ELECTRIC VEHICLE TECHNOLOGY EXPLAINED

ELECTRIC VEHICLE TECHNOLOGY EXPLAINED

SECOND EDITION

James Larminie
Oxford Brookes University, UK

John Lowry
Consultant Engineer, Swindon, UK

WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2012

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Larminie, James
Electric vehicle technology explained / James Larminie, John Lowry. –
Second Edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-119-94273-3 (cloth)
1. Electric vehicles–Technological innovations. 2. Electric vehicles–
Design and construction. I. Lowry, John. II. Title.
TL220.L37 2012
629.22′93 – dc23
2012006649

A catalogue record for this book is available from the British Library.

Print ISBN: 9781119942733

Set in 10/12pt Times by Laserwords Private Limited, Chennai, India.

Contents

About the Author **xiii**

Preface **xv**

Acknowledgments **xvii**

Abbreviations **xix**

Symbols **xxiii**

1 Introduction **1**
1.1 A Brief History 2
1.1.1 Early Days 2
1.1.2 The Middle of the Twentieth Century 7
1.1.3 Developments towards the End of the Twentieth Century and the Early Twenty-First Century 8
1.2 Electric Vehicles and the Environment 13
1.2.1 Energy Saving and Overall Reduction of Carbon Emissions 14
1.2.2 Reducing Local Pollution 15
1.2.3 Reducing Dependence on Oil 15
1.3 Usage Patterns for Electric Road Vehicles 15
Further Reading 17

2 Types of Electric Vehicles – EV Architecture **19**
2.1 Battery Electric Vehicles 19
2.2 The IC Engine/Electric Hybrid Vehicle 19
2.3 Fuelled EVs 24
2.4 EVs using Supply Lines 25
2.5 EVs which use Flywheels or Supercapacitors 25
2.6 Solar-Powered Vehicles 26
2.7 Vehicles using Linear Motors 27
2.8 EVs for the Future 27
Further Reading 27

3 Batteries, Flywheels and Supercapacitors **29**
3.1 Introduction 29

3.2	Battery Parameters	30
	3.2.1 Cell and Battery Voltages	30
	3.2.2 Charge (or Amphour) Capacity	31
	3.2.3 Energy Stored	32
	3.2.4 Specific Energy	33
	3.2.5 Energy Density	33
	3.2.6 Specific Power	34
	3.2.7 Amphour (or Charge) Efficiency	34
	3.2.8 Energy Efficiency	35
	3.2.9 Self-discharge Rates	35
	3.2.10 Battery Geometry	35
	3.2.11 Battery Temperature, Heating and Cooling Needs	35
	3.2.12 Battery Life and Number of Deep Cycles	35
3.3	Lead Acid Batteries	36
	3.3.1 Lead Acid Battery Basics	36
	3.3.2 Special Characteristics of Lead Acid Batteries	38
	3.3.3 Battery Life and Maintenance	40
	3.3.4 Battery Charging	40
	3.3.5 Summary of Lead Acid Batteries	41
3.4	Nickel-Based Batteries	41
	3.4.1 Introduction	41
	3.4.2 Nickel Cadmium	41
	3.4.3 Nickel Metal Hydride Batteries	44
3.5	Sodium-Based Batteries	46
	3.5.1 Introduction	46
	3.5.2 Sodium Sulfur Batteries	47
	3.5.3 Sodium Metal Chloride (ZEBRA) Batteries	48
3.6	Lithium Batteries	50
	3.6.1 Introduction	50
	3.6.2 The Lithium Polymer Battery	50
	3.6.3 The Lithium Ion Battery	51
3.7	Metal–Air Batteries	52
	3.7.1 Introduction	52
	3.7.2 The Aluminium–Air Battery	52
	3.7.3 The Zinc–Air Battery	53
3.8	Supercapacitors and Flywheels	54
	3.8.1 Supercapacitors	54
	3.8.2 Flywheels	56
3.9	Battery Charging	59
	3.9.1 Battery Chargers	59
	3.9.2 Charge Equalisation	60
3.10	The Designer's Choice of Battery	63
	3.10.1 Introduction	63
	3.10.2 Batteries which are Currently Available Commercially	63
3.11	Use of Batteries in Hybrid Vehicles	64
	3.11.1 Introduction	64

