



Review article

The heating triangle: A quantitative review of self-heating methods for lithium-ion batteries at low temperatures

Haijun Ruan^{a,b,*}, Jorge Varela Barreras^{c,d,1}, Marco Steinhardt^{e,1}, Andreas Jossen^e, Gregory J. Offer^{f,g}, Billy Wu^{b,g,**}

^a Institute for Clean Growth and Future Mobility, Coventry University, Coventry, CV1 5FB, UK

^b Dyson School of Design Engineering, Imperial College London, London, UK

^c Department of Electronic Engineering, Technical University of Catalonia, Vilanova i la Geltru, Spain

^d Department of Civil and Environmental Engineering, Imperial College London, London, UK

^e Technical University of Munich (TUM), TUM School of Engineering and Design, Institute for Electrical Energy Storage Technology (EES), Arcisstrasse 21, 80333, Munich, Germany

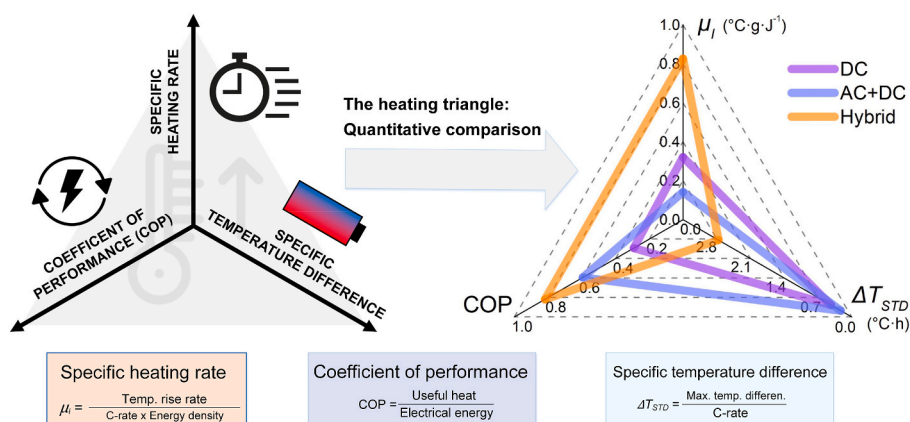
^f Department of Mechanical Engineering, Imperial College London, London, UK

^g The Faraday Institution, Didcot, UK

HIGHLIGHTS

- Self-heating methods are not just reviewed but also quantitatively evaluated/compared.
- Heating triangle introduced as a universal quantitative indicator for heating comparison.
- Heating triangle metrics are calculated and discussed for each self-heating approach.
- Same self-heating method shows very similar metrics irrespective of study case.
- Critical insights gained lead to new research directions towards advanced self-heating.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
lithium-ion battery
Low temperature
Preheating
Self-heating

ABSTRACT

Lithium-ion batteries at low temperatures have slow recharge times alongside reduced available power and energy. Battery heating is a viable way to address this issue, and self-heating techniques are appealing due to acceptable efficiency and speed. However, there are a lack of studies quantitatively comparing self-heating methods rather than qualitatively, because of the existence of many different batteries with varied heating parameters. In this work, we review the current state-of-the-art self-heating methods and propose the heating

* Corresponding author. Institute for Clean Growth and Future Mobility, Coventry University, Coventry, CV1 5FB, UK.

** Corresponding author. Dyson School of Design Engineering, Imperial College London, London, UK.

E-mail addresses: haijun.ruan@coventry.ac.uk (H. Ruan), billy.wu@imperial.ac.uk (B. Wu).

¹ These authors contributed equally to this work.

<https://doi.org/10.1016/j.jpowsour.2023.233484>

Received 16 June 2023; Received in revised form 24 July 2023; Accepted 3 August 2023

Available online 22 August 2023

0378-7753/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Thermal management Metrics

triangle as a new quantitative indicator for comparing self-heating methods, towards identifying/developing effective heating approaches. We define the heating triangle which considers three fundamental metrics: the specific heating rate ($^{\circ}\text{C}\cdot\text{g}\cdot\text{J}^{-1}$), coefficient of performance (COP) (—), and specific temperature difference ($^{\circ}\text{C}\cdot\text{hr}$), enabling a quantitative assessment of self-heating methods using data reported in the literature. Our analysis demonstrates that very similar metrics are observed for the same type of self-heating method, irrespective of the study case, supporting the universality of the proposed indicator. With the comparison insights, we identify research gaps and new avenues for developing advanced self-heating methods. This work demonstrates the value of the proposed heating triangle as a standardised approach to compare heating methods and drive innovation.

Nomenclature

ΔT	Temperature rise/increase ($^{\circ}\text{C}$)
μ_I	Specific heating rate ($^{\circ}\text{C}\cdot\text{g}\cdot\text{J}^{-1}$)
ΔT_{STD}	Specific temperature difference ($^{\circ}\text{C}\cdot\text{hr}$)
E_p	Energy density ($\text{Wh}\cdot\text{kg}^{-1}$)
c_p	Specific heat capacity ($\text{J}\cdot^{\circ}\text{C}^{-1}\cdot\text{g}^{-1}$)
Q_{bat}	Battery nominal capacity (Ah)
k_{bat}	Battery thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
L_{bat}	Characteristic length of heat transfer (m)
h	Convective heat transfer coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}$)
T_{amb}	Ambient temperature ($^{\circ}\text{C}$)
T_{tgt}	Target temperature ($^{\circ}\text{C}$)
I_{heat}	Heating current (A)
U_{bat}	Battery voltage (V)
R_{ext}	External heating resistance (Ω)
f_{AC}	AC frequency (Hz)
q_{gen}	Heat generation rate (W)
R_b	Battery lumped resistance/impedance (Ω)
U_{ocv}	Open circuit voltage (V)
m	Battery mass (g)
T	Battery temperature ($^{\circ}\text{C}$)
q_{loss}	Heat loss/dissipation rate (W)
A	The area that heat convection occurs (m^2)
$\dot{T}$	Temperature rise rate ($^{\circ}\text{C}\cdot\text{min}^{-1}$)
I_{C-rate}	Heating C-rate (h^{-1} or hr^{-1})
E_H	Total energy used for heating (Wh)
E_{bat}	Maximum available energy (Wh)
e_h	Energy consumption (%)
DOD	SOC loss/capacity consumption (%)

$\tilde{V}_{soc}$	Average OCV during heating (V)
Q_{loss}	Capacity consumption (Ah)
$\bar{V}$	Battery nominal voltage (V)
ΔT_b	Maximum temperature difference ($^{\circ}\text{C}$)
SOC_0	Initial SOC of heating (%)
t_h	Heating duration (s)
$\hat{U}_p$	Equivalent polarization voltage (V)
$\hat{R}_b$	Equivalent heating resistance (Ω)

Abbreviations

AC	Alternating current
CC	Constant current
COP	Coefficient of performance
CV	Constant voltage
DC	Direct current
EV	Electric vehicles
HSH	Hybrid self-heating
LCO	LiCoO_2
LFP	LiFePO_4
LMO	LiMn_2O_4
NMC111	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$
NMC532	$\text{LiNi}_{0.5}\text{Mn}_{0.3}\text{Co}_{0.2}\text{O}_2$
NMC622	$\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$
OCV	Open circuit voltage
PC	Pulse current
SAC	Sinusoidal AC
SOC	State of charge
SOH	State of health

1. Introduction

Lithium-ion batteries have relatively high energy and power densities, as well as reasonable lifetimes, leading to their mainstream adoption in electric vehicles (EV) [1,2]. However, they suffer from poor performance at low temperatures due to sluggish kinetics and mass transport issues [3–5]. The available energy and power are dramatically decreased at sub-zero temperatures, with charging rates particularly limited due to the high risk of lithium plating [5–7]. Improving electrode materials and the electrolyte is one way to resolve this challenge [8,9], but commercialization of material innovations can take significant time [4,7,10,11]. Since the kinetic and transport processes are highly temperature dependent, the performance of the batteries can be restored after being warmed up [12,13]. Therefore, preheating the battery is a viable approach to enhance battery performance; enabling higher EV adoption in cold regions.

Indeed, considerable research efforts have been dedicated to formulating battery heating methods, with these generally classified as external or internal heating methods [14–17]. For external heating

methods, the battery is warmed up using the heat transferred from external sources (e.g. heaters), where the state-of-charge (SOC) is kept unchanged [18–20]. This method is useful, however, the relatively low through-plane thermal conductivity of batteries (ranging from 0.40 to $1.03 \text{ W m}^{-1} \text{ K}^{-1}$ [21]) limits the heat transfer rate [22], leading to long heating times and large temperature gradients. Moreover, the lengthy heat transfer pathway generally exists in external heating applications, which causes appreciable heat dissipation to the surroundings [22–25], resulting in higher energy consumption; prolonging the heating duration.

Conversely, for internal heating, where batteries are warmed up using self-generated heat, and there is no impact by the long heat transfer pathways, nor the limited thermal conductivity of batteries [26–29]. Therefore, the heating efficiency and speed is usually high with good temperature uniformity. Provided that the heating energy comes from the battery, the internal heating method is termed internal self-heating, which is independent of external power sources [10,12,30,31].

Recently, a new hybrid self-heating (HSH) method, integrating internal and external heating without additional external power [22,32], has been developed to further shorten the heating time and enhance the

heating efficiency.

Whilst many heating methods have been developed, their validation has been generally done on different battery types [15–17]. The existence of many different batteries with varied heating parameters, thus, makes it complicated to perform a fair quantitative comparison. For example, the energy consumption during heating highly depends on a range of factors such as specific heat capacity, and energy density (Fig. 1a, Eq. (S3) in Supplementary Note S1). Xu et al. [32], for instance, reported that 4% of the battery capacity was used for a 20 °C temperature rise for their cell with an energy density of 191 Wh·kg⁻¹, while Jiang et al. [33] reported a 6.6% capacity utilisation for a temperature rise of 23 °C for a cell with an energy density of 128 Wh·kg⁻¹. Thus, energy (capacity) consumption during battery heating is not a fair metric to assess heating methods. Moreover, the target heating temperature is often varied, and heat generation is generally different at different temperatures due to the diverse activation energies of the various electrochemical processes [3,14–16,19].

In addition, some heating parameters, such as heating current, differ broadly between studies. For example, sometimes parameters are selected conservatively, such as the heating C-rate of 1.3 C in Ref. [32], and sometimes aggressively, such as the heating C-rate of above 8 C in Ref. [34]. The issue is obviously that heating time is shorter with higher heating current [14,33,35,36], due to higher heat generation (Supplementary Fig. S1). Therefore, only using the temperature-rise rate or heating time is not sufficient to fairly evaluate different heating methods. For example, the rate of temperature increase was 3.39 °C·min⁻¹ at 1.9 C in Ref. [37] while it reached 8.6 °C·min⁻¹ at 4 C in Ref. [38].

Thus, the varied use of different battery types and different heating parameters makes it challenging to establish a fair quantitative comparison between different heating methods (Fig. 1b), and explains why almost all the comparative studies in the literature so far focus on qualitative rather than quantitative indicators. For example, Hu et al. [15], Wu et al. [16] and Wang et al. [17], reviewed different heating methods using qualitative ratings and displayed the results in the form of a 1–5 star scale [15], plus-minus signs [16] or a radar chart without values on axes [17], respectively.

To bridge this gap, this review paper defines a new universal indicator: the heating triangle, to achieve a fair quantitative comparison between self-heating methods. We highlight the advantages and shortcomings of the self-heating methods using quantitative metrics, and provide underpinning insights, toward the identification of new pathways to develop advanced self-heating methods.

The remaining part of this paper is organized as follows. The self-heating methods are classified and briefly described in Section 2, with a discussion of key factors influencing heating performance. Section 3 defines the heating triangle and subsequently Section 4 quantitatively compares self-heating methods. Section 5 discusses the rationality of defined triangle metrics and identifies the research gaps and directions,

followed by conclusions in Section 6.

2. Self-heating methods

2.1. Classification of self-heating methods

The term battery self-heating refers to the fact that it is heated by its own energy. Self-heating methods thus include internal self-heating methods, where the heat is only generated from the battery, and hybrid self-heating methods, where the heat comes from the heaters inside/outside the battery without an additional power supply [15,16,22]. Internal self-heating methods can be classified based on the heating current waveforms, which include direct-current (DC), and alternating current (AC) plus DC (AC + DC) heating methods, as shown in Fig. 2a. The DC heating method is commonly used in the discharge direction (Fig. 2b), i.e. DC self-heating [39], as there is a high risk of lithium plating during charging at low temperatures [5,40,41]. Constant current (CC) and constant voltage (CV) modes are the two types of DC heating approaches [15–17]. The pure AC, including pure sinusoidal AC (SAC) and pure pulse current (PC), can effectively warm up the battery but an external power source is required [42–44], thus the pure AC heating method is not considered as a self-heating method [15,45]. When there is the DC component in the AC signals, we strictly term the heating method as an AC + DC approach [33,46], although some references [10,37,38] term this an AC heating method, under the condition of including small DC component. The AC + DC heating method comprises the SAC discharge [10,37], and PC discharge [38,47,48] approaches (Fig. 2a). The hybrid self-heating method is also called the compound self-heating method, where both the internal battery heat and heat from the electrical load are used (Fig. 2b), with both the heating energies coming from the battery [22,32,49,50]. The external heat can be transferred to the battery from heaters either in or outside the battery [22]. An example of internal heating elements includes the work by Wang et al. [51] whereby the battery is heated by internal heat generation and the heat from an embedded Nickel foil, and thus this is classified as a HSH method. In HSH methods, the current waveforms can be DC or AC + DC, with DC often utilized due to its simplicity [22,32,34,51,52].

