Electric Forklift

Battery design

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Problem Description

- Background:
  - Demand of electric vehicle in industrial application.
  - Carbon reduction
  - Electromobility revolution
- Problem Statement:

Forklift truck for use during double shifts (16 hours) with a maximum power of 10 kW and a mean power of 2.5 kW.

- Requirement:
  - Low cost
  - High reliability
  - Low maintenance
  - High temperature range

Assumptions

- Indoor Application
- Double Shifts Duration = 16 Hours (15 Working Hour + 1 Hour Break)
- 6 Working Days/Week, 4.3 Week/Month, 12 Months Operation = 310 Days/Year
- Operating Strategy: Opportunity Charging
  - Overnight Charging
  - Charging in Breaks

Capacity Requirement: Power and Energy Demand

- Mean Power Requirement = 2.5 kW
- Operating Hours / Day = 15 Hours
- Total Energy Requirement per day = 2.5 kW $\times$ 15h = 37.5 kWh
- DOD = 75% → increase cycle lifetime

- Battery Energy Requirement: 37.5 kWh / 0.75 = 50 kWh

Battery Technology: Comparison

Battery Type	Lead Acid	NiCd	NiMH	Li-ion		
Parameters				Cobalt	Manganese	Phosphate
Energy density (Wh/L)	60-110	50-150	140-300	560	420	333
Life Cycle (80% DOD)	200-300	1000	300-500	500-1000	500-1000	3000
Fast-Charge Time	8-16h	1h	2-4h	2-4h	1h or less	1h or less
Nominal Cell voltage	2 V	1.2 V	1.2V	3.6V	3.8V	3.3V
Maintenance Requirement	3-6 Months	1-2 months	2-3 months	Not Required		
Cost $/ kWh	100-200	300-600	300-600	300-350	300-350	300-400

[1][2][3][4][5]

