh/DumpPc* are introduced as expressed in Eq. (5):

$$Ph_{k,t} + DumpPh_{k,t} = Fv_{k,t} \times COPh_{k,t}$$

$$Pc_{k,t} + DumpPc_{k,t} = Fv_{k,t} \times COPc_{k,t}$$
(5)

Dumped heating/cooling is assigned a very low cost and included in the objective function Eq. (3) to force for surplus thermal production to be stored rather than dumped.

The balance of the thermal storages is obtained by Eq. (6):

$$Sh_t = Sh_{t-1} - Slh_t + ShIn_t - ShOut_t$$

$$Sc_t = Sc_{t-1} - Slc_t + ScIn_t - ScOut_t$$
(6)

where the heating/cooling storage content *Sh/Sc* [kWh] is equal to the storage content in the previous time interval minus the storage loss *Slh/Slc* plus net production to the storage.

The heating/cooling storage loss *Slh/Slc* is given by Eq. (7):

$$Slh_{t} = sleh_{t} + \frac{Sh_{t}}{\overline{sh}_{t}} \times sldh_{t}$$

$$Slc_{t} = slec_{t} + \frac{Sc_{t}}{\overline{sc}_{t}} \times sldc_{t}$$
(7)

where *sleh/slec* is the heating/cooling storage loss when the storage is empty, and the differential heating/cooling loss *sldh/sldc* is the



Fig. 4. Case study: hourly space cooling and water heating demand (kWh/h).

storage loss when the storage is full minus the empty storage loss rate. Storage loss in full and empty state is established according to Eqs. (11) and (12).

Furthermore, the mathematical problem is subject to the boundary conditions of maximum production capacity and thermal storage capacities determined by Eq. (8):

$$\begin{array}{l}
Pc_{k,t} \leq \overline{p}c_{k,t} \\
Sh_t \leq \overline{sh}_t \\
Sc_t \leq \overline{sc}_t
\end{array}$$
(8)

As technical considerations suggest that real-world operation should also minimize the number of compressor starts and stops (switches), and that transient characteristics may be ignored for discrete operation (minimum 1 h between switches) the analysis will apply a constraint by which the compressor unit is only allowed to operate at full capacity within each hour. For this purpose, a binary variable U is introduced, which constrains the compressor unit's electricity consumption to either zero or full capacity as expressed in Eq. (9):

$$Fv_{HP,t} = U \times \frac{\overline{pc}_{HP,t}}{COPc_{HP,t}}, \text{ where } U \in \{0, 1\}$$
(9)

To summarize, the short-term least-cost planning problem for the TB may be expressed as the mixed-integer linear program in Eq. (10):

$$maximize f(x) \tag{10}$$

subject to Eqs. (4)–(9).

Notice that the objective function is set to maximize due to the sign convention according to which costs are negative and benefits are positive.

COMPOSE solves this mixed-integer linear programming problem according to Eq. (10), i.e. by minimizing the economic cost of operation under given constraints. For any given set of parameter values, COMPOSE will identify the most feasible operational strategy. In addition to the resulting energy balance and costs, the optimal operation is associated with an electricity consumption profile, which COMPOSE subsequently uses to find the intermittency-friendliness coefficient Rc and marginal CO₂ emissions in accordance with the methodology described earlier.

3.5. Thermal storage loss

Thermal storage losses are calculated on the basis of thermal conduction losses from free standing insulated tanks. Heat losses from radiation and convection are considered to be insignificant and are ignored. The thermal conduction loss for the heat storage in empty state *sleh* [kWh] is found from Eq. (11).

$$sleh_t = \sum_{t=1}^{T} \frac{\kappa A(T_{in,t} - T_{ambient,t})}{r}$$
(11)

where κ [W/(mK)] is the thermal conductivity, A [m²] is the surface area of the storage tank, T_{in} [K] is the return water temperature, $T_{ambient}$ [K] is the ambient temperature, and r [m] is the thickness of the insulation material. The differential storage loss *sldh* is the full storage loss rate minus the empty storage loss rate as expressed in Eq. (12).

$$sldh_t = \sum_{t=1}^{l} \frac{\kappa A(T_{out,t} - T_{ambient,t})}{r} - sleh_t$$
(12)

Expressions similar to Eqs. (11) and (12) are used for the cold storage.