2.2. Heating performance areas/indicators

When considering suitable low-temperature heating methods, there are six typical performance areas and/or indicators: heating duration, coefficient of performance (COP), energy consumption, battery degradation, temperature gradient, and engineering implementation (Fig. 2c) [15–17,22].

When choosing a heating method, a reduction in heating duration, energy consumption, battery degradation, and temperature gradients along with an increased COP, and easy engineering implementation are desirable, but there are usually conflicting goals. For example, for the

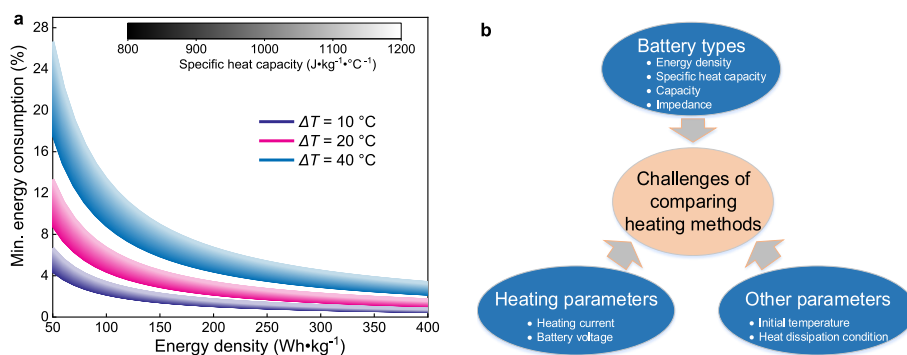


Fig. 1. a, The minimum energy consumption of batteries with different energy densities and specific heat capacities for three temperature rise ranges (ΔT). The calculation of minimum energy consumption is described in Supplementary Note S1. b, illustration of challenges for comparing heating methods.

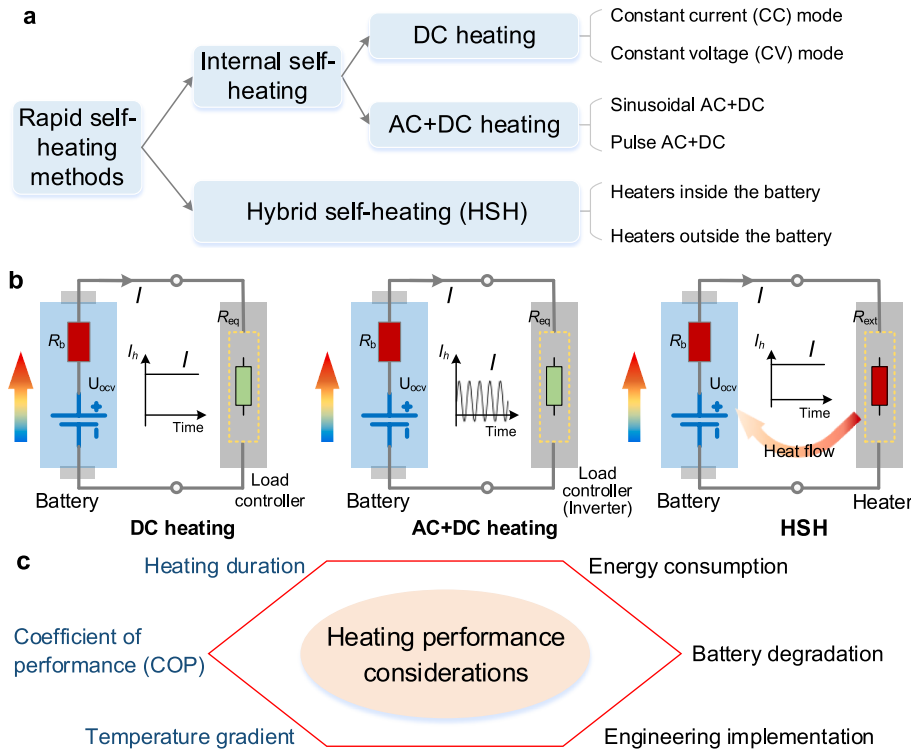


Fig. 2. a, Classification of self-heating methods (See collected methods in [Supplementary Table S1](#)); b, equivalent circuit of three self-heating methods; c, heating performance areas/indicators. In [Fig. 2b](#), the battery is simply represented by the open circuit voltage (OCV) and its resistance (R_b), while the loading and heating controllers are represented by their equivalent resistances, R_{eq} and R_{ext} , respectively. (See representative experimental set-up of the three self-heating methods in [Supplementary Fig. S2](#)).

HSH method in Ref. [22], a very short heating duration of 16.8 s from $-30\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$ at 100% SOC is accompanied by a high degradation of 7.9% over 500 heating cycles, while a low degradation of 1.2% can be achieved with a relative slow heating duration of 86 s.

The heating duration is indicated by the rate of temperature increase, with a high value resulting in a short heating duration. The COP represents the ratio of useful heat supplied (stored energy in the battery) to the electrical energy required, which corresponds to the heating efficiency. The energy consumption is also an indicator to show the efficiency of the heating method, but it is a metric mainly driven by the battery heat capacity, energy density, and temperature increase (ΔT , See [Fig. 1a](#)). For that the COP is a more suitable metric, as discussed later.

In the literature, several studies suggest a high impact of the heating process on battery degradation, examples being a capacity fade of 7.7% [47] and $\sim 7.2\%$ [51] after 200 and 500 heating cycles, respectively, but usually this is reported as low [28,33,35,38]. For example, after 600 heating cycles, Jiang et al. [33] found the capacity remained relatively constant; Li et al. [38] demonstrated the capacity fade was only 0.5% after 5000 heating cycles. This highly depends on the heating methods and the particular type of cell [1,2,53,54], but also is influenced by the intrinsic complexity of the degradation mechanisms [55–57]. Therefore, we consider that it is very challenging to define a universal metric to compare heating methods irrespective of the battery and the heating parameters. Therefore, here we do not propose a metric to evaluate battery degradation. Instead, we are only analysing quantitatively some of the influencing parameters, such as temperature gradient. Temperature gradients within the battery corresponds to the maximum temperature difference, with a high rate of temperature-rise generally leading to non-uniform temperature profiles.

Engineering implementation includes many aspects, such as cost, weight increase, safety, and reliability, which are seldom mentioned in the reported heating works and are not easy to compare quantitatively [15–17,58]. The DC discharge heating method is easy to implement, but implementing the HSH method embedded with Nickel foils in the battery [50,51] is more challenging, as the battery structure needs to be modified with uncertainty around safety and reliability. The AC + DC

heating method using the motor and its drive circuitry to generate heating current is not as difficult to implement, and the additional weight and volume would be low [38]. On the other hand, considering battery cooling is important for thermal management system design [25, 39,59], therefore, integrating heating and cooling methods is preferable.

2.3. Factors influencing heating performance

Qualitatively, links between the heating performance of different methods and internal, external, and methodological aspects are illustrated in [Table 1](#). The internal metrics often refer to battery parameters, such as energy density (E_p), specific heat capacity (c_p) and battery states, while the external parameters generally include the heat transfer conditions and ambient temperatures. The methodological parameters depend on the heating method, two examples of which are the heating current and battery voltage.

2.3.1. Internal parameters

Reversible entropic heat generation is generally negligible under AC excitation and is relatively low under the high DC currents [14,22,33, 35]. Thus, the battery heat generation is dominated by the irreversible heat generation (q_{gen}), expressed as:

$$q_{gen} = I_{heat} \cdot (U_{OCV} - U_{bat}) \approx I_{heat}^2 \cdot R_b \quad (1)$$

where I_{heat} , U_{OCV} , U_{bat} , and R_b represent the heating current ($I_{heat} > 0$ denotes a discharge process), the open circuit voltage (OCV), battery terminal voltage, and battery lumped resistance (impedance), respectively. Battery SOC and state-of-health (SOH) have an effect on the heat generation (q_{gen}) of different self-heating methods and thus the heating duration, as battery impedance (R_b) changes with the SOC and SOH [33, 60–62]. The impedance of batteries with different energy densities (E_p) generally varies [63]. In general, higher power density requires the reduction of cell resistance, e.g. based on thinner electrodes and separators, thicker tabs and current collectors, reduced particle sizes for the active materials or higher loadings of conductive materials in the cathode [64–66]. Thus, the E_p is considered to have an influence on the

Table 1

Internal, external and methodological parameters that significantly affect the heating duration, energy consumption, COP, temperature gradient and battery degradation for self-heating methods.

Key influencing factors		Heating performance				
		Heating duration	Energy consumption	COP	Temperature gradient	Battery degradation
Internal	OCV / SOC	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	◆	▲ ■ ◆
	SOH	▲ ■ ◆	▲ ■ ◆			
	c_p	▲ ■ ◆	▲ ■ ◆		◆	
	E_p	▲ ■ ◆	▲ ■ ◆		◆	
	Q_{bat}	▲ ■ ◆			▲ ■ ◆	
	k_{bat}	◆	◆	◆	◆	
	L_{bat}	◆	◆	◆	◆	
External	h	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	
	T_{amb}	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	
Methodological	T_{tgt}	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆	▲ ■ ◆
	I_{heat}	▲ ■ ◆			◆	▲ ■ ◆
	U_{bat}	▲ ■ ◆			◆	▲ ■ ◆
	R_{ext}	◆		◆	◆	◆
	f_{AC} / Heating equipment	■		■		■

k_{bat} : Thermal conductivity of batteries; L_{bat} : Characteristic length of heat transfer within the battery; h : Convective heat transfer coefficient; Q_{bat} : Battery nominal capacity.

heat generation and heating duration. For the same battery materials, a battery with a high capacity (Q_{bat}) generally has a low resistance and the capacity (Q_{bat}) impacts the heating duration. The specific heat capacity (c_p) affects the rate of temperature rise (Eq. (2)) and thus the heating duration.

$$mc_p \frac{dT}{dt} = q_{gen} - q_{loss} \quad (2)$$

$$q_{loss} = h \cdot A \cdot (T - T_{amb}) \quad (3)$$

where m , c_p , T , T_{amb} , A , and h represent the mass, specific heat capacity, and temperature of the battery, the ambient temperature, the area that heat convection occurs, and the convective heat transfer coefficient, respectively.

The thermal conductivity (k_{bat}) and characteristic length of heat transfer (L_{bat}) within the battery have almost no effect on the rate of temperature rise of the internal self-heating methods. This is because the heat transfer processes are quite slow in the battery under the good heat insulation between the battery and surroundings, and relatively uniform battery internal heat generation [22,67,68]. However, they essentially influence the heat propagation for the HSH methods due to the heat transferred from external heaters [69–71], and thus impact the heating duration, energy consumption, COP, and temperature gradient.

Heating at an extremely low or high SOC is often not permitted for the self-heating methods as it may accelerate battery degradation [17, 72,73]. For example, AC + DC loads can make the battery voltage at high SOC go over the upper voltage limit, while the three self-heating methods can render the voltage of batteries at low SOC go below the lower voltage. Heating at a high SOC/OCV for the HSH methods likely leads to a high temperature gradient, such as $\sim 30^\circ\text{C}$ [34,50], which

causes local overheating and may influence battery degradation [74, 75]. This can be explained by the high heat generation from the external heaters due to the high heating current at the high SOC/OCV.

2.3.2. External parameters

The external parameters, h , T_{amb} , affect the heat dissipation (q_{loss}) [14,22,76,77], as shown in Eq. (3), and thus influences the heating duration, energy consumption, COP, and temperature gradients for the three self-heating methods.

2.3.3. Methodological parameters

The target temperature (T_{tgt}) of heating is often different, such as 0°C in Refs. [22,51], 5.6°C in Ref. [35], 10°C in Ref. [41], 29.1°C in Ref. [38], 60°C in Ref. [4], which is generally determined by the expected battery performance [7,13,18]. This greatly impacts the heating duration and energy consumption, and also influences the COP, temperature gradients, and degradation of batteries [18,78]. The applied heating current and battery voltage likely impact the heat generation and degradation of batteries [3,22,35,79,80]. For the HSH methods, the heat generation relies, in part, on the external heating resistance (R_{ext}) [22,32,34,51,52]. Furthermore, R_{ext} also affects the heating current and battery voltage [22,51] and thus influences battery degradation. For the AC + DC heating methods, the heat generation depends on the AC frequency (f_{AC}) [3,14,33,35,81] and special heating equipment is generally needed to generate AC + DC signals, which influence the COP.