Battery Technology: Comparison & Selection

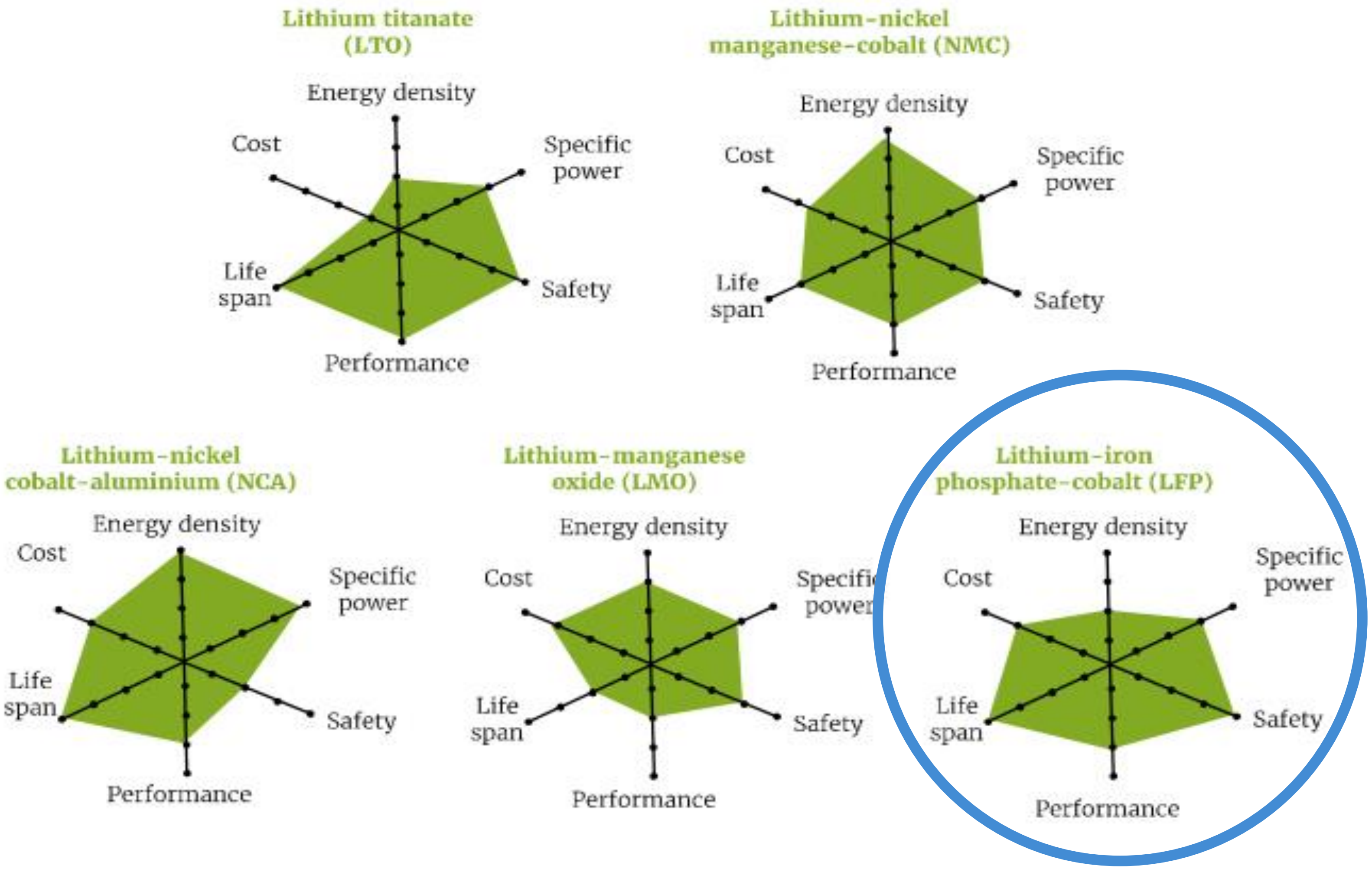

Fig: Comparison of different battery technologies based on selection parameters [7]

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Battery Technology : Lithium Iron Phosphate ($LiFePO_4$)

Major advantages of Lithium Iron Phosphate [5] :

- Very safe and secure technology (No Thermal Runaway)
- Very low toxicity for environment (use of iron, graphite and phosphate)
- Calendar life > 10 years
- Cycle life : from 2000 to several thousand (DOD dependence)
- Operational temperature range: up to 70°C
- Very low internal resistance. Stability or even decline over the cycles
- Constant power throughout the discharge range
- Ease of recycling
- High Specific Power

Battery Technology: Lithium Iron Phosphate ($LiFePO_4$)

The actual number of cycles that can be performed depends on several factors:

- Level of power in **C-Rate**
- Depth of Discharge (DOD)
- Operational environment : temperature, humidity, etc.