	3.11.2 IC/Battery Electric Hybrids	64
	3.11.3 Battery/Battery Electric Hybrids	64
	3.11.4 Combinations using Flywheels	65
	3.11.5 Complex Hybrids	65
3.12	Battery Modelling	65
	3.12.1 The Purpose of Battery Modelling	65
	3.12.2 Battery Equivalent Circuit	66
	3.12.3 Modelling Battery Capacity	68
	3.12.4 Simulating a Battery at a Set Power	71
	3.12.5 Calculating the Peukert Coefficient	75
	3.12.6 Approximate Battery Sizing	76
3.13	In Conclusion	77
	References	78
4	**Electricity Supply**	**79**
4.1	Normal Existing Domestic and Industrial Electricity Supply	79
4.2	Infrastructure Needed for Charging Electric Vehicles	80
4.3	Electricity Supply Rails	81
4.4	Inductive Power Transfer for Moving Vehicles	82
4.5	Battery Swapping	84
	Further Reading	85
5	**Fuel Cells**	**87**
5.1	Fuel Cells – A Real Option?	87
5.2	Hydrogen Fuel Cells – Basic Principles	89
	5.2.1 Electrode Reactions	89
	5.2.2 Different Electrolytes	90
	5.2.3 Fuel Cell Electrodes	93
5.3	Fuel Cell Thermodynamics – An Introduction	95
	5.3.1 Fuel Cell Efficiency and Efficiency Limits	95
	5.3.2 Efficiency and the Fuel Cell Voltage	98
	5.3.3 Practical Fuel Cell Voltages	100
	5.3.4 The Effect of Pressure and Gas Concentration	101
5.4	Connecting Cells in Series – The Bipolar Plate	102
5.5	Water Management in the PEMFC	106
	5.5.1 Introduction to the Water Problem	106
	5.5.2 The Electrolyte of a PEMFC	107
	5.5.3 Keeping the PEM Hydrated	109
5.6	Thermal Management of the PEMFC	110
5.7	A Complete Fuel Cell System	111
5.8	Practical Efficiency of Fuel Cells	114
	References	114
6	**Hydrogen as a Fuel – Its Production and Storage**	**115**
6.1	Introduction	115
6.2	Hydrogen as a Fuel	117

6.3 Fuel Reforming 118
6.3.1 Fuel Cell Requirements 118
6.3.2 Steam Reforming 118
6.3.3 Partial Oxidation and Autothermal Reforming 120
6.3.4 Further Fuel Processing – Carbon Monoxide Removal 121
6.3.5 Practical Fuel Processing for Mobile Applications 122
6.3.6 Energy Efficiency of Reforming 123
6.4 Energy Efficiency of Reforming 124
6.5 Hydrogen Storage I – Storage as Hydrogen 124
6.5.1 Introduction to the Problem 124
6.5.2 Safety 124
6.5.3 The Storage of Hydrogen as a Compressed Gas 125
6.5.4 Storage of Hydrogen as a Liquid 127
6.5.5 Reversible Metal Hydride Hydrogen Stores 129
6.5.6 Carbon Nanofibres 131
6.5.7 Storage Methods Compared 131
6.6 Hydrogen Storage II – Chemical Methods 132
6.6.1 Introduction 132
6.6.2 Methanol 133
6.6.3 Alkali Metal Hydrides 135
6.6.4 Sodium Borohydride 136
6.6.5 Ammonia 140
6.6.6 Storage Methods Compared 142
References 143