3. The heating triangle

To enable a quantitative assessment, we introduce the heating triangle as a new universal indicator (Fig. 3). The heating triangle

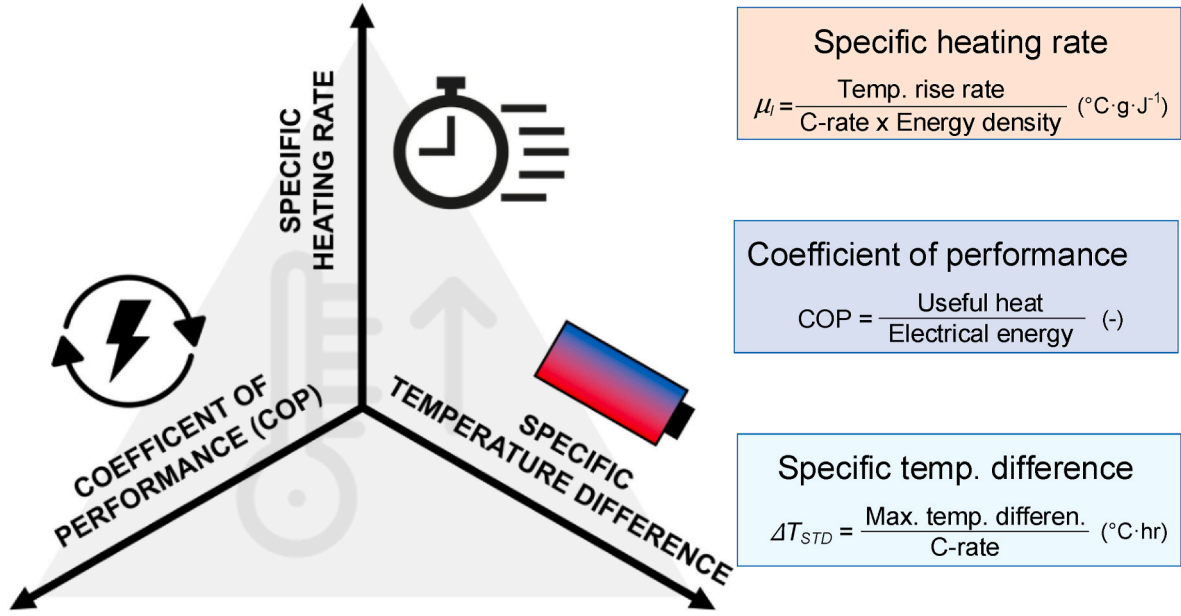


Fig. 3. The heating triangle: three fundamental quantitative evaluation metrics. The specific heating rate relates to the heating speed and heating duration. The COP reflects the energy consumption and indicates the heating efficiency. The specific temperature difference links with the temperature gradient, and thus local overheating risk and the uneven degradation of batteries.

considers three fundamental quantitative metrics: the specific heating rate ($^\circ\text{C} \cdot \text{g} \cdot \text{J}^{-1}$), the coefficient of performance (COP) ($-$), and the specific temperature difference ($^\circ\text{C} \cdot \text{hr}$).

During heating, it is ideal to minimise heat loss from the battery to its surroundings as much as possible, with different insulation materials used [3,14–16,22,33–35,51,52]. For example, insulation such as polyfoam, insulation cotton, and others have been used to wrap the batteries, where convective heat transfer coefficients between ~ 0 and $9.6 \text{ W m}^{-2} \cdot \text{K}$ [33,34,38,48,51,52] have been achieved. Thus, these values are generally consistent with each other, and the variation in external heating parameters on heating performance is limited and can be ignored, allowing for the focus to be on internal and methodological parameters.

As we discussed in Section 2.3.1, battery resistance generally shows a positive correlation with energy density. While it often has a negative relationship with battery capacity, a simple example of which several cells connected in parallel decrease resistance but increase capacity. Thus, the energy density and capacity that usually vary with batteries, pose a great influence on battery heat generation and heating speed. Furthermore, the heat generation and heating speed increase with the heating current (Eq. (1)). Therefore, accounting for the dominant internal and methodological influencing parameters on heating speed, we define the specific heating rate (μ_I , $^\circ\text{C} \cdot \text{g} \cdot \text{J}^{-1}$) as the temperature-rise rate ($\dot{T}$) and battery capacity (Q_{bat}) per heating current (I_{heat} , A) and energy density (E_p , $\text{Wh} \cdot \text{kg}^{-1}$), expressed as:

$$\mu_I = \frac{\dot{T} \cdot Q_{bat}}{I_{heat} \cdot E_p} \quad (4)$$

We consider the heating current (I_{heat}), rather than the square of heating current (I_{heat}^2) in Eq. (4), as the heat generation depends on the heating current (I_{heat}) in some cases, such as the HSH methods [22,32,34,51,52], where it equals $I_{heat} \cdot U_{ocv}$. We define the heating C-rate (I_{C-rate}) as I_{heat}/Q_{bat} with the unit of h^{-1} or hr^{-1} , and the specific heating rate (μ_I , $^\circ\text{C} \cdot \text{g} \cdot \text{J}^{-1}$) is describe by the temperature-rise rate ($\dot{T}$) per heating C-rate (I_{C-rate} , h^{-1} or hr^{-1}) and energy density (E_p , $\text{Wh} \cdot \text{kg}^{-1}$), expressed as:

$$\mu_I = \frac{\dot{T}}{I_{C-rate} \cdot E_p} \quad (5)$$

The specific heating rate (μ_I) describes the temperature ($^\circ\text{C}$) increase per unit mass (g) when 1 J heat is absorbed, which is proportional to the inverse of the specific heat capacity ($(\text{J} \cdot ^\circ\text{C}^{-1} \cdot \text{g}^{-1})^{-1}$). Thus, it allows for the fair comparison between self-heating speeds. More relevant discussion will be performed later.

The COP is commonly used in heating/cooling systems, which indicates the ratio of useful heating to the energy input, with a higher COP equating to higher efficiency and lower specific energy consumption. For battery self-heating, the COP can be described by:

$$\text{COP} = \frac{m \cdot c_p \cdot \Delta T}{E_H} \cdot \frac{1 [\text{Wh}]}{3600 [\text{J}]} = \frac{m \cdot c_p \cdot \Delta T}{3600 \cdot e_h \cdot E_{bat}} = \frac{c_p \cdot \Delta T}{3600 \cdot e_h \cdot E_p} \quad (6)$$

where E_H , E_{bat} , and ΔT stand for the total energy (Wh) used in the heating system, the maximum available energy (Wh) in the battery, and temperature difference ($^\circ\text{C}$) between the initial and target heating temperatures, respectively. e_h is the energy consumption (%) during heating, which equals the per cent relative to the maximum available energy in the battery, but it is rarely reported in the heating papers. Alternatively, the capacity consumption, i.e. DOD (depth-of-discharge) during heating, is often presented [32,33,38,51,52,82], which represents the per cent relative to the maximum available capacity in the battery. We thus need to convert the capacity consumption (DOD) to energy consumption, expressed as:

$$E_H \approx Q_{loss} \cdot \bar{V}_{soc} \approx \text{DOD} \cdot Q_{bat} \cdot \bar{V}_{soc} \quad (7)$$

where $\bar{V}_{soc}$, Q_{loss} and Q_{bat} are the average OCV and capacity consumption (Ah) during heating, and the nominal capacity (Ah) of batteries, respectively. Therefore, the conversion coefficient, which is the ratio of energy consumption (e_h , %) and DOD, can be expressed as:

$$\frac{e_h}{\text{DOD}} = \frac{E_H/E_{bat}}{\text{DOD}} \approx \frac{Q_{bat} \cdot \bar{V}_{soc}}{E_{bat}} \approx \frac{\bar{V}_{soc}}{\bar{V}} \quad (8)$$

where $\bar{V}$ is the nominal voltage of batteries. Consequently, when given the capacity consumption (DOD), the COP can be approximately calculated as:

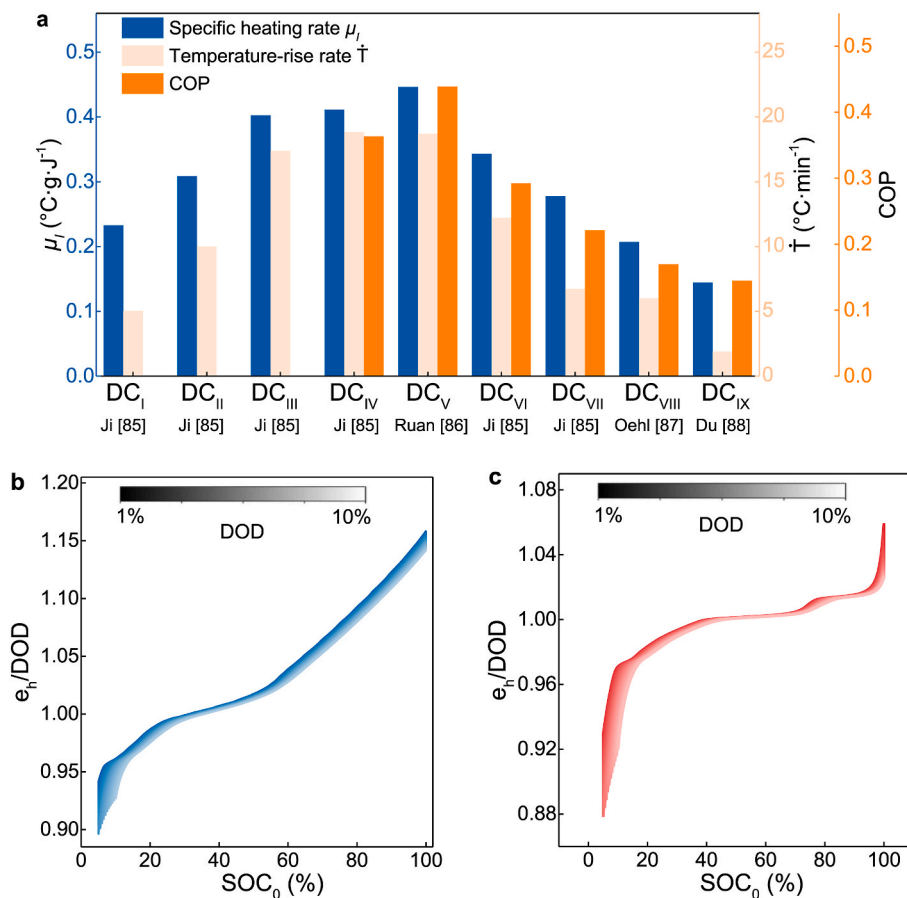


Fig. 4. a, Quantitative comparison of typical DC heating methods from the specific heating rate (μ_t), the temperature-rise rate ($\dot{T}$), and COP during heating. There is missing data on COP for the CC modes because the reference did not report the energy/capacity consumption. The conversion coefficient, i.e. ratio of energy consumption (e_h , %) and capacity consumption (DOD) of b, NMC battery at 0 °C and c, LFP battery at -10 °C with different DOD under different starting SOC of heating (SOC₀). The OCV data refers to Refs. [89,90]. The metrics in Fig. 4a are calculated based on the data in Table 2, Fig. 4b, c, and Supplementary Table S2.

discharge energy lost in the load controller. The COP ranges from 0.14 to 0.44, with an average of 0.29, showing a low heating efficiency.

As shown in Table 2, there is only one study providing experimental data on the temperature gradient for DC methods. For that case the gradient is low as generally expected for DC methods, given that the heat generation is uniformly distributed within the battery volume [84] and generally good heat insulation with surroundings.

4.2. AC + DC heating

We collect seven typical AC + DC heating methods and find the temperature-rise rate ($\dot{T}$) varies with different heating parameters (Table 3), with its values between 2.29 and 9.48 $^{\circ}\text{C}\cdot\text{min}^{-1}$ (Fig. 5). Similarly, the specific heating rate (μ_t) shows a narrow difference, and it is almost the same with values from 0.14 to 0.20 $^{\circ}\text{C}\cdot\text{g}^{-1}\cdot\text{s}^{-1}$, except for the AC + DC_{II} method. The μ_t of AC + DC heating methods appears to be not correlated with the AC frequency, which likely results from the difference in the proportion of AC and DC components. This may be explained by the similar voltage limits for different batteries which are taken as the constraints during selecting the heating current [33,46], and the resultant similar current for heating.

The COP for the typical AC + DC heating methods varies from 0.27 to 0.86 (Fig. 5b), with an average value of 0.59. Since the energy dense batteries are utilized in the AC + DC_{VI} method [38], the energy consumption percent per temperature rise ($e_h/\Delta T$) is quite low (Fig. 5b), which can be explained by Fig. 1a, and Supplementary Note S1, but the COP is comparable to other AC + DC methods (AC + DC_{II} and AC + DC_{IV} [33,92]). This implies the proposed new metric, COP, provides a fair comparison between approaches, by removing the major influencing factors. The COP of AC + DC_V [93] is the lowest (Fig. 5b), as only the pulse discharge current is used without the current in the charging

direction and the DC component is high (Supplementary Eq. (S14)). Although the pulse heating current can be considered as AC + DC current, only discharge current is applied to the battery, and thus like the DC discharge case, the COP is low due to the energy lost in the load controller (Supplementary Eq. (S12)).