4. Proof-of-concept design and case study assumptions

The TB solution is designed for a single-family residential building in San Jose, CA (PG&E service area) and compared to the continued use of existing end-use appliances, which use electricity for providing hot tap water heating and space cooling services. While viable, the analysis does not consider replacing gas-fired



Fig. 5. Heat pump cycles in PV diagrams for R744. Danfoss (top) and Sanyo (bottom).

heating supply, nor is existing space heating demand considered for replacement.

Two cost models are assessed and compared: Current consumer costs according to PG&E's tariff schedule, and optional Smart Grid costs according to an economic real-time pricing schedule based on PG&E's day-ahead spot market.

4.1. PG&E's system: loads, intermittent renewables, marginal producers

For the day of July 19, 2011 in PG&E's system, Fig. 2 plots the hourly electricity loads and the hourly production from intermittent renewables, while Fig. 3 plots the hourly day-ahead spot market prices for electricity.

In 2009, PG&E's generation mix was 35% natural gas (mainly combined-cycle gas turbines (CCGT)), 47% CO₂ neutral supply (nuclear, hydro, renewables), 1% coal, and 16% un-specified. We assume that natural gas fired CCGT is the dispatchable marginal producer when the day-ahead spot market price for electricity is above CCGT's short-term marginal costs, while CO₂ neutral producers are marginally dispatched whenever electricity prices are below this threshold.

Identifying this threshold, we find that the Californian average natural gas spot price was 15.63 USD per MWh in the week of

Table	2
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PG&E's E1 electricity tariff by component.

Tariff component	Unit	Value
Generation (under baseline)	USD/kWh	0.03552
Distribution (under baseline)	USD/kWh	0.03603
Transmission and other utility costs	USD/kWh	0.05078
Total	USD/kWh	0.12333

Table 3

Key results for simulated cycles for Danfoss and Sanyo CO₂ heat pumps.

Result	Unit	Danfoss	Sanyo
Carnot efficiency	-	0.19	0.23
Electricity consumption	kW	0.61	0.49
Heat production	kW	2.17	1.83
Cooling production	kW	1.52	1.50
COP cooling	-	2.49	3.07
COP heating	-	3.54	3.73
COP total	-	6.02	6.81

operation according to the weekly report from the US Energy Information Administration [15]. According to the Californian Energy Commission, the average thermal efficiency of CCGT plants in operation is 53.7% measured for the lower heating value of natural gas. Furthermore, based on international figures [16], we assume a transmission and handling cost for natural gas of 2.21 USD per MWh, and a variable cost of CCGT operation of 3.73 USD per MWh. Thus, CCGT's short-term marginal cost of operation is found to be 36.95 USD per MWh.

According to the marginal system methodology described earlier, this implies that for hours where the spot market price is below 36.95 USD per MWh, electricity consumption is technically CO_2 neutral as illustrated in Fig. 3.

4.2. PG&E's system: tariffs

For the analysis using current consumer costs according to PG&E's tariffs, the standard option applicable to residential single-family dwellings is the E1 tariff schedule. The E1 baseline electricity price for San Jose is USD 0.12233 per kWh composed of generation cost, distribution cost, and additional transmission and utility costs as specified in Table 2.

For the analysis using optional Smart Grid tariffs based on PG&E's day-ahead spot market, the fixed generation cost component of E1 in Table 2 is replaced by the hourly day-ahead spot market prices illustrated in Fig. 3. The unweighted average electricity price under this real-time pricing schedule is USD 0.11779 per kWh, which is less than 4% lower than the E1 tariff. This suggests that the chosen day exhibits an approximately average market performance making it useful for analysis.