7 Electric Machines and their Controllers 145
7.1 The ‘Brushed’ DC Electric Motor 145
7.1.1 Operation of the Basic DC Motor 145
7.1.2 Torque Speed Characteristics 147
7.1.3 Controlling the Brushed DC Motor 151
7.1.4 Providing the Magnetic Field for DC Motors 152
7.1.5 DC Motor Efficiency 153
7.1.6 Motor Losses and Motor Size 156
7.1.7 Electric Motors as Brakes 156
7.2 DC Regulation and Voltage Conversion 159
7.2.1 Switching Devices 159
7.2.2 Step-Down or ‘Buck’ Regulators 161
7.2.3 Step-Up or ‘Boost’ Switching Regulator 162
7.2.4 Single-Phase Inverters 165
7.2.5 Three Phase 167
7.3 Brushless Electric Motors 169
7.3.1 Introduction 169
7.3.2 The Brushless DC Motor 169
7.3.3 Switched Reluctance Motors 173
7.3.4 The Induction Motor 177
7.4 Motor Cooling, Efficiency, Size and Mass 179

	7.4.1 Improving Motor Efficiency	179
	7.4.2 Motor Mass	181
7.5	Electric Machines for Hybrid Vehicles	182
7.6	Linear Motors	185
	References	185
8	**Electric Vehicle Modelling**	**187**
8.1	Introduction	187
8.2	Tractive Effort	188
	8.2.1 Introduction	188
	8.2.2 Rolling Resistance Force	188
	8.2.3 Aerodynamic Drag	189
	8.2.4 Hill Climbing Force	189
	8.2.5 Acceleration Force	189
	8.2.6 Total Tractive Effort	191
8.3	Modelling Vehicle Acceleration	191
	8.3.1 Acceleration Performance Parameters	191
	8.3.2 Modelling the Acceleration of an Electric Scooter	193
	8.3.3 Modelling the Acceleration of a Small Car	197
8.4	Modelling Electric Vehicle Range	198
	8.4.1 Driving Cycles	198
	8.4.2 Range Modelling of Battery Electric Vehicles	204
	8.4.3 Constant Velocity Range Modelling	210
	8.4.4 Other uses of Simulations	210
	8.4.5 Range Modelling of Fuel Cell Vehicles	212
	8.4.6 Range Modelling of Hybrid Electric Vehicles	215
8.5	Simulations – A Summary	215
	References	216
9	**Design Considerations**	**217**
9.1	Introduction	217
9.2	Aerodynamic Considerations	217
	9.2.1 Aerodynamics and Energy	217
	9.2.2 Body/Chassis Aerodynamic Shape	220
9.3	Consideration of Rolling Resistance	222
9.4	Transmission Efficiency	223
9.5	Consideration of Vehicle Mass	227
9.6	Electric Vehicle Chassis and Body Design	229
	9.6.1 Body/Chassis Requirements	229
	9.6.2 Body/Chassis Layout	230
	9.6.3 Body/Chassis Strength, Rigidity and Crash Resistance	231
	9.6.4 Designing for Stability	234
	9.6.5 Suspension for Electric Vehicles	234
	9.6.6 Examples of Chassis used in Modern Battery and Hybrid Electric Vehicles	235
	9.6.7 Chassis used in Modern Fuel Cell Electric Vehicles	235