The maximum temperature difference (ΔT_b), below 1.6 °C (Table 3), is low with AC + DC internal self-heating methods, which is generally expected because the heat generation is uniformly distributed within the battery and good heat insulation measures are usually taken.

4.3. Hybrid self-heating

The seven typical HSH methods are compared in Table 4 and Fig. 6. We show that the temperature-rise rate ($\dot{T}$) is largely different, with the maximum of 96.0 $^{\circ}\text{C}\cdot\text{min}^{-1}$ and the minimum of 0.35 $^{\circ}\text{C}\cdot\text{min}^{-1}$. However, the specific heating rate (μ_t) calculated by removing the varied battery and methodological influence is almost the same, with values between 0.49 and 1.15 $^{\circ}\text{C}\cdot\text{g}^{-1}\cdot\text{s}^{-1}$. This highlights the advantage of the proposed metric to find the common characterization of the same type of heating method, which contributes to fairly comparing different heating methods.

The COP of different HSH methods ranges from 0.63 to 1.12, with the average value of 0.82. The COP that is above 1 is likely attributed to the uncertainty of the used specific heat capacity during the COP calculation (More explanation described in Discussion section). Due to the less heat dissipation to the surroundings with the heaters embedded in the battery, the COP of HSH methods using the inserted Nickel foils (HSH_V, HSH_{VI} and HSH_{VII} [34,51,99]) generally exhibits a high COP (>0.78). The $e_h/\Delta T$ in the HSH_{IV} method [98] is rather high owing to the low energy density (96 Wh $\cdot\text{kg}^{-1}$) of the battery but the COP is not so low (0.80). This again indicates energy consumption highly depends on

Table 3
Heating parameters and conditions, battery parameters, and maximum temperature difference for the typical AC + DC heating methods. Other parameters are listed in Supplementary Table S2.

References	Heating parameters		Heating conditions		Battery parameters			ΔT_b (°C)			
			SOC ₀ (%)	t_h (s)	T_{amb} (°C)	T_{gr} (°C)	Thermal condition		Battery types	c_p (J·K ⁻¹ ·g ⁻¹)	E_p (Wh·kg ⁻¹)
AC + DC _h , Mohan et al. [91]	10Hz pulse current		60	274	-20	10.8	h : 5 W·m ⁻² ·K ⁻¹	2.3 Ah fresh 26650 LFP/Gr	1.109	105	-
AC + DC _{int} , Jiang et al. [33]	754Hz SAC		100	600	-20.8	2.1	h : 2.04 W·m ⁻² ·K ⁻¹	35 Ah fresh pouch NMC/Gr	1.177	128.2	1.6
AC + DC _{int} , Shang et al. [37]	833Hz SAC		-	354	-20	0	In the climate chamber	2.5 Ah 18650 NMC/Gr	-	~200	-
AC + DC _{int} , Shang et al. [92]	22 kHz SAC		100	162	-10	10	h : 5.32 W·m ⁻² ·K ⁻¹	2.0 Ah 18650 LCO/Gr	1.05	164	-
AC + DC _{int} , Qu et al. [93]	0.5s pulse current		50	300	-7	29.1	h : 9.6 W·m ⁻² ·K ⁻¹	50 Ah fresh prismatic NMC532/Gr	1.126	262	-
AC + DC _{int} , Li et al. [38]	1.6s Pulse (4C/4C)		100	132	-20	0	In the climate chamber	2.5 Ah 18650 NMC/Gr	-	200	0.3
AC + DC _{int} , Zhang et al. [94]	10 kHz SAC										

NMC532: LiNi_{0.5}Mn_{0.3}Co_{0.2}O₂; LCO: LiCoO₂.

NMC532: LiNi_{0.5}Mn_{0.3}Co_{0.2}O₂; LCO: LiCoO₂.

battery parameters and the COP offers a fair metric for heating comparison.

The specific temperature difference (ΔT_{STD}) varies from 0.57 to 4.75 °C·hr. Despite the low temperature gradient in the HSH_I method due to the low heating current [96], its ΔT_{STD} is pretty high, due to the only one external heater used. For HSH_{IV} and HSH_{VI} methods [98,99], two heaters are used, with the ΔT_{STD} obviously decreased, and the HSH_{VII} [34], with three heaters features the lowest ΔT_{STD} . With the greater number of heaters, both the short heat transfer pathway and low heat generation of each heater are achieved, which facilitates uniform temperature distribution during heating.

4.4. Summary of quantitative comparison

With the three proposed universal metrics, we find the same type of heating methods show very similar performance (Fig. 7), and thus we can quantitatively compare the three types of typical self-heating methods, regardless of the different methodological parameters and battery types. The specific heating rate (μ_I) is the lowest for AC + DC heating methods (Fig. 7a), primarily due to the lower AC resistance. As multiple dynamic processes, such as charge-transfer, double layer charging and diffusion, are involved during DC excitation [3,14,33,35,54], the DC resistance is often higher than the AC resistance of batteries, and the μ_I is thus higher for DC heating methods. The μ_I for HSH methods is the highest. Including the external heating can be equivalently taken as the increase of battery heating resistance [22,32], thus resulting in the high μ_I in HSH methods. The average μ_I of DC heating methods is 2.2 times the AC + DC methods, while that of HSH methods is 2.6 times the DC methods.

The COP of DC heating methods is the lowest (Fig. 7b), because the energy of the battery discharged to the load controller is not used. With the utilization of the discharge energy in HSH methods, the COP is significantly increased and we find HSH methods show the highest average COP (above 0.82), increasing by 181% compared to DC heating. The COP of AC + DC heating methods is relatively high (0.59), because the relatively low DC component compared with the applied heating current leads to less energy consumption (Supplementary Eq. (S14)). The HSH methods exhibit a 38% higher COP than the AC + DC heating methods, which is likely attributed to the recycling of the discharge energy and the low heat dissipation to the surroundings due to the fast heating speed.

The temperature gradient within the battery is high for the HSH methods (Fig. 7c), due to integrating external heating. Since the thermal conductivity of batteries is limited with the through-plane values ranging from 0.40 to 1.03 W m⁻¹ K⁻¹ [21,101,102], there is a large temperature difference within the battery. The specific temperature difference (ΔT_{STD}) within the battery reaches 2.68 °C·hr for the HSH methods. While for the other self-heating methods, the ΔT_{STD} is low and below 0.41 °C·hr, due to just including the internal self-heating.

It should be mentioned that the temperatures, capacity consumption (DOD), starting SOC (SOC₀) for heating, and current, which are measured in various ways (including varied sensors) in different references, would pose uncertainty to the calculated triangular metrics. This would be one reason for the variance of each calculated indicator in Fig. 7a, b and c. To make a consistent comparison, it is suggested to calibrate the sensing precision for measuring temperature, current and capacity in each heating paper.

5. Discussion

5.1. Rationality analysis on triangle metrics

We investigate the physical meaning of the defined metric, μ_I . If the heat dissipation is neglected, deduced from Eq. (2) (See Supplementary Note S2), the specific heating rate, μ_I , equals the ratio of the (equivalent)

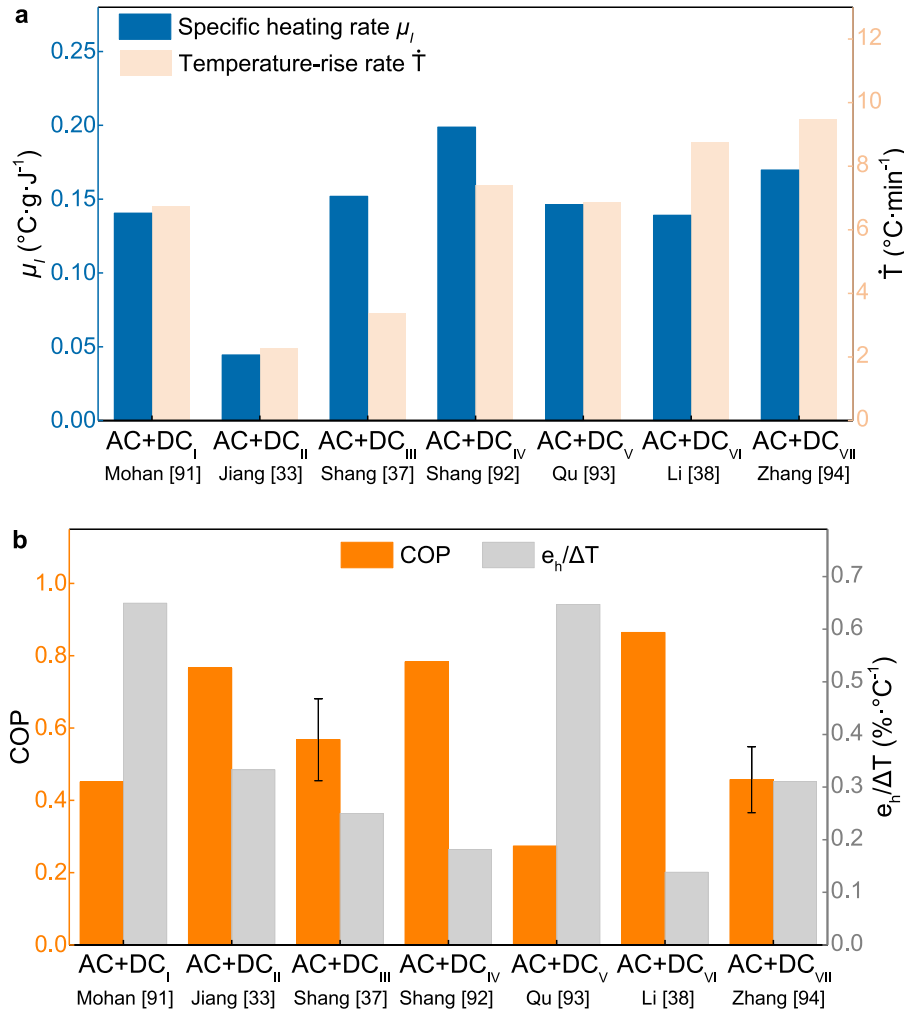


Fig. 5. Quantitative comparison of typical AC + DC heating methods from **a.** the specific heating rate (μ_I), and the temperature-rise rate ($\dot{T}$); **b.** COP and energy consumption per temperature rise ($e_h/\Delta T$) during heating. The metrics are calculated based on the basic data in Table 3 and Supplementary Table S2, and/or the conversion coefficient data in Fig. 4b and c. As there is missing data on c_p for AC + DC_{III} and AC + DC_{VII}, the COP is calculated using the assumed c_p with values in 0.8–1.2 J K⁻¹ g⁻¹ [95].

polarization voltage ($\hat{U}_p$) to the nominal voltage ($\bar{V}$) divided by the specific heat capacity (c_p), expressed as:

$$\mu_I = \frac{1}{c_p} \frac{\hat{U}_p}{\bar{V}}, \quad \hat{U}_p = \begin{cases} U_{ocv} - U_{bat}, & \text{DC, AC + DC} \\ U_{ocv}, & \text{Hybrid} \end{cases} \quad (11)$$

Here the polarization voltage in the DC and AC + DC heating is the difference between the OCV and battery terminal voltage (considering battery discharge), generally including ohmic (instantaneous) polarization, activation polarization, and diffusion (concentration) polarization [35], while the equivalent polarization voltage in the HSH involves battery total polarization and the voltage in the external heaters [22].

Eq. (11) theoretically suggests μ_I is proportional to the inverse of the specific heat capacity, which holds true for every self-heating method, implying a universal indicator. As the medians of the specific heat capacity of different batteries range from 912 to 1168 J °C⁻¹ g⁻¹ [21], indicating a limited difference, this metric (μ_I) can allow a fair comparison between different self-heating methods although they are experimentally validated on various batteries. Furthermore, we conclude that a higher polarization voltage leads to a higher μ_I for the same battery. A high polarization voltage is significantly desired for rapid self-heating, but battery voltage should be generally kept in between the lower and upper voltages. As the voltage limits are kept the same under various conditions [33,43], the polarization voltage would be roughly kept constant by modulating the heating current and independent of temperatures. On the other hand, the battery types, such as different chemistries, show a reduced influence on the ratio of

polarization voltage and the nominal voltage. Thus, the μ_I can be quantitatively comparable for different batteries with various heating parameters.