4.3. Reference building heating and cooling technology and demand

In 2003, the "California Statewide Residential Appliance Saturation Study" surveyed 21,920 residential customers for information about appliances and end-use among households [17]. For singlefamily residential buildings in PG&E's service area, the study finds that 9% use conventional electric resistance heaters for water heating and 39% use conventional central A/C units for space cooling. For the purpose of this study, we assume that a conventional electric resistance heater has a conversion efficiency of 100%, while a conventional central A/C system has an effective COP of 3.0, roughly assuming a CEER 13 standard.

For water heating, the survey finds that electricity consumption for electrical water heating ranges from 1567 kWh per year in multi-family units in large buildings to 3079 kWh per year in single family houses with an average of 2585 kWh per year, corresponding to an average daily electricity consumption of 7.08 kWh. An empirically based hourly distribution of hot water consumption is not available for California specifically, but the distribution may be assumed to be rather similar in all developed countries. In this analysis, the hourly demand for hot water is found by

Table 4		
Techno-economic j	parameters for	options

	Variable	Unit	Reference	Thermal battery
Description			Electric water heater + central A/C	TB with CO ₂ HP and thermal storages
Cooling demand	dc	kWh/year	3324 (see Fig. 4 for distribution)	
Water heating demand	dh	kWh/year	2585 (see Fig. 4 for distribution)	
Cooling capacity	$\overline{pc}_k = HP$	kW	5.0 (continuous)	5.0 (discrete)
COP cooling	$COPc_{k=HP}$	-	3.0	3.0
COP heating	$COPh_{k=H}$	-	_	3.7
Auxiliary heating capacity	$\overline{Ph}_k = aux$	kW	6.0 (contin	nuous)
Auxiliary heating efficiency	$COPh_{k=aux}$	-	1.0	
Cold storage capacity	<u>sc</u>	L(kWh)	0	1000 (10.47)
Hot storage capacity	sh	L(kWh)	0	200 (10.47)

distributing the daily average according to the week-day demand pattern of a typical family household suggested by a study made of a 4-person family (2 adults and 2 children) living in a single family house in Denmark [18]. The resulting hourly water heating demand is illustrated in Fig. 4.

For space cooling, the survey finds that the electricity consumption of central A/C units ranges from just over 700 kWh per year for town homes to just over 1400 kWh per year for single family dwellings, with an average of 1108 kWh per year. The monthly demand for space cooling is established by distributing the average electricity consumption according to historical monthly average temperatures for San Jose [19] with a cut-off temperature of 17 °C. As a result, the electricity consumption in July is 192.7 kWh corresponding to a daily average of 6.2 kWh. The hourly consumption is found by distributing the average daily consumption according to recorded hourly temperatures for this day using the above cut-off temperature. The resulting hourly space cooling demand is illustrated in Fig. 4. This approach assumes that automatic thermostats are installed that respond to outdoor temperatures. In reality, some delay will occur as the building provides some storage capacity that tends to level out variations in energy demand.

The illustrated demands refer to the actual end-use energy demand, not the subsequent fuel or electricity consumption of the supply technologies.

Table 5

Result	Summe	u

	Unit	Reference	TB E1	TB real-time
<i>Rc</i>	-	-0.11	0.36	0.46
Electricity consumption	kWh/day	9.15	3.33	3.42
Marginal CO ₂ emissions	kg	2.02	0	0
Economic cost of operation	USD/day	1.09	0.41	0.31

Furthermore, it is assumed that the existing electric resistance heater has a 6 kW heating capacity, while the existing central A/C has a 5 kW cooling capacity, corresponding to reasonable and conventional design capacities in this context.

4.4. TB design parameters

The TB conversion component is a CO_2 compressor in a heat pump cycle optimized for simultaneous production of useful heating and cooling. Furthermore, an electrical resistance heater is included for auxiliary purposes.