9.7	General Issues in Design	237
	9.7.1 Design Specifications	237
	9.7.2 Software in the use of Electric Vehicle Design	237
10	**Design of Ancillary Systems**	**239**
10.1	Introduction	239
10.2	Heating and Cooling Systems	239
10.3	Design of the Controls	242
10.4	Power Steering	244
10.5	Choice of Tyres	245
10.6	Wing Mirrors, Aerials and Luggage Racks	245
10.7	Electric Vehicle Recharging and Refuelling Systems	245
11	**Efficiencies and Carbon Release Comparison**	**247**
11.1	Introduction	247
11.2	Definition of Efficiency	248
11.3	Carbon Dioxide Emission and Chemical Energy in Fuel	248
12	**Electric Vehicles and the Environment**	**253**
12.1	Introduction	253
12.2	Vehicle Pollution – The Effects	253
12.3	Vehicle Pollution in Context	256
12.4	The Role of Regulations and Lawmakers	256
	Further Reading	258
13	**Power Generation for Transport – Particularly for Zero Emissions**	**259**
13.1	Introduction	259
13.2	Power Generation using Fossil Fuels	260
13.3	Alternative and Sustainable Energy	260
	13.3.1 Solar Energy	260
	13.3.2 Wind Energy	262
	13.3.3 Hydroelectricity	263
	13.3.4 Tidal Energy	264
	13.3.5 Marine Currents	266
	13.3.6 Wave Energy	266
	13.3.7 Biomass Energy	267
	13.3.8 Obtaining Energy from Waste	267
	13.3.9 Geothermal Energy	267
13.4	Nuclear Energy	267
	13.4.1 Nuclear Fission	267
	13.4.2 Nuclear Fusion	268
13.5	In Conclusion	269
	Further Reading	269
14	**Recent Electric Vehicles**	**271**
14.1	Introduction	271

14.2	Low-Speed Rechargeable Battery Vehicles	271
	14.2.1 Electric Bicycles	271
	14.2.2 Electric Mobility Aids	272
	14.2.3 Low-Speed Vehicles	274
14.3	Battery-Powered Cars and Vans	274
	14.3.1 Peugeot 106 and the Partner	274
	14.3.2 The GM EV1	275
	14.3.3 The Nissan Leaf	279
	14.3.4 The Mitsubishi MiEV	279
14.4	Hybrid Vehicles	279
	14.4.1 The Honda Insight	280
	14.4.2 The Toyota Prius	281
	14.4.3 The Chevrolet Volt	283
14.5	Fuel-Cell-Powered Bus	284
14.6	Conventional High-Speed Trains	286
	14.6.1 Introduction	286
	14.6.2 The Technology of High-Speed Trains	288
14.7	Conclusion	289
	References	290
15	**The Future of Electric Vehicles**	**291**
15.1	Introduction	291
15.2	The Tesla S	291
15.3	The Honda FCX Clarity	292
15.4	Maglev Trains	292
15.5	Electric Road–Rail Systems	294
15.6	Conclusion	295
	Further Reading	296
Appendices: MATLAB® Examples		**297**
	Appendix 1: Performance Simulation of the GM EV1	297
	Appendix 2: Importing and Creating Driving Cycles	298
	Appendix 3: Simulating One Cycle	300
	Appendix 4: Range Simulation of the GM EV1 Electric Car	302
	Appendix 5: Electric Scooter Range Modelling	304
	Appendix 6: Fuel Cell Range Simulation	306
	Appendix 7: Motor Efficiency Plots	308
Index		**311**

About the Author

John Lowry is a professional engineer who graduated in Mechanical Engineering from Imperial College, London University. He holds a PhD from Queen Mary College, London University. He was formerly a university lecturer and is currently a consultant engineer. He is a Fellow of the Institution of Mechanical Engineers, the Institute of Energy and the Institute of Engineering and Technology.

Preface

Electric vehicle technology is now in its third century of development and is likely to advance rapidly in the coming years.

Electric trains are widely used and modern high-speed trains are competitive with air travel in terms of journey speed over shorter land routes. In energy terms they use less than 10% of the fuel per passenger kilometre than air transport.

Electric road vehicles have not achieved the commercial success that internal combustion engine vehicles have; however, battery technology has now developed to the point where electric vehicles are being commercially produced. Future battery developments are likely to accelerate the use of electric road vehicles in the next few years.

Small electric vehicles such as golf buggies and personnel carriers in airports have become well established. Electric bicycles are becoming increasingly popular and are considered one of the fastest ways to move about crowded cities.