For different types of self-heating methods, the equivalent polarization voltages ($\hat{U}_p$) are often different. For example, as shown in Eq. (12), the $\hat{U}_{pHSH}$ for the HSH methods is usually the battery OCV (Eq. (11)), indicating the inclusion of internal and external heating, and thus the maximum. While the $\hat{U}_{pAC+DC}$ for the AC + DC methods is the RMS (Root mean square) value, generally less than the peak value, which is similar to the AC resistance lower than DC resistance, and thus the minimum. Then, we determine the heating speed (μ_I average values, $\tilde{\mu}_I$) for three self-heating methods, which aligns with the quantitative comparison results in Section 4.4.

$$\hat{U}_{pAC+DC} \leq \hat{U}_{pDC} \leq \hat{U}_{pHSH} \Rightarrow \tilde{\mu}_{IAC+DC} \leq \tilde{\mu}_{IDC} \leq \tilde{\mu}_{IHSH} \quad (12)$$

We try to provide the underpinning insight for the heating speed by exploring the equivalent resistance during heating. Based on Eq. (11), we can deduce that the equivalent heating resistance ($\hat{R}_b$) is proportional to the μ_I/I_{heat} , expressed as:

$$\hat{R}_b \propto \frac{\mu_I}{I_{heat}} \quad (13)$$

Fig. 7d illustrates the μ_I/I_{heat} value of different self-heating methods. For the HSH methods, it is high at the low current, but low at high current, even lower than that of the AC + DC heating methods. Thus it is not easy to directly compare the equivalent heating resistance for

Table 4
Heating parameters and conditions, battery parameters, and maximum temperature difference for typical HSH heating methods. Other parameters are listed in Supplementary Table S2.

References	Heating parameters			Heating conditions			Battery parameters			
	SOCo (%)	t_h (s)	T_{amb} (°C)	T_{gr} (°C)	Thermal condition		Battery types	c_p (J K ⁻¹ g ⁻¹)	E_p (Wh kg ⁻¹)	ΔT_b (°C)
HSH _I Zhang et al. [96]	94	2880	-40 ^a	-2.4	In the climate chamber		35 Ah Pouch LMO/Gr	1.100	120	-
HSH _{II} Shang et al. [97]	-	114	-20	0	$h = 15.9$ W m ⁻² K ⁻¹		2.5 Ah 18650 NMC/Gr	0.8–1.72 ^b	~200	-
HSH _{III} Xu et al. [32]	100	107	-29.8	-2	In the climate chamber		13.5 Ah fresh cell	-	191.3	3–7 ^c
HSH _{IV} Ruan et al. [98]	100	52	-29.8	-2	$h = 5.98$ W m ⁻² K ⁻¹		8.0 Ah Pouch NMC111/Gr	1.127	96	14.79
HSH _V Wang et al. [51]	100	29.6	-30	0	$h_i = \sim 0$ W m ⁻² K ⁻¹		7.5 Ah fresh pouch NMC532/Gr	1.00	170	~30
HSH _{VI} Zhang et al. [99]	100	12.5	-20	-20	In the climate chamber		10.0 Ah Pouch NMC622/Gr	1.195	17.8	17.8
HSH _{VII} Yang et al. [34]	100	19.4	-20	-20	In the climate chamber				3.19	3.19

NMC622: LiNi_{0.6}Mn_{0.2}Co_{0.2}O₂; LMO: LiMn₂O₄; a: the initial battery temperature is -19.3 °C; $\Delta T = 16.9$ °C; b: c_p comes used from other references [95,100]; c: the ΔT_b is estimated from Ref. [32].

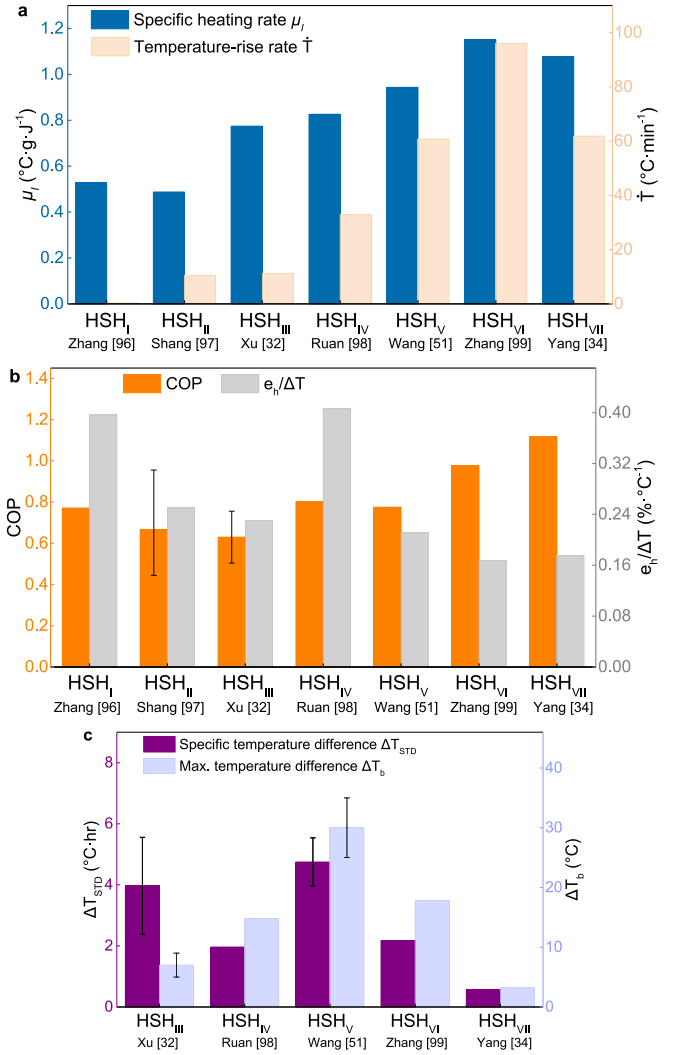


Fig. 6. Quantitative comparison of typical HSH heating methods from a. the specific heating rate (μ_t), and the temperature-rise rate ($\dot{T}$); b. the COP, and energy consumption per temperature rise ($e_h/\Delta T$); c. specific temperature difference (ΔT_{STD}) and maximum temperature difference (ΔT_b) during heating. The metrics are calculated based on the basic data in Table 4 and Supplementary Table S2, and the conversion coefficient data in Fig. 4b and c. As there is missing data on c_p for HSH_{II}, the COP is calculated using the assumed c_p with values in 0.8–1.72 J K⁻¹ g⁻¹ [95,97].

different self-heating methods. This is because the battery resistance highly depends on heating current, battery types and temperatures [36, 103,104,105]. We observe there is a decreasing trend of the μ_t/I_{heat} with the increasing current, which can be explained by the resistance dependency on the current, especially for the charge transfer and mass diffusion resistance [36,42,106]. Although the heating conditions, such as the non-adiabatic conditions, impact the calculation of equivalent heating resistance (Eq. (13)), battery resistance exponentially decreases with the current [36,106,107], and thus the heating current dominates the variation of equivalent heating resistance and it is challenging to use the heating resistance to essentially indicate the heating speed.

We further explore the relationship between the temperature-rise rate ($\dot{T}$) and other parameters, such as the heating current, the square of heating current, energy consumption and energy consumption per temperature rise ($e_h/\Delta T$). We find a weak correlation between the $\dot{T}$ and the energy consumption ($\rho = -0.482$, Supplementary Fig. S3c) for the HSH methods, and the strongest correlation between the $\dot{T}$ and I_{C-rate} ($\rho = 0.984$, Supplementary Fig. S3a). This strong correlation can be

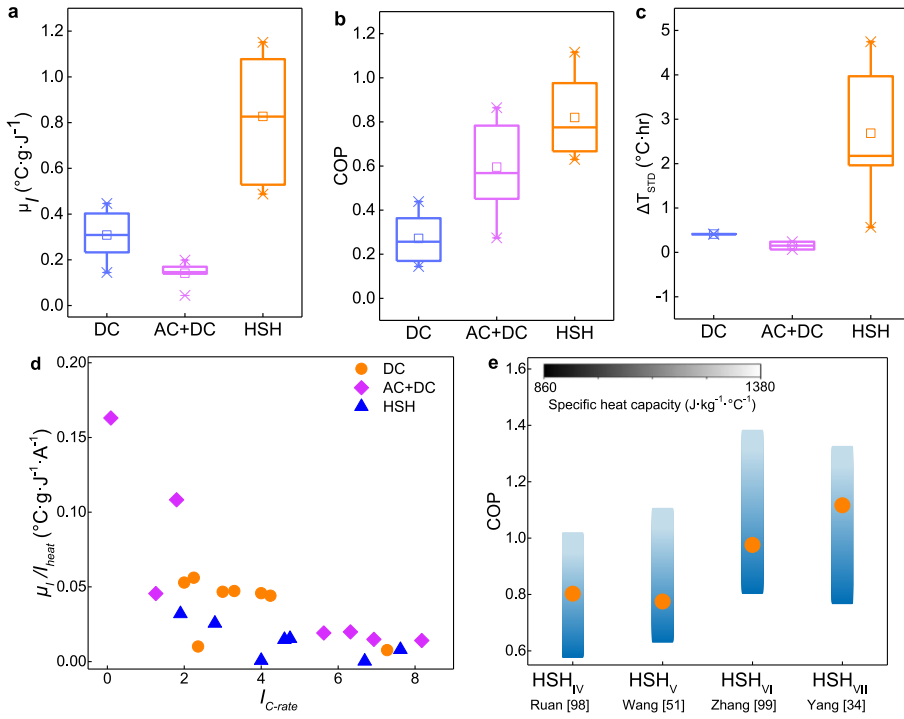


Fig. 7. Quantitative comparison of three types of self-heating methods with new metrics, a. the specific heating rate (μ_I), b. the COP, and c. the specific temperature difference (ΔT_{STD}) within the battery. The data comes from Figs. 4–6; d. The calculated μ_I/I_{heat} values of different self-heating methods, with the data coming from Fig. 4 to 6; e. the COP calculated with different specific heat capacities for four HSH methods (the other parameters are kept unchanged). The specific heat capacity ranges from 860 to 1380 $\text{J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$ for pouch batteries [21]. The orange ones represent the COP calculated with the specific heat capacity provided in the corresponding references [34,51,98,99]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

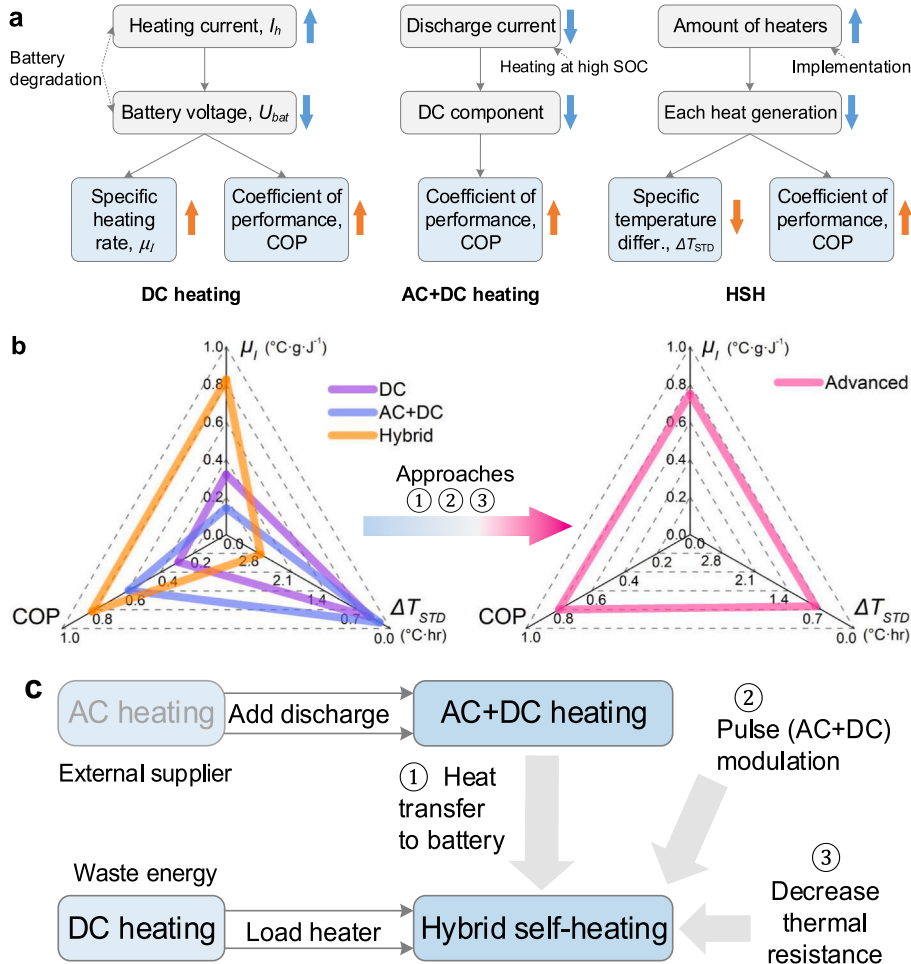


Fig. 8. a, The illustration of the approaches that can enhance the heating performance for different self-heating methods; b, The triangular metrics of the three types of self-heating methods and the near-perfect triangular values for the advanced self-heating method; c, The promising pathways to develop advanced self-heating approaches. The numbers, ①, ②, and ③, represent three potential paths and their specific description can be found in Supplementary Fig. S5.

explained by the heat generation of $U_{ocv} * I_{heat}$ for HSH methods, with the OCV during heating at high SOC almost the same. For the AC + DC heating methods, the strong correlation between the $\dot{T}$ and I_{C-rate} ($\rho = 0.874$, Supplementary Fig. S4a) and weak correlation between the $\dot{T}$ and other parameters are observed. This highlights the rationality of the defined metric, μ_I , which is calculated with the heating C-rate current (I_{C-rate}).