- **~3000** cycles at **75% DoD.**

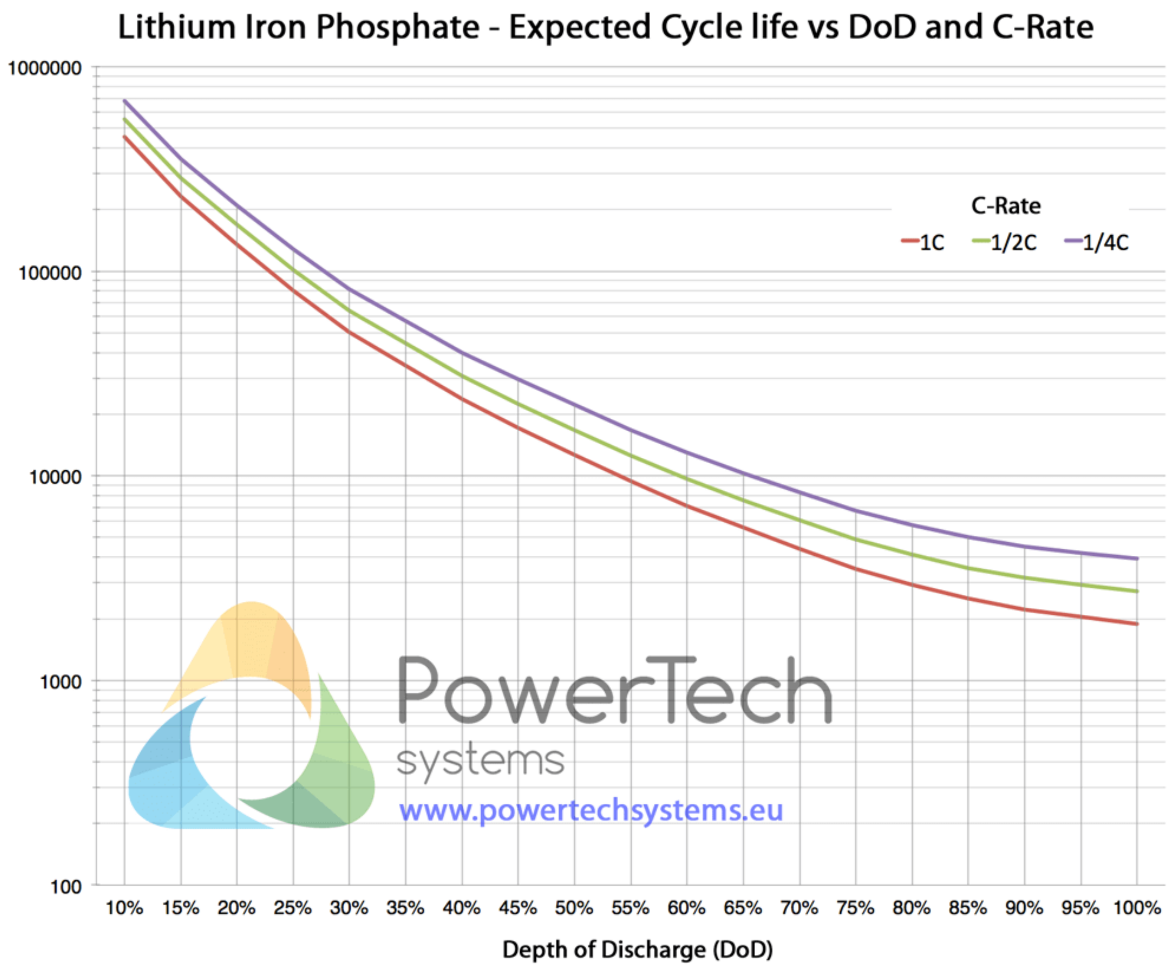


Fig: Cycle Life vs. DOD [5]

Technical Analysis: Battery Cell (1/2)

Parameters	Value
Model	Cylindrical 22650 battery cell
Nominal Voltage	3.2 Volt
Nominal Capacity	2 Ah
Weight	0.0405 Kg
Cost	1.35 Euro / Cell
Full Cycle Lifetime	1500 Times
Volume	2.47×10^{-5} m^3 / Cell

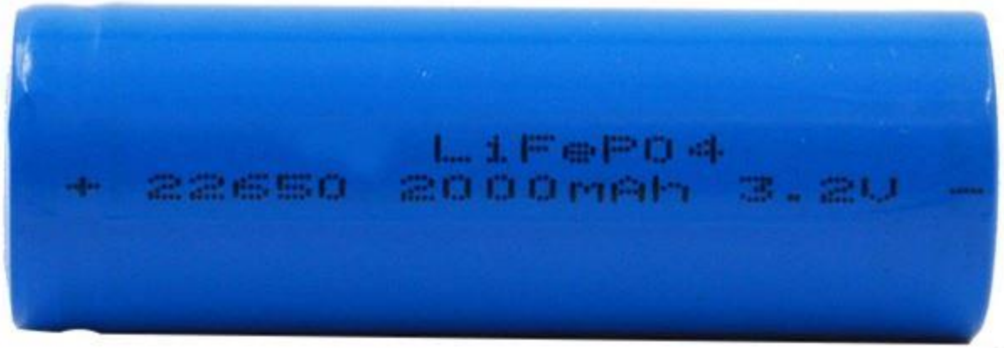


Fig: Selected reference battery cell [6]

Technical Analysis: Battery Pack Design (2/2)