Potential environmental benefits which can result from the use of electric vehicles are substantial when the vehicles use electricity that is generated from sources which use highly efficient modern generating stations or which use nuclear or sustainable energy. Environmental benefits include zero exhaust emissions in the vicinity of the vehicles, reduced dependence on fossil fuels and reduced overall carbon emissions.

This book explains both the technology of electric vehicles and how they affect the environment. The book is designed for engineers and scientists who require a thorough understanding of electric vehicle technology and its effects on the environment.

John Lowry

Acknowledgments

The authors would like to put on record their thanks to the following companies and organisations that have made this book possible:

Ballard Power Systems Inc., Canada
DaimlerChrysler Corp., USA and Germany
The Ford Motor Co., USA
FreeGo Electric Bikes Ltd, UK
General Motors Corp., USA
GfE Metalle und Materialien GmbH, Germany
Groupe Enerstat Inc., Canada
Hawker Power Systems Inc., USA
The Honda Motor Co. Ltd
Johnson Matthey Plc, UK
MAN Nutzfahrzeuge AG, Germany
MES-DEA SA, Switzerland
Micro Compact Car Smart GmbH
Mitsubishi Motors Corporation
National Motor Museum Beaulieu
Nissan Motor Manufacturing (UK) Ltd
Parry People Movers Ltd, UK
Paul Scherrer Institute, Switzerland
Peugeot SA, France
Powabyke Ltd, UK
Richens Mobility Centre, Oxford, UK
Saft Batteries, France
SR Drives Ltd, UK
Tesla Motors Inc.

Toyota Motor Co. Ltd
Wamfler GmbH, Germany
Varta/Johnson Controls
Zytek Group Ltd, UK

In addition we would like to thank friends and colleagues who have provided valuable comments and advice. We are also indebted to our families who have helped and put up with us while we devoted time and energy to this project. Special thanks are also due to Dr Peter Moss, formerly of The Defence Academy, Cranfield University, for reading and commenting on the draft manuscript.

Abbreviations

ABS	Anti-lock brake system
AC	Alternating current
AFC	Alkaline fuel cell
BLDC	Brushless DC (motor)
BOP	Balance of plant
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CARB	California Air Resources Board
CCGT	Combined cycle gas turbine
CFD	Computational fluid dynamics
CHP	Combined heat and power
CJR	Central Japan Railway
CNG	Compressed natural gas
CPO	Catalytic partial oxidation
DC	Direct current
DMFC	Direct methanol fuel cell
DOH	Degree of hybridisation
DOHC	Double overhead cam
ECCVT	Electronically controlled continuous variable transmission
ECM	Electronically commutated motor
EFTC	Electric Fuel Transportation Company
EMF	Electromotive force
EPA	Environmental Protection Agency
EPS	Electric power steering
ETSU	Energy Technology Support Unit (a UK government organisation)
EUDC	Extra-Urban Driving Cycle
EV	Electric vehicle
FC	Fuel cell
FCV	Fuel cell vehicle
FHDS	Federal Highway Driving Schedule
FUDS	Federal Urban Driving Schedule
GM	General Motors
GM EV1	General Motors Electric Vehicle 1

GNF	Graphitic nanofibre
GRP	Glass reinforced plastic
GTO	Gate turn-off
HEV	Hybrid electric vehicle
HHV	Higher heating value
HSR	High-speed rail
HSST	High-speed surface train
IC	Internal combustion
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IGBT	Insulated gate bipolar transistor
IMA	Integrated Motor Assist
IPT	Inductive power transfer
JET	Joint Euorpean Torus
kph	Kilometres per hour
LH_2	Liquid (cryogenic) hydrogen
LHV	Lower heating value
LIB	Lithium ion battery
LPG	Liquid petroleum gas
LSV	Low-speed vehicle
MCFC	Molten carbonate fuel cell
MeOH	Methanol
MEA	Membrane electrode assembly
MOSFET	Metal oxide semiconductor field effect transistor
mph	Miles per hour
NASA	National Aeronautics and Space Administration
NEDC	New European Driving Cycle
NiCad	Nickel cadmium (battery)
NiMH	Nickel metal hydride (battery)
NL	Normal litre, 1 litre at NTP
NOx	Nitrous oxides
NTP	Normal temperature and pressure (20 °C and 1 atm or 1.013 25 bar)
OCV	Open-circuit voltage
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane OR polymer electrolyte membrane (different names for the same thing which fortunately have the same abbreviation)
PEMFC	Proton exchange membrane fuel cell OR polymer electrolyte membrane fuel cell
PM	Permanent magnet OR particulate matter
POX	Partial oxidation
ppb	Parts per billion
ppm	Parts per million
PROX	Preferential oxidation
PSA	Pressure swing absorption