We find the COP calculation results relate to the specific heat capacity, when using Eqs. (6) and (9). For example, in the HSH_{II} method [97], using the specific heat capacity of $1.72 \text{ J g}^{-1} \text{ }^\circ\text{C}^{-1}$ that comes from Ref. [100], the COP is calculated as near 0.95 but it is only 0.50 with the median value of $0.905 \text{ J g}^{-1} \text{ }^\circ\text{C}^{-1}$ for the cylindrical battery specific heat capacity [21]. The uncertainty of the specific heat capacity leads to the great difference of the calculated COP (Fig. 7e). Thus, the COP will be higher than 1 if the overestimated specific heat capacity is used. This demonstrates the significance of the accurately estimated specific heat capacity for the COP evaluation. Despite the uncertainty in calculating the COP, the COP is still a useful metric to indicate the heating efficiency. With the emerging effective identification methods for the specific heat capacity [21,108,109], the COP calculation will be more accurate to reflect the true heating efficiency.

5.2. Approaches for heating performance enhancement

Based on the quantitative evaluation of DC self-heating methods, we find increasing the DC heating current induces a low averaged battery voltage, thus resulting in a high heating speed and a high COP (Fig. 8a, Eq. (11), and Supplementary Eq. (S12)). Therefore, to achieve a better heating performance, a higher DC is expected, but the possible battery degradation should be accounted for.

For the AC + DC heating methods, the low DC component means low energy consumption under the same heating speed, as the DC discharge leads to the energy loss. Decreasing the equivalent resistance in the AC + DC generating circuit generally leads to a reduced DC component [33], thus contributing to a high COP but battery voltage during self-heating at high SOC should be paid attention to as it may go over the upper voltage limit.

Regarding the HSH methods, increasing the amount of heaters results in a low ΔT_{STD} due to the reduced heat generation of each external heater. The uniform heating with sufficient heat transfer and less energy wasted on the heaters benefits a high COP. But the concern of the increased amount of heaters lies in the implementation which is not easy, and possible to decrease energy density for battery systems.

5.3. Outlook for advanced self-heating methods

We further evaluate the three types of self-heating methods with the heating triangular metrics: μ_I , COP, and ΔT_{STD} (Fig. 8b). By making use of the discharge energy and adding external heating, the HSH method shows a high COP and a high heating speed (μ_I), and it is thus preferable to warm the battery up. The heating speed (μ_I) of AC + DC heating methods is low but the temperature rise rate with a high current is acceptable [38]. Most importantly, the ΔT_{STD} is low and the COP is relatively high, therefore, it is another preferred self-heating method for batteries at low temperatures.

While the AC + DC and HSH methods are superior from a quantitative perspective using the heating triangle, both methods have shortcomings, with a low μ_I for AC + DC heating methods, and a high ΔT_{STD} for HSH methods (Fig. 8b). We suggest three research directions to improve the existing heating methods to achieve an improved pre-heating performance. The first one is transferring the heat from the AC + DC generating circuit to the batteries (Fig. 8c, Supplementary Fig. S5). The AC + DC generator is often required to be specially designed, such as the soft-switching resonance circuit [33], modifying the control of EVs' drive circuitry [38], high-frequency switched

capacitor circuit [94], inductor ladder-based circuit [110] and H-bridge high-frequency circuit [67]. Electrical losses occur in the AC + DC generator and its temperature is generally higher than the battery. If the heat is transferred to the battery, this method will exhibit similar characteristics to the HSH method and the μ_I will increase. The second research direction is to control the heating current in the HSH methods. The DC is generally used for the HSH methods, and if adding relaxation periods (pulse discharging), the heat accumulation will be low and the temperature gradient is expected to be decreased. When modulated, the heating current looks like the AC + DC (exactly pulse current + DC), and how to determine the relaxation/pulse periods remains an open question. The third research direction is to decrease the thermal resistance of batteries. The high temperature gradient within the battery for the HSH methods is essentially caused by a high thermal resistance of batteries. Tab-heating is a possible means to reduce temperature gradients within the battery for the HSH methods, and modifying the tab design, like the tab design for cooling [111], will facilitate the heat flow and reduce the thermal resistance. Therefore, strengthening the heat-transfer capability of battery tabs is a potential candidate to develop an advanced thermal management system integrating excellent heating and cooling performance.

We further explore the research gaps in battery self-heating. When conducting quantitative investigations of self-heating methods, we find almost all the approaches are experimentally validated with fresh batteries, and few with aged batteries. In particular, it remains uncertain about how the heating performance varies with battery aging, and aging adaptive approaches [112] are desired to explore. Besides, we quantitatively compared 23 self-heating cases despite the existing more than 30 references, as the internal and/or methodological parameters are not accessible for many heating cases. It is highly suggested that all the developed heating methods should comprehensively describe the used parameters for ease of quantitative comparison. Furthermore, few research presented the internal temperatures of batteries during heating. Exploring internal temperatures/states using new sensors [113] is expected to deeply understand battery heating processes, with more data generated for contributing to deep quantitative analysis of self-heating.

Finally, we acknowledge that battery degradation is a key heating performance, and with more reported degradation data for heating, it might be possible to formulate another universal metric to evaluate battery degradation during heating in the future.

6. Conclusions

This article develops a new way to review battery self-heating methods, which removes the application specific influencing factors to quantitatively compare heating approaches rather than qualitatively. To enable universal quantitative comparison of heating methods, we define the heating triangle. This is composed of three fundamental quantitative metrics (see Fig. 3): the specific heating rate (μ_I , $^\circ\text{C}\cdot\text{g}\cdot\text{J}^{-1}$), coefficient of performance (COP), and specific temperature difference (ΔT_{STD} , $^\circ\text{C}\cdot\text{hr}$).

Instead of using the usual temperature-rise rate, we propose the specific heating rate (μ_I) to characterise heating speed, due to the strong correlation between the temperature-rise rate and heating current (I_{heat}). We consider the energy density and capacity in the proposed metric (μ_I) to reduce the influence from battery types. The COP is used to describe the heating efficiency rather than adopting the commonly used energy/capacity consumption, since consumption highly depends on the battery internal parameters (e.g. energy density). The specific temperature difference (ΔT_{STD}) is used to quantify the temperature non-uniformity of different batteries during various heating, which indicates the temperature gradient within batteries after removing the dominant influencing factor (e.g. heating C-rate).

Even with different heating parameters and batteries, the same type of self-heating method is demonstrated to show very similar values for the three metrics. For example, it turns out that the short heating duration of several heating methods is only attributed to the high

heating current. Therefore, the proposed heating triangle has the potential to become a standard approach for a fair comparative assessment of heating methods.

We calculate the mean and uncertainty for each metric and then compare quantitatively the self-heating methods. The average specific heating rate of DC heating methods is 2.2x the AC + DC heating methods due to the high equivalent polarization voltage when having similar voltage limits. But the AC + DC heating method is superior in terms of COP, which can be explained by the low discharged DC used when adding AC. The internal self-heating methods feature a uniform temperature distribution, with a specific temperature difference below 0.41 °C·hr. The specific heating rate of the hybrid self-heating method is more than 2.6x the other self-heating methods, which is essentially attributed to the high heat generation due to integrating internal and external battery heat. Furthermore, its COP increases by >38% compared with other methods. The primary drawback of the hybrid self-heating method is the high specific temperature difference of reaching 2.68 °C·hr due to the limited heat-transfer capability (low thermal conductivity) of batteries.

With quantitative comparison insights, we identify that for each self-heating method, increasing the equivalent polarization voltage is an ideal means to enhance specific heating rate and shorten heating duration. Enhancing the polarization voltage and reducing the DC component are effective ways to enhance the COP of DC and AC + DC self-heating methods, respectively, while good heat insulation benefits a higher COP for all heating methods.

Every self-heating method is found to have a shortcoming and we present three promising pathways to remove the drawbacks of preferred self-heating methods (AC + DC and hybrid self-heating). It is expected that these approaches will enhance the heating speed and/or reduce temperature gradients by blending the AC + DC and hybrid self-heating concepts, and/or decreasing the thermal resistances of batteries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was kindly supported by the Faraday Institution's Industrial Fellowship (FIIF-013), the EPSRC Impact Acceleration Award (EP/X52556X/1), the EPSRC Faraday Institution's Multi-Scale Modelling Project (EP/S003053/1, grant number FIRG003), the EPSRC Joint UK-India Clean Energy Centre (JUICE) (EP/P003605/1), the EPSRC Integrated Development of Low-Carbon Energy Systems (IDLES) project (EP/R045518/1), and by the German Federal Ministry for Economic Affairs and Energy (BMWi) (03 ET6153C iMoBatt).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jpowsour.2023.233484>.

References

- [1] Kristen A. Severson, Peter M. Attia, Norman Jin, Nicholas Perkins, Benben Jiang, Zi Yang, H. Michael, Chen, et al., Data-driven prediction of battery cycle life before capacity degradation, *Nat. Energy* 4 (5) (2019) 383–391.
- [2] Billy Wu, W. Dhammika Widanage, Shichun Yang, Xinhua Liu, Battery digital twins: perspectives on the fusion of models, data and artificial intelligence for smart battery management systems, *Energy and AI* 1 (2020), 100016.
- [3] Hao Ge, Jun Huang, Jianbo Zhang, Zhe Li, Temperature-adaptive alternating current preheating of lithium-ion batteries with lithium deposition prevention, *J. Electrochem. Soc.* 163 (2) (2015) A290.
- [4] Xiao-Guang Yang, Teng Liu, Chao-Yang Wang, Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles, *Nat. Energy* 6 (2) (2021) 176–185.
- [5] Haijun Ruan, Bingxiang Sun, Weige Zhang, Xiaojia Su, Xitian He, Quantitative analysis of performance decrease and fast-charging limitation for lithium-ion batteries at low temperature based on the electrochemical model, *IEEE Trans. Intell. Transport. Syst.* 22 (1) (2020) 640–650.
- [6] Anna Tomaszewska, Zhengyu Chu, Xuning Feng, Simon O'kane, Xinhua Liu, Jingyi Chen, Chenzhen Ji, et al., Lithium-ion battery fast charging: a review, *ETransportation* 1 (2019), 100011.
- [7] Xiao-Guang Yang, Guangsheng Zhang, Shanhai Ge, Chao-Yang Wang, Fast charging of lithium-ion batteries at all temperatures, *Proc. Natl. Acad. Sci. USA* 115 (28) (2018) 7266–7271.
- [8] Xiao-Guang Yang, Teng Liu, Chao-Yang Wang, Innovative heating of large-size automotive Li-ion cells, *J. Power Sources* 342 (2017) 598–604.
- [9] Shuoyuan Mao, Meilin Han, Xuebing Han, Jie Shao, Yong Lu, Languang Lu, Minggao Ouyang, Analysis and Improvement measures of driving range Attenuation of electric vehicles in winter, *World Electric Vehicle Journal* 12 (4) (2021) 239.
- [10] Yunlong Shang, Chong Zhu, Gaopeng Lu, Qi Zhang, Naxin Cui, Chenghui Zhang, Modeling and analysis of high-frequency alternating-current heating for lithium-ion batteries under low-temperature operations, *J. Power Sources* 450 (2020), 227435.
- [11] Ziyu Song, Heath Hofmann, Jianqiu Li, Jun Hou, Xiaowu Zhang, Minggao Ouyang, The optimization of a hybrid energy storage system at subzero temperatures: energy management strategy design and battery heating requirement analysis, *Applied energy* 159 (2015) 576–588.
- [12] Deyang Huang, Ziqiang Chen, Shiyao Zhou, Self-powered heating strategy for lithium-ion battery pack applied in extremely cold climates, *Energy* 239 (2022), 122095.
- [13] Xiao-Guang Yang, Teng Liu, Yue Gao, Shanhai Ge, Yongjun Leng, Donghai Wang, Chao-Yang Wang, Asymmetric temperature modulation for extreme fast charging of lithium-ion batteries, *Joule* 3 (12) (2019) 3002–3019.
- [14] Jianbo Zhang, Hao Ge, Zhe Li, Zhanming Ding, Internal heating of lithium-ion batteries using alternating current based on the heat generation model in frequency domain, *J. Power Sources* 273 (2015) 1030–1037.
- [15] Xiaosong Hu, Yusheng Zheng, A. Howey David, Hector Perez, Aoife Foley, Michael Pecht, "Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives.", *Prog. Energy Combust. Sci.* 77 (2020), 100806.
- [16] Shujie Wu, Rui Xiong, Hailong Li, Victor Nian, Suxiao Ma, The state of the art on preheating lithium-ion batteries in cold weather, *J. Energy Storage* 27 (2020), 101059.
- [17] Yujie Wang, Xingchen Zhang, Zonghai Chen, Low temperature preheating techniques for Lithium-ion batteries: Recent advances and future challenges, *Appl. Energy* 313 (2022), 118832.
- [18] Jae Hwan Ahn, Hoon Kang, Ho Seong Lee, Hae Won Jung, Changhyun Baek, Yongchan Kim, Heating performance characteristics of a dual source heat pump using air and waste heat in electric vehicles, *Appl. Energy* 119 (2014) 1–9.
- [19] Tao Zhu, Haitao Min, Yuanbin Yu, Zhongmin Zhao, Tao Xu, Yang Chen, Xinyong Li, Cong Zhang, An optimized energy management strategy for preheating vehicle-mounted li-ion batteries at subzero temperatures, *Energies* 10 (2) (2017) 243.
- [20] Ruijia Fan, Caizhi Zhang, Yi Wang, Chenzhen Ji, Zaiqiang Meng, Lei Xu, Yang Ou, Cheng Siong Chin, Numerical study on the effects of battery heating in cold climate, *J. Energy Storage* 26 (2019), 100969.
- [21] Marco Steinhardt, Jorge V. Barreras, Haijun Ruan, Billy Wu, J. Offer Gregory, Andreas Jossen, "Meta-analysis of experimental results for heat capacity and thermal conductivity in lithium-ion batteries: a critical review.", *J. Power Sources* 522 (2022), 230829.
- [22] Haijun Ruan, Bingxiang Sun, Tao Zhu, Xitian He, Xiaojia Su, Andrew Cruden, Wenzhong Gao, Compound self-heating strategies and multi-objective optimization for lithium-ion batteries at low temperature, *Appl. Therm. Eng.* 186 (2021), 116158.
- [23] Dong-Yeon Lee, Chung-Won Cho, Jong-Phil Won, Youn Cheol Park, Moo-Yeon Lee, Performance characteristics of mobile heat pump for a large passenger electric vehicle, *Appl. Therm. Eng.* 50 (1) (2013) 660–669.
- [24] Xin Ye, Yaohua Zhao, Zhenhua Quan, Thermal management system of lithium-ion battery module based on micro heat pipe array, *Int. J. Energy Res.* 42 (2) (2018) 648–655.
- [25] Lin Liang, Yaohua Zhao, Yanhua Diao, Ruyang Ren, Heran Jing, Inclined U-shaped flat microheat pipe array configuration for cooling and heating lithium-ion battery modules in electric vehicles, *Energy* 235 (2021), 121433.
- [26] T.A. Stuart, A. Hande, HEV battery heating using AC currents, *J. Power Sources* 129 (2) (2004) 368–378.
- [27] Yudi Qin, Xiaoru Chen, Tomaszewska Anna, Huan Chen, Yifan Wei, Hengzhi Zhu, Yalun Li, et al., Lithium-ion batteries under pulsed current operation to stabilize future grids, *Cell Reports Physical Science* (2021), 100708.
- [28] Shanshan Guo, Rui Xiong, Weixiang Shen, Fengchun Sun, Aging investigation of an echelon internal heating method on a three-electrode lithium ion cell at low temperatures, *J. Energy Storage* 25 (2019), 100878.