The heat pump's steady-state operational conditions are established on the basis of parameters for CO₂ compressor operation obtained from previous experimental studies [20]. We have compared the characteristics of two CO₂ compressors: Sanyo's two-stage inverter-type model CV153 and Danfoss' single-stage TN1416. Both compressors hold a 1500 W cooling capacity under



Fig. 6. The intermittency-friendliness coefficient Rc by function of storage volume.



Fig. 7. Electricity consumption profiles, demand, and accumulated energy content (kWh) of thermal storages over period of operation. Existing option (top), TB with E1 tariffs (middle), and TB with real-time tariffs (bottom).

design operating conditions. The Sanyo compressor is a hermetic 2-stage rolling compressor with a volume ratio of 1.55, an isentropic efficiency of 0.698, and a discharge pressure of 100 bars. The Danfoss compressor is a semi-hermetic reciprocating piston compressor with an isentropic efficiency of 0.58 and a discharge pressure of 90 bars.

The characteristics of these compressors are applied to the slightly larger capacities required in the case study TB. This is a reasonable assumption at this point, as the TB may in fact utilize several smaller compressors in parallel to allow for better partial load characteristics, or even opt for a large compressor with slightly better characteristics.

The heat pump cycles with each of the two compressors have been modeled using Coolpack/EES software [21] for a steadystate mode that simultaneously produces useful hot water at 70 °C and useful cold water at 10°C. Fig. 5 illustrates the design cycle including steady-state parameters, while Table 3 summarizes key cycle results. The Sanyo compressor provides a heating capacity of 1.87 kW and a cooling capacity of 1.50 kW using 0.49 kW of electricity. This corresponds to a heating COP of 3.7, and a cooling COP of 3.0. For simultaneous supply of useful heat and cooling, the Sanyo heat pump reaches a total thermal COP of 6.7, which is the highest COP of the two compressors. While the choice of compressor for the TB will depend upon various end-use aspects, particularly the ratio between heating and cooling demands in order to minimize the dumping of thermal production, the higher COP of the Sanyo compressor is here decisive for the subsequent use in the techno-economic case-study.

With no storage, the reference system is necessarily operated continuously within each hour. However, the TB is assumed to operate only at full capacity within each hour as devised in the mathematical unit dispatch model above. This reduces the number of on-off switches, thus, allowing for a realistically simulated operation according to steady-state parameters, while also increasing the life time of the compressor.

Today, thermal storage tanks are often left without insulation; however, to reduce thermal losses, both thermal storage tanks are insulated with 10 mm BASF water tank foam having a thermal conductivity of 0.035 W/(mK). While the material is among the best available options in terms of thermal conductivity, similar low thermal conduction losses may be obtained with other materials at greater thickness. Both storages are located indoors at a constant ambient temperature of $20 \,^\circ\text{C}$.

The hot thermal storage supplies heat to cold potable water at 70 °C with a return temperature from the heat exchanger of 20 °C. The potable water increases in temperature from 8 °C to 60 °C. The cold thermal storage supplies cooling to a chilled water system at 5 °C with a return temperature from the heat exchanger of 15 °C. Thermal losses for empty storage states (20 °C for hot thermal storage, 15 °C for cold thermal storage) are insignificant and are ignored for both storages.

Key parameters are summarized in Table 4.

5. Techno-economic results

Key techno-economic results are summarized in Table 5

5.1. Thermal storage sizing

Fig. 6 illustrates the relationship between the size of each storage and the intermittency-friendliness coefficient Rc as a result of the identified least-cost operational strategy for each option with variable storage capacities. The highest value for Rc is found for a hot storage volume of 200 L and a cold storage volume of 1000 L, which are the volumes used subsequently.

5.2. Electricity consumption profiles and Rc

Fig. 7 illustrates the net electricity consumption profiles and accumulated storage content as a result of the identified least-cost operational strategy for each option. It is observed that both TB options dispatch operation to only a few hours, operating at full capacity within these hours and utilizing the storages effectively. For the TB with real-time tariffs, the auxiliary electric resistance heater is utilized during the first few hours of the days; awaiting the low-price hours that allow the TB to operate at full capacity during those hours.