PTFE	Polytetrafluoroethylene
PZEV	Partial zero-emission vehicle
RRIM	Reinforced reaction injection moulding
SAE	Society of Automotive Engineers
SFUDS	Simplified Federal Urban Driving Schedule
SL	Standard litre, 1 litre at STP
SLI	Starting, lighting and ignition
SMC	Sheet moulding compound
SOC	State of charge
SOFC	Solid oxide fuel cell
SRM	Switched reluctance motor
STP	Standard temperature and pressure
SULEV	Super ultra-low-emission vehicle
SUV	Sports utility vehicle
TDI	Toyota Direct Ignition
TGV	*Train à grande vitesse*
VOC	Volatile organic compound
VRLA	Valve-regulated (sealed) lead acid (battery)
WOT	Wide open throttle
ZEBRA	Zero Emissions Battery Research Association
ZEV	Zero-emission vehicle

Symbols

Letters are used to stand for variables, such as mass, and also as chemical symbols in chemical equations. The distinction is usually clear from the context, but for even greater clarity italics are used for variables and ordinary text for chemical symbols, so H stands for enthalpy, whereas H stands for hydrogen.

In cases where a letter can stand for two or more variables, the context always makes it clear which is intended.

a	Acceleration
A	Area
B	Magnetic field strength
C	Amphour capacity of a battery OR capacitance of a capacitor
C_3	Amphour capacity of a battery if discharged in 3 hours, the '3 hour rate'
C_d	Drag coefficient
C_p	Peukert capacity of a battery, the same as the amphour capacity if discharged at a current of 1 amp
CR	Charge removed from a battery, usually in amphours
CS	Charge supplied to a battery, usually in amphours
d	Separation of the plates of a capacitor, OR distance travelled
DoD	Depth of discharge, a ratio changing from 0 (fully charged) to 1 (empty)
e	Magnitude of the charge on one electron, 1.602×10^{-19} coulombs
E	Energy OR Young's modulus OR EMF (voltage)
E_b	Back EMF (voltage) of an electric motor in motion
E_f	Field winding
E_s	Supplied EMF (voltage) to an electric motor
f	Frequency
F	Force OR Faraday constant, the charge on 1 mole of electrons, 96 485 coulombs
F_{ad}	Force needed to overcome the wind resistance on a vehicle
F_{la}	Force needed to give linear acceleration to a vehicle
F_{hc}	Force needed to overcome the gravitational force of a vehicle down a hill
F_{rr}	Force needed to overcome the rolling resistance of a vehicle
F_{te}	Tractive effort, the forward driving force on the wheels

$F_{\omega a}$	Force at the wheel needed to give rotational acceleration to the rotating parts of a vehicle
g	Acceleration due to gravity
G	Gear ratio OR rigidity modulus OR Gibbs free energy (negative thermodynamic potential)
H	Enthalpy
I	Current OR moment of inertia OR second moment of area (the context makes it clear)
I_m	Motor current
J	Polar second moment of area
k	Peukert coefficient
k_c	Copper losses coefficient for an electric motor
k_i	Iron losses coefficient for an electric motor
k_w	Windage losses coefficient for an electric motor
KE	Kinetic energy
K_m	Motor constant
L	Length
m	Mass
$\dot{m}$	Mass flowrate
m