- [29] Lei Zhang, Wentao Fan, Zhenpo Wang, Weihai Li, Dirk Uwe Sauer, Battery heating for lithium-ion batteries based on multi-stage alternative currents, *J. Energy Storage* 32 (2020), 101885.
- [30] Yunlong Shang, Kailong Liu, Naxin Cui, Qi Zhang, Chenghui Zhang, A sine-wave heating circuit for automotive battery self-heating at subzero temperatures, *IEEE Trans. Ind. Inf.* 16 (5) (2019) 3355–3365.
- [31] Chong Zhu, Yue Cao, Hua Zhang, Fei Lu, Xi Zhang, Comprehensive design and optimization of an onboard resonant self-heater for EV battery, *Energy* 7 (2) (2020) 452–463.
- [32] Jun Xu, Xuesong Mei, Haitao Wang, Junping Wang, A hybrid self-heating method for batteries used at low temperature, *IEEE Trans. Ind. Inf.* 17 (7) (2020) 4714–4723.
- [33] Jiuchun Jiang, Haijun Ruan, Bingxiang Sun, Leyi Wang, Wenzhong Gao, Weige Zhang, A low-temperature internal heating strategy without lifetime reduction for large-size automotive lithium-ion battery pack, *Appl. Energy* 230 (2018) 257–266.
- [34] Xiao-Guang Yang, Guangsheng Zhang, Chao-Yang Wang, Computational design and refinement of self-heating lithium ion batteries, *J. Power Sources* 328 (2016) 203–211.
- [35] Haijun Ruan, Jiuchun Jiang, Bingxiang Sun, Weige Zhang, Wenzhong Gao, Zeyu Ma, A rapid low-temperature internal heating strategy with optimal frequency based on constant polarization voltage for lithium-ion batteries, *Appl. Energy* 177 (2016) 771–782.
- [36] Jiangong Zhu, Zechang Sun, Xuezhe Wei, Haifeng Dai, An alternating current heating method for lithium-ion batteries from subzero temperatures, *Int. J. Energy Res.* 40 (13) (2016) 1869–1883.
- [37] Yunlong Shang, Bing Xia, Naxin Cui, Chenghui Zhang, Chunting Chris Mi, "An automotive onboard AC heater without external power supplies for lithium-ion batteries at low temperatures.", *IEEE Trans. Power Electron.* 33 (9) (2017) 7759–7769.
- [38] Yalun Li, Xinlei Gao, Yudi Qin, Jiuyu Du, Dongxu Guo, Xuning Feng, Languang Lu, Xuebing Han, Minggao Ouyang, "Drive circuitry of an electric vehicle enabling rapid heating of the battery pack at low temperatures.", *iScience* 24 (1) (2021), 101921.
- [39] Xiaogang Wu, Zhixin Wei, Yizhao Sun, Jinlei Sun, Jiuyu Du, Integrated all-climate heating/cooling system design and preheating strategy for lithium-ion battery pack, *Batteries* 8 (10) (2022) 179.
- [40] Yu Tian, Lin Cheng, Hailong Li, Jiuyu Du, Rui Xiong, Detecting undesired lithium plating on anodes for lithium-ion batteries—A review on the in-situ methods, *Appl. Energy* 300 (2021), 117386.
- [41] Nikolaos Wassiliadis, Jakob Schneider, Alexander Frank, Wildfeuer Leo, Xue Lin, Andreas Jossen, Markus Lienkamp, "Review of fast charging strategies for lithium-ion battery systems and their applicability for battery electric vehicles.", *J. Energy Storage* 44 (2021), 103306.
- [42] Junqiu Li, Danni Sun, Zhixiong Chai, Haifu Jiang, Chao Sun, Sinusoidal alternating current heating strategy and optimization of lithium-ion batteries with a thermo-electric coupled model, *Energy* 186 (2019), 115798.
- [43] Shanshan Guo, Rui Xiong, Kan Wang, Fengchun Sun, A novel echelon internal heating strategy of cold batteries for all-climate electric vehicles application, *Appl. Energy* 219 (2018) 256–263.
- [44] Yudi Qin, Jiuyu Du, Languang Lu, Ming Gao, Haase Frank, Jianqiu Li, Minggao Ouyang, A rapid lithium-ion battery heating method based on bidirectional pulsed current: heating effect and impact on battery life, *Appl. Energy* 280 (2020), 115957.
- [45] Wei Li, Yi Xie, Xiaosong Hu, Manh-Kien Tran, Michael Fowler, Satyam Panchal, Jintao Zheng, Kailong Liu, An internal heating strategy for lithium-ion batteries without lithium plating based on self-adaptive alternating current pulse, *IEEE Trans. Veh. Technol.* 72 (5) (2022) 5809–5823.
- [46] Shanshan Guo, Ruixin Yang, Weixiang Shen, Yongsheng Liu, Shenggang Guo, DC-AC hybrid rapid heating method for lithium-ion batteries at high state of charge operated from low temperatures, *Energy* 238 (2022), 121809.
- [47] Rui Xiong, Zhengyang Li, Ruixin Yang, Weixiang Shen, Suxiao Ma, Fengchun Sun, Fast self-heating battery with anti-aging awareness for freezing climates application, *Appl. Energy* 324 (2022), 119762.
- [48] Sang-Hyeon Ha, Jae-In Lee, Hyunki Yoon, Tae-Ryong Park, Jaell Baek, Jae-Sang Kim, Gun-Woo Moon, Frequency-variable resonant self-heating technique for lithium-ion batteries at low temperature, *IEEE Trans. Aero. Electron. Syst.* 58 (4) (2022) 3399–3410.
- [49] Cheng Lin, Zhenyi Tao, Yu Tian, Variable duty cycle heating strategy based online two-dimensional model for self-heating lithium-ion battery, *J. Energy Storage* 55 (2022), 105572.
- [50] Xuzhi Du, Lei Zhao, Zhigang Yang, Zheyang Jin, A closed-loop control on temperature difference of a lithium-ion battery by pulse heating in cold climates, *J. Energy Storage* 57 (2023), 106311.
- [51] Chao-Yang Wang, Guangsheng Zhang, Shanhai Ge, Terrence Xu, Ji Yan, Xiao-Guang Yang, Yongjun Leng, Lithium-ion battery structure that self-heats at low temperatures, *Nature* 529 (7587) (2016) 515–518.
- [52] Guangsheng Zhang, Shanhai Ge, Xiao-Guang Yang, Yongjun Leng, Dan Marple, Chao-Yang Wang, Rapid restoration of electric vehicle battery performance while driving at cold temperatures, *J. Power Sources* 371 (2017) 35–40.
- [53] Yi Li, Kailong Liu, Aoife M. Foley, Alana Zülke, Maitane Berecibar, Elise Nanini-Maury, Joeri Van Mierlo, Harry E. Hoster, Data-driven health estimation and lifetime prediction of lithium-ion batteries: a review, *Energy* 113 (2019), 109254.
- [54] Jacqueline S. Edge, O'Kane Simon, Prosser Ryan, Niall D. Kirkaldy, Anisha N. Patel, Alastair Hales, Abir Ghosh, et al., Lithium ion battery degradation: what you need to know, *Phys. Chem. Chem. Phys.* 23 (14) (2021) 8200–8221.
- [55] Trishna Raj, Andrew A. Wang, Charles W. Monroe, David A. Howey, Investigation of Path-dependent degradation in lithium-ion batteries, *Renew. Sustain. Energy Rev.* 3 (12) (2020) 1377–1385.
- [56] Haijun Ruan, Jingyi Chen, Weilong Ai, Billy Wu, Generalised diagnostic framework for rapid battery degradation quantification with deep learning, *Energy and AI* 9 (2022), 100158.
- [57] Jake Sowe, Jorge Varela Barreras, Michael Schimpe, Billy Wu, Chiara Candelise, Jenny Nelson, Sheridan Few, Model-informed battery current derating strategies: simple methods to extend battery lifetime in islanded mini-grids, *J. Energy Storage* 51 (2022), 104524.
- [58] Kailong Liu, Xiaosong Hu, Zhile Yang, Yi Xie, Shengzhong Feng, Lithium-ion battery charging management considering economic costs of electrical energy loss and battery degradation, *Energy Convers. Manag.* 195 (2019) 167–179.
- [59] Mingyun Luo, Jiaqi Song, Ziye Ling, Zhengguo Zhang, Xiaoming Fang, Phase change material coat for battery thermal management with integrated rapid heating and cooling functions from -40°C to 50°C , *Mater. Today Energy* 20 (2021), 100652.
- [60] Haijun Ruan, Bingxiang Sun, Jiuchun Jiang, Weige Zhang, Xitian He, Xiaojia Su, Jingji Bian, Wenzhong Gao, A modified-electrochemical impedance spectroscopy-based multi-time-scale fractional-order model for lithium-ion batteries, *Electrochim. Acta* 394 (2021), 139066.
- [61] Andrew Weng, Peyman Mohtat, M. Attia Peter, Valentin Sulzer, Suhak Lee, Greg Less, Anna Stefanopoulou, "Predicting the impact of formation protocols on battery lifetime immediately after manufacturing.", *Joule* 5 (11) (2021) 2971–2992.
- [62] Antti Aitio, David A. Howey, Predicting battery end of life from solar off-grid system field data using machine learning, *Joule* 5 (12) (2021) 3204–3220.
- [63] Jason B. Quinn, Thomas Waldmann, Karsten Richter, Michael Kasper, Margret Wohlfahrt-Mehrens, Energy density of cylindrical Li-ion cells: a comparison of commercial 18650 to the 21700 cells, *J. Electrochem. Soc.* 165 (14) (2018) A3284.
- [64] Matthieu Dubarry, Cyril Truchot, Bor Yann Liaw, Cell degradation in commercial LiFePO₄ cells with high-power and high-energy designs, *J. Power Sources* 258 (2014) 408–419.
- [65] Michael J. Lain, Brandon James, Emma Kendrick, Design strategies for high power vs. high energy lithium ion cells, *Batteries* 5 (4) (2019) 64.
- [66] Michael Quarti, Andreas Bayer, Wolfgang G. Bessler, "Trade-off between energy density and fast-charge capability of lithium-ion batteries: a model-based design study of cells with thick electrodes.", *Electrochemical Science Advances* 3 (1) (2023), e2100161.
- [67] Zhongxiaobang Hu, Li Yang, Furong Liu, Bo Zhao, Weibo Li, Ruixin Yang, Changjun Xie, Ying Shi, Thermal characteristics investigation of lithium-ion battery under high-frequency AC excitation in low-temperature Environment, *IEEE Transactions on Transportation Electrification* 8 (1) (2021) 407–419.
- [68] Xiaogang Wu, Zhe Chen, Zhiyang Wang, Analysis of low temperature preheating effect based on battery temperature-rise model, *Energies* 10 (8) (2017) 1121.
- [69] Jingwen Weng, Xiaqing Yang, Dongxu Ouyang, Mingyi Chen, Guoqing Zhang, Jian Wang, Comparative study on the transversal/lengthwise thermal failure propagation and heating position effect of lithium-ion batteries, *Appl. Energy* 255 (2019), 113761.
- [70] Zhiguo Lei, Yuwen Zhang, Xueguo Lei, Improving temperature uniformity of a lithium-ion battery by intermittent heating method in cold climate, *Int. J. Heat Mass Tran.* 121 (2018) 275–281.
- [71] Zhiguo Lei, Yuwen Zhang, Xueguo Lei, Temperature uniformity of a heated lithium-ion battery cell in cold climate, *Appl. Therm. Eng.* 129 (2018) 148–154.
- [72] Heze You, Haifeng Dai, Lizhen Li, Xuezhe Wei, Guangshuai Han, Charging strategy optimization at low temperatures for Li-ion batteries based on multi-factor coupling aging model, *IEEE Trans. Veh. Technol.* 70 (11) (2021) 11433–11445.
- [73] Tianze Wang, Xiaogang Wu, Shaobing Xu, Heath Hofmann, Jiuyu Du, Jianqiu Li, Minggao Ouyang, Ziyu Song, Performance of plug-in hybrid electric vehicle under low temperature condition and economy analysis of battery pre-heating, *J. Power Sources* 401 (2018) 245–254.
- [74] Yan Zhao, Yatish Patel, Teng Zhang, J. Offer Gregory, "Modeling the effects of thermal gradients induced by tab and surface cooling on lithium ion cell performance.", *J. Electrochem. Soc.* 165 (13) (2018) A3169.
- [75] Hansen Wang, Yangying Zhu, Sang Cheol Kim, Allen Pei, Yanbin Li, David T. Boyle, Hongxia Wang, et al., Underpotential lithium plating on graphite anodes caused by temperature heterogeneity, *Proc. Natl. Acad. Sci. USA* 117 (47) (2020) 29453–29461.
- [76] Haijun Ruan, Jiuchun Jiang, Bingxiang Sun, Wenzhong Gao, Leyi Wang, Weige Zhang, Online estimation of thermal parameters based on a reduced wide-temperature-range electro-thermal coupled model for lithium-ion batteries, *J. Power Sources* 396 (2018) 715–724.
- [77] Dafen Chen, Jiuchun Jiang, Gi-Heon Kim, Chuanbo Yang, Pesaran Ahmad, Comparison of different cooling methods for lithium ion battery cells, *Appl. Therm. Eng.* 94 (2016) 846–854.
- [78] Ian A. Hunt, Yan Zhao, Yatish Patel, G.J. Offer, Surface cooling causes accelerated degradation compared to tab cooling for lithium-ion pouch cells, *J. Electrochem. Soc.* 163 (9) (2016) A1846.
- [79] Gang Ning, Bala Haran, Branko N. Popov, Capacity fade study of lithium-ion batteries cycled at high discharge rates, *J. Power Sources* 117 (1–2) (2003) 160–169.
- [80] Michael Schimpe, Jorge V. Barreras, Billy Wu, Gregory J. Offer, Battery degradation-aware current derating: an effective method to prolong lifetime and ease thermal management, *J. Electrochem. Soc.* 168 (6) (2021), 060506.