On the basis of the electricity consumption profiles, the Rc for the existing option is found to be negative, -0.11, increasing to 0.36 for the TB with E1 tariffs, and increasing further to 0.46 for the TB with real-time tariffs. Thus, the TB offers a significant Rc improvement over the existing system, and the TB with real-time tariffs provides the highest Rc.

5.3. Electricity consumption and system-wide CO₂ emissions

Due to the preference that the TB with real-time tariffs will have for low price hours, it is likely to exhibit higher thermal losses than the TB with E1 tariffs. In fact, it is found that the electricity consumption of the TB with real-time tariffs is 3.42 kWh/day, which is slightly higher than the electricity consumption of the TB with E1 tariffs of 3.33 kWh/day. Still, both TB options offer a reduction in electricity consumption of 63–64% compared to the 9.15 kWh/day consumed by the reference option.

However, higher electricity consumption is not necessarily a problem for the TB with real-time tariffs. The ability to support intermittent renewables and reduce emissions are critical criteria rather than the electricity consumption. The preference for low price hours correlates with lower CO_2 emissions, and the TB with real-time tariffs will always offer similar or lower CO_2 emissions than the TB with E1 tariffs. Nevertheless, in this case, both TB options result in zero CO_2 emissions as both options only consume electricity during hours in which the day-ahead spot market price for electricity is lower than the short-term marginal cost of CCGT. The existing option emits 2 kg of CO_2 per day.

5.4. Economic cost of operation

The operational cost for the existing option is found to be 1.12 USD per day; for the TB with E1 tariffs, 0.41 USD per day, and for the TB with real-time tariffs, 0.31 USD per day. Thus, both TB options offer significant reductions in operational costs. The TB with real-time tariffs results in a 72% cost reduction compared to the existing option, and a 25% cost reduction compared to the TB with E1 tariffs.

6. Conclusion

A Smart Grid enabling concept for providing heating and cooling to buildings in a configuration that supports intermittent renewables in the energy system, while minimizing operational costs and CO_2 emissions, is introduced and investigated.

The so-called thermal battery (TB) converts electricity simultaneously to hot and cold reservoirs at useful temperature levels using a high-pressure CO_2 compression heat pump. An optimized TB design is offered for a proof-of-concept case study in which the TB replaces an existing electrical hot water heater and a central A/C unit, and the techno-economic consequences are evaluated.

It is concluded that the TB with real-time tariffs allows for significant improvements in the intermittency-friendliness of operation *Rc* (improves from -0.11 to 0.46), lower CO₂ emissions (reduced to zero), and lower operational costs (reduced by 72%).

The findings provide initial support for the hypothesis that if electricity generated by intermittent sources is destined for thermal end-uses, then technologies allowing for immediate conversion to thermal energy and thermal storage close to these end-uses, will be more cost-effective in meeting Smart Grid enabling objectives than any electro-chemical and mechanical storage option.

As for technical model and assumptions, related experimental and numerical studies suggest that the optimization of simultaneous heating and cooling systems is very delicate [9,10,22]. The system COP depends on multiple parameters such as compressor speed and efficiency, water inlet temperature and flow rates, pumping power, heat exchanger dimensions and heat transfer coefficients. In this study, compressor work as well as output cooling and heating capacities are constant. Under these conditions, the system COP at a given discharge pressure become a function of the CO₂ evaporator temperature and the gas cooler outlet temperature only, achieving a system COP for dual-mode operation of 6.7. While this is within the range of previous results, experimental results, with specified conditions and considering the prevailing difference in test facilities, will help to formulate a more precise TB model for simultaneous heating and cooling.

In future research, we will investigate both the empirical validity in terms of the operational claims for the TB, as well as the comparative techno-economic consequences for a more extensive set of options and locations.

In perspective, in order for real-time tariffs to be available to consumers and thus facilitate the development of Smart Grid enabling technologies, such as the TB, utilities must act to offer the necessary tariff schedules.

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