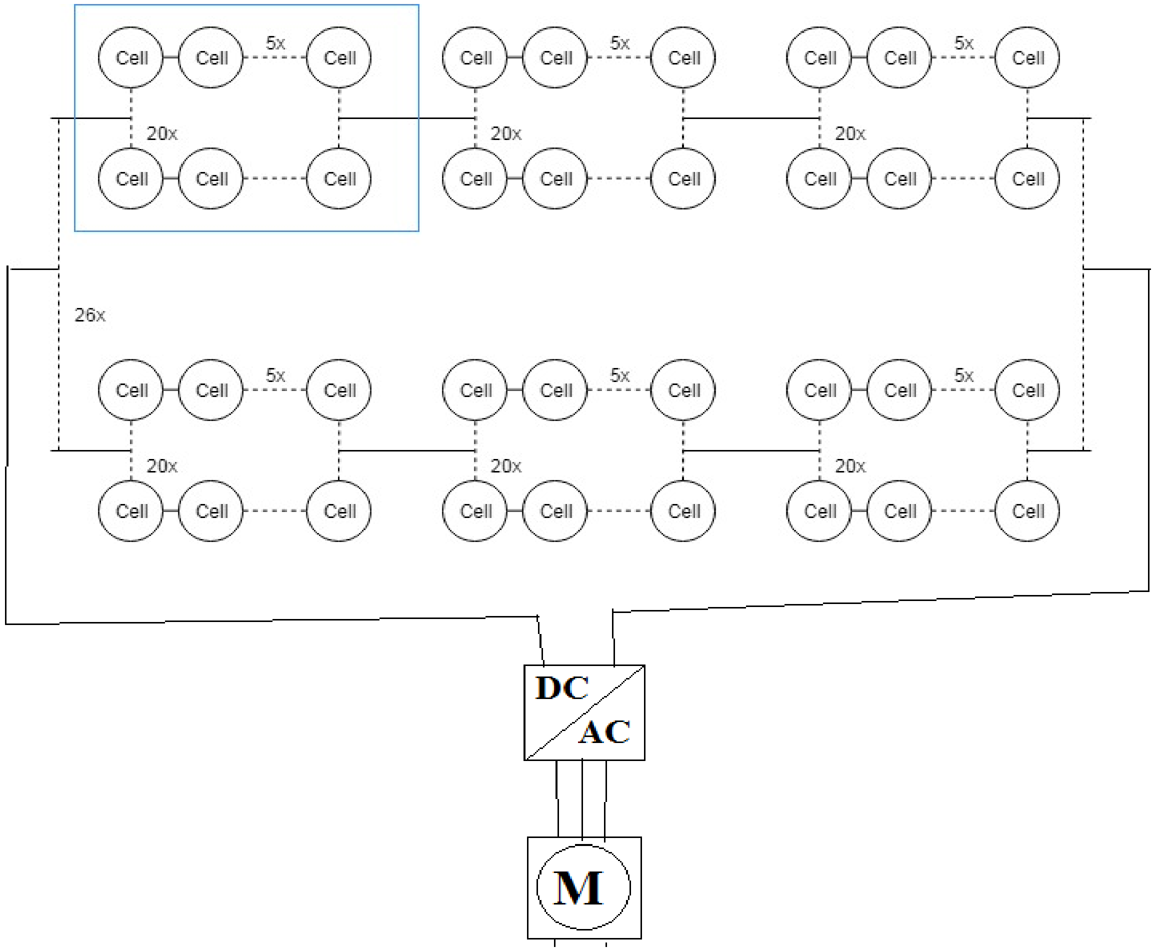


Fig. Schematic diagram of designed battery pack

Fig. Battery Pack [11]

$V_{pack} = 3.2 \times 5 = 16\,Volts$ $C_{pack} = 2\,Ah \times 20 = 40\,Ah$	One Pack: 5 Cells in Series 20 strings in parallel
$V_{total} = V_{pack} \times 3 = 48\,Volts$ $C_{total} = C_{pack} \times 26 = 1040\,Ah$	Complete Battery: 3 Packs in Series 26 strings in parallel

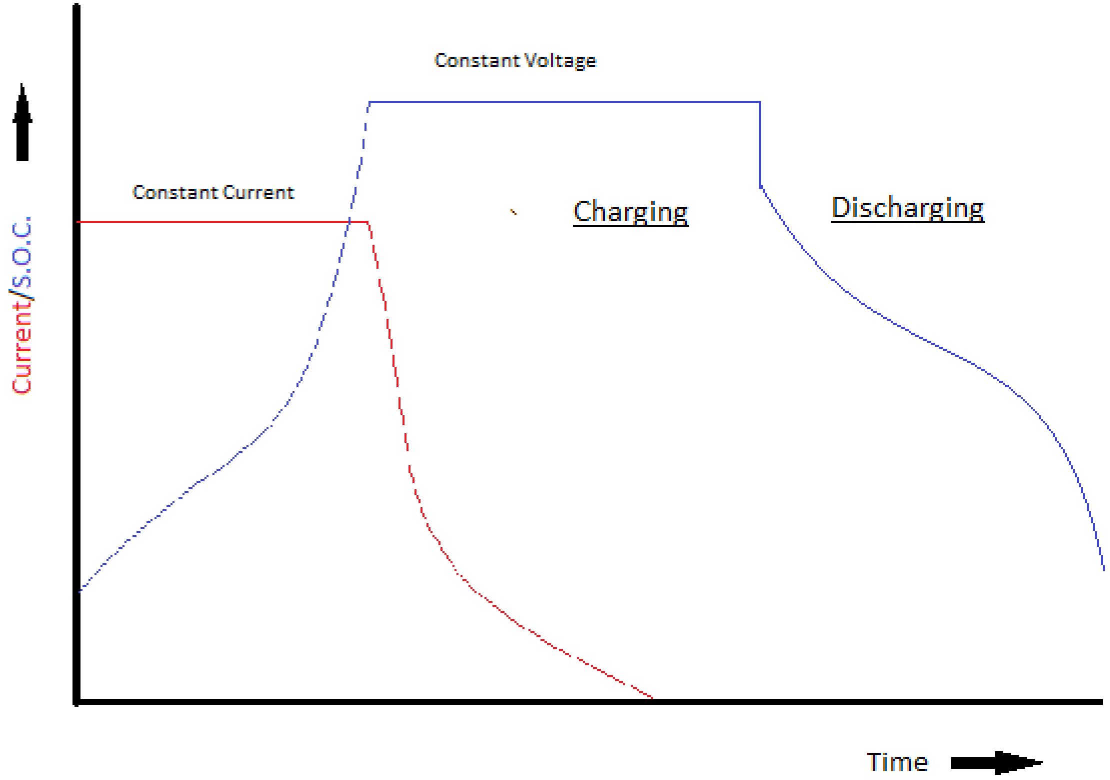
$$Number\ of\ Cells = 7800$$

Technical Analysis: Battery Pack Design – Specifications (2/2)

- Energy:
  - $C_{total} \times V_{total} = 49.92\ kWh$
- Weight:
  - $Number\ of\ Cells \times {}^{Weight}/_{Cell} = 315.9\ kg$
- Volume:
  - $Number\ of\ Cells \times {}^{Volume}/_{Cell} = 192.72\ Litre$
- Cost:
  - $Number\ of\ Cells \times {}^{Cost}/_{Cell} = 10530\ Euro$
- Lifetime
  - 310 Full Cycles a year.
  - ${}^{Cycle\ Lifetime}/_{Cycle\ in\ a\ year} = 4.8\ years\ of\ usage$

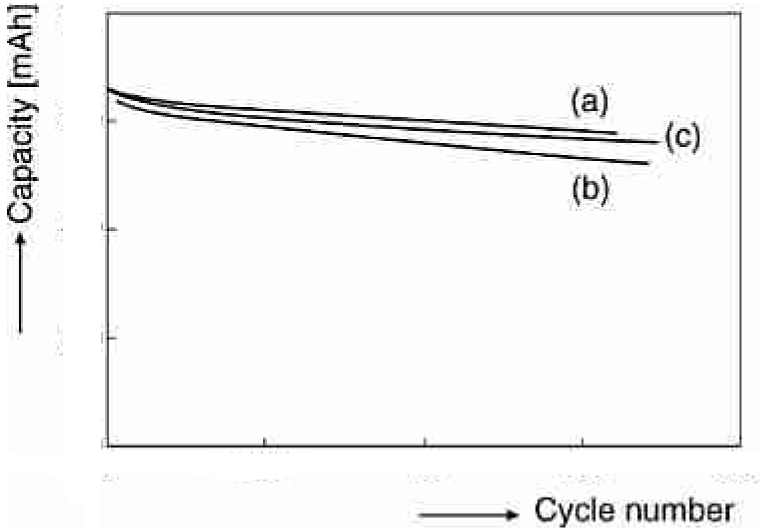
Standard Charging Strategy (1/3)

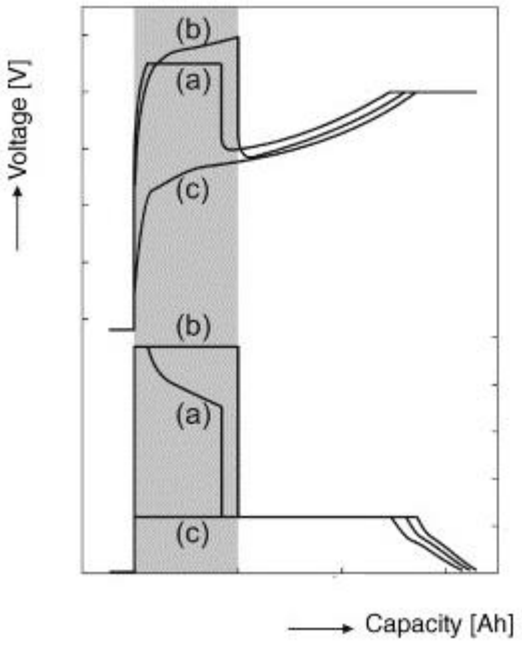
- CC-CV Charging
- Cut-off Voltage at 3.05V
- Cut-off Current at 0.05 C

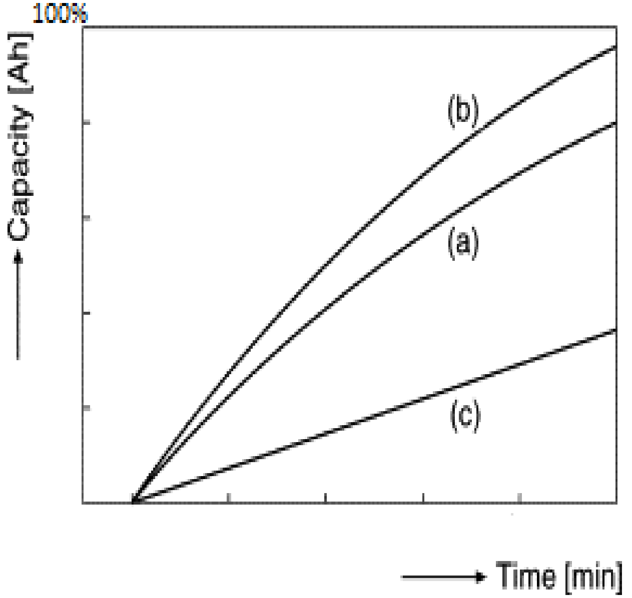


Boost Charging Strategy (2/3)

- $(CCCV)^2$ or CC-CC-CV strategy
- Even charging with extremely high currents up to 5 C-rate, does not affect the temperature change more than 10 °C.







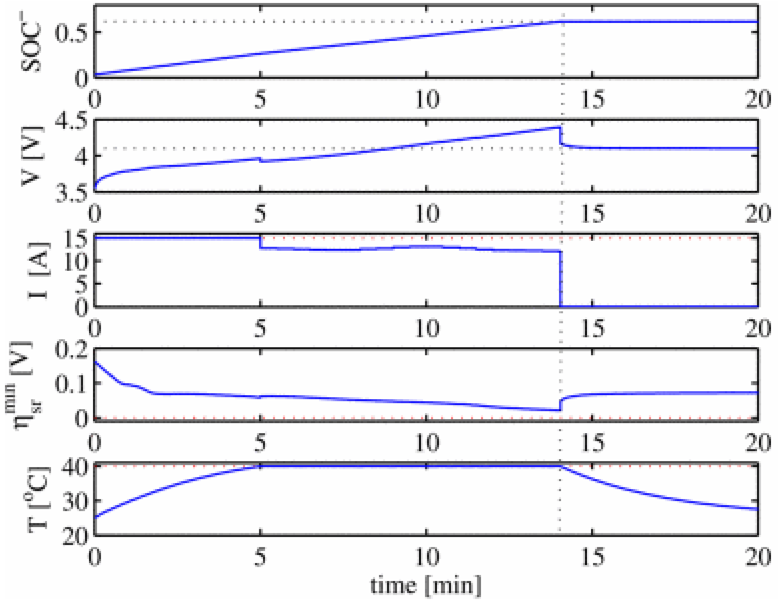
Source: P.H.L. Notten, J.H.G. O. h. Veld, and J.R.G. van Beek, “Boostcharging Li-ion batteries: A challenging new charging concept,” Journal of Power Sources, vol. 145, no. 1, pp. 89–94, 2005.

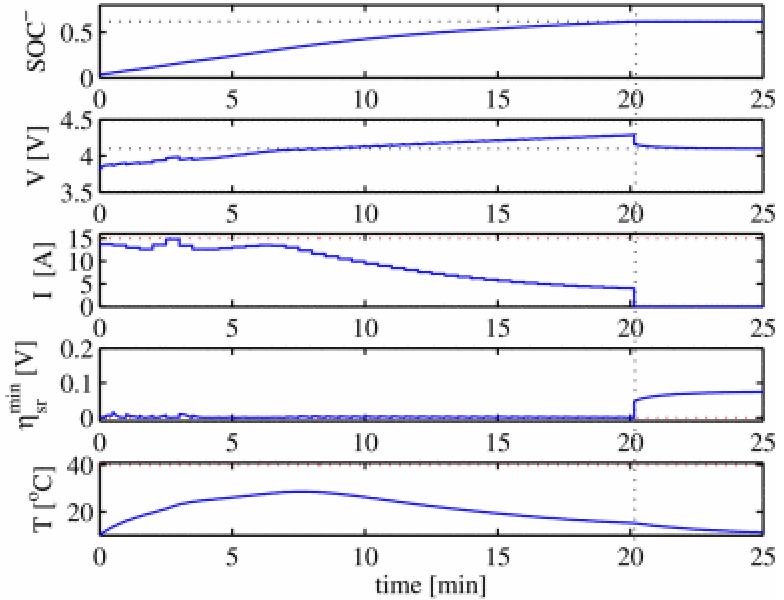
Optimal Charging Strategy (3/3)

- Three Constraints:

1. $0 \leq I(t) \leq I_{max}$
2. $T(t) \leq T_{max}$
3. $\eta_{sr}(x,t) = \phi_s(x,t) - \phi_e(x,t) > 0$

T=25°C





T=10°C

Source: R. Klein et al., “Optimal charging strategies in lithium-ion battery,” in American Control Conference (ACC), 2011: June 29 - July 1 2011, San Francisco, CA, USA, San Francisco, CA, 2011, pp. 382–387.

Battery Management System (BMS)

- Master Slave Configuration is used for Li-ion battery pack
- Voltage measurement, temperature measurement, and charge balancing are done by slave system with parallel connected blocks
- Slave transfers local information to the Master module
- Reduce wiring connection
- Communication is done by CANbus and RS-485 system

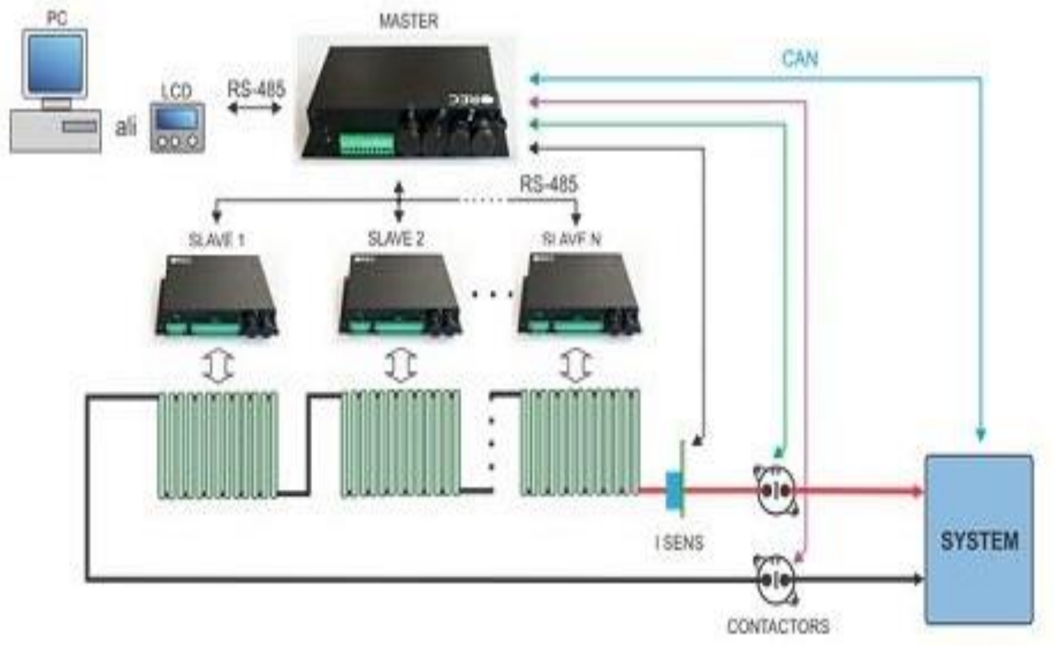


Fig: REC Battery Management System [8]

Thermal Management of Lithium-ion Battery Pack (1/2)

- Forklift batteries are usually used for high power application. So, batteries need to cool down to avoid thermodynamic instability and proper voltage distribution
- Internal short circuit, ambient temperature, and overcharging causes the battery to overheat
- Lithium plating might occur due to low temperature during the winter season and due to high charging current rate. So, battery pack need to be operated properly
- Air Cooling System is chosen for our Forklift battery system

Thermal Management of Lithium-ion Battery Pack (2/2)

- Why air cooling system? [9]
  - Lower cost
  - Simple design
  - No possibility of leakage
  - Maintenance easier
  - No requirement of separate cooling procedure
  - Elimination of the possibility of short circuit due to fluid

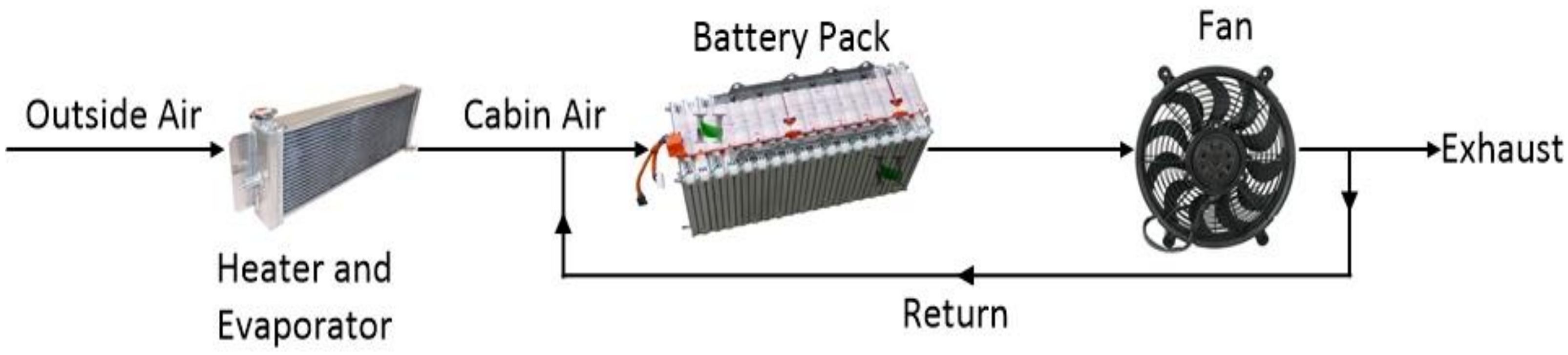


Fig: Air cooling system for Lithium-ion battery [9]

Fig: Air inlet system of Hyster Forklift [10]

Economic Analysis: Electric Forklifter (1/2)

Electrical based		
Electricity Cost [12]	0,3	Euro/kWh
Battery cells cost	10530	Euro
Operation day	310	Days/year
Energy Requirement per day	50	kWh
Annual Energy Consumption	15500	KWh/year
Annual electricity cost	4650	Euro/year
Operation & Maintenance (O&M)	1%	Total invest 1st year
BMS + Power Electronics drive [17]	1000	Euro
AC Motor [13]	2500	Euro
Battery cells years of usage	4.8	Year
Annual Interest/Discount rate	5%	
Initial Investment	14030	Euro
Cost per year	4790.3	Euro
Cost change battery	10530	Euro
Net Present Value	***-66809.15***	***Euro (For 10 Years)***
Annuity	***-8652.09***	***Euro***

Economic Analysis: Gasoline Based Forklifter (2/2)

Gasoline Based		
Cost of Forklift [14]	12500	Euro
Cost of Gasoline [15]	1.26	Per liter
Operating Hours/day	15	Hours
Operation & Maintenance (O&M)	125	1% forklift cost per year
Efficiency [16]	3	liters per hour
Operating Hours	4650	Per year
Annual Fuel Cost	13950	Euro
Initial Investment	12500	Euro
Annual Cost (Fuel cost + O&M)	14075	Euro
Annual Interest/Discount rate	5%	
Net Present Value	***-121183.42***	***Euro***
Annuity	***-15693.8***	***Euro***

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Questions

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