- [81] Xiaogang Wu, Zhihao Cui, Ersong Chen, Jiuyu Du, Capacity degradation minimization oriented optimization for the pulse preheating of lithium-ion batteries under low temperature, *J. Energy Storage* 31 (2020), 101746.
- [82] Ryan S. Longchamps, Xiao-Guang Yang, Shanhai Ge, Teng Liu, Chao-Yang Wang, "Transforming rate capability through self-heating of energy-dense and next-generation batteries.", *J. Power Sources* 510 (2021), 230416.
- [83] Nan Piao, Xuning Gao, Huicong Yang, Zhenqiang Guo, Guangjian Hu, Hui-Ming Cheng, Feng Li, Challenges and development of lithium-ion batteries for low temperature environments, *eTransportation* 11 (2022), 100145.
- [84] Yudi Qin, Zhoucheng Xu, Yueqiang Wu, Languang Lu, Xuebing Han, Jiuyu Du, Minggao Ouyang, Temperature distribution of lithium ion battery module with inconsistent cells under pulsed heating method, *Appl. Therm. Eng.* 212 (2022), 118529.
- [85] Yan Ji, Chao Yang Wang, Heating strategies for Li-ion batteries operated from subzero temperatures, *Electrochim. Acta* 107 (2013) 664–674.
- [86] Haijun Ruan, Jiuchun Jiang, Bingxiang Sun, Xiaojia Su, Xitian He, Kejie Zhao, An optimal internal-heating strategy for lithium-ion batteries at low temperature considering both heating time and lifetime reduction, *Appl. Energy* 256 (2019), 113797.
- [87] Joachim Oehl, Andreas Gleiter, Daniel Manka, Fill Alexander, Kai Peter Birke, High frequency alternating current heating method for Li-Ion cells based on boost converter topology, *J. Energy Storage* 53 (2022), 105169.
- [88] Jiuyu Du, Zhe Chen, Feiqiang Li, Multi-objective optimization discharge method for heating lithium-ion battery at low temperatures, *IEEE Access* 6 (2018) 44036–44049.
- [89] Fangdan Zheng, Yinjiao Xing, Jiuchun Jiang, Bingxiang Sun, Jonghoon Kim, Michael Pecht, Influence of different open circuit voltage tests on state of charge online estimation for lithium-ion batteries, *Applied energy* 183 (2016) 513–525.
- [90] Yinjiao Xing, Wei He, Michael Pecht, Kwok Leung Tsui, State of charge estimation of lithium-ion batteries using the open-circuit voltage at various ambient temperatures, *Appl. Energy* 113 (2014) 106–115.
- [91] Shankar Mohan, Youngki Kim, G. Anna, Stefanopoulou, Energy-conscious warm-up of li-ion cells from subzero temperatures, *IEEE Trans. Ind. Electron.* 63 (5) (2016) 2954–2964.
- [92] Yunlong Shang, Kailong Liu, Naxin Cui, Nan Wang, Ke Li, Chenghui Zhang, A compact resonant switched-capacitor heater for lithium-ion battery self-heating at low temperatures, *IEEE Trans. Power Electron.* 35 (7) (2019) 7134–7144.
- [93] Z.G. Qu, Z.Y. Jiang, Qiong Wang, Experimental study on pulse self-heating of lithium-ion battery at low temperature, *Int. J. Heat Mass Tran.* 135 (2019) 696–705.
- [94] Yuanxi Zhang, Yaning Yang, Yunlong Shang, Naxin Cui, A high frequency AC heater based on switched capacitors for lithium-ion batteries at low temperature, *J. Energy Storage* 42 (2021), 102977.
- [95] Xiaoxuan Zhang, Reinhardt Klein, Anantharaman Subbaraman, Sergei Chumakov, Xiaobai Li, Jake Christensen, Christian Linder, Sun Ung Kim, Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method, *J. Power Sources* 412 (2019) 552–558.
- [96] Chengning Zhang, Xin Jin, Junqiu Li, PTC self-heating experiments and thermal modeling of lithium-ion battery pack in electric vehicles, *Energies* 10 (4) (2017) 572.
- [97] Yunlong Shang, Chong Zhu, Yuhong Fu, Chunting Chris Mi, An integrated heater equalizer for lithium-ion batteries of electric vehicles, *IEEE Trans. Ind. Electron.* 66 (6) (2018) 4398–4405.
- [98] Haijun Ruan, Bingxiang Sun, Andrew Cruden, Tao Zhu, Jiuchun Jiang, Xitian He, Xiaojia Su, Engy Ghoniem, Optimal external heating resistance enabling rapid compound self-heating for lithium-ion batteries at low temperatures, *Appl. Therm. Eng.* 200 (2022), 117536.
- [99] Guangsheng Zhang, Shanhai Ge, Terrence Xu, Xiao-Guang Yang, Hua Tian, Chao-Yang Wang, Rapid self-heating and internal temperature sensing of lithium-ion batteries at low temperatures, *Electrochim. Acta* 218 (2016) 149–155.
- [100] S.J. Drake, D.A. Wetz, J.K. Ostanek, S.P. Miller, J.M. Heinzl, A. Jain, Measurement of anisotropic thermophysical properties of cylindrical Li-ion cells, *J. Power Sources* 252 (2014) 298–304.
- [101] Marco Steinhardt, Elisabeth Irene Gillich, Maximilian Stiegler, Andreas Jossen, Thermal conductivity inside prismatic lithium-ion cells with dependencies on temperature and external compression pressure, *J. Energy Storage* 32 (2020), 101680.
- [102] Marco Steinhardt, Elisabeth Irene Gillich, Rheinfeld Alexander, Ludwig Kraft, Markus Spielbauer, Böhlen Oliver, Andreas Jossen, Low-effort determination of heat capacity and thermal conductivity for cylindrical 18650 and 21700 lithium-ion cells, *J. Energy Storage* 42 (2021), 103065.
- [103] Jiangong Zhu, Zechang Sun, Xuezhe Wei, Haifeng Dai, Weijun Gu, Experimental investigations of an AC pulse heating method for vehicular high power lithium-ion batteries at subzero temperatures, *J. Power Sources* 367 (2017) 145–157.
- [104] Jiuchun Jiang, Haijun Ruan, Bingxiang Sun, Weige Zhang, Wenzhong Gao, Linjing Zhang, A reduced low-temperature electro-thermal coupled model for lithium-ion batteries, *Appl. Energy* 177 (2016) 804–816.
- [105] Sebastian Ludwig, Ilya Zilberman, F. Horschke Max, Tim Wohlers, Andreas Jossen, "Pulse resistance based online temperature estimation for lithium-ion cells.", *J. Power Sources* 490 (2021), 229523.
- [106] Sijia Liu, Jiuchun Jiang, Wei Shi, Zeyu Ma, Hongyu Guo, Butler–volmer-equation-based electrical model for high-power lithium titanate batteries used in electric vehicles, *IEEE Trans. Ind. Electron.* 62 (12) (2015) 7557–7568.
- [107] Wladislaw Waag, Christian Fleischer, Dirk Uwe Sauer, On-line estimation of lithium-ion battery impedance parameters using a novel varied-parameters approach, *J. Power Sources* 237 (2013) 260–269.
- [108] Maan Al-Zareer, Andrew Michalak, Carlos Da Silva, Cristina H. Amon, Predicting specific heat capacity and directional thermal conductivities of cylindrical lithium-ion batteries: a combined experimental and simulation framework, *Appl. Therm. Eng.* 182 (2021), 116075.
- [109] Jiacheng He, Rekabra Youssef, Md Sazzad Hosen, Mohsen Akbarzadeh, Joeri Van Mierlo, Maitane Berecibar, A novel methodology to determine the specific heat capacity of lithium-ion batteries, *J. Power Sources* 520 (2022), 230869.
- [110] Chong Zhu, Yunlong Shang, Fei Lu, Yan Jiang, Chenwen Cheng, Chris Mi, Core temperature estimation for self-heating automotive lithium-ion batteries in cold climates, *IEEE Trans. Ind. Inf.* 16 (5) (2019) 3366–3375.
- [111] Shen Li, Niall Kirkaldy, Cheng Zhang, Krishnakumar Gopalakrishnan, Tazdin Amietszajew, Laura Bravo Diaz, Jorge Varela Barreras, et al., Optimal cell tab design and cooling strategy for cylindrical lithium-ion batteries, *J. Power Sources* 492 (2021), 229594.
- [112] Haijun Ruan, Jorge Varela Barreras, Timothy Engstrom, Merla Yu, Robert Millar, Billy Wu, Lithium-ion battery lifetime extension: a review of derating methods, *J. Power Sources* 563 (2023), 232805.
- [113] Cheng Zhang, Tazdin Amietszajew, Li Shen, Monica Marinescu, Gregory Offer, Chongming Wang, Yue Guo, Rohit Bhagat, Real-time estimation of negative electrode potential and state of charge of lithium-ion battery based on a half-cell-level equivalent circuit model, *J. Energy Storage* 51 (2022), 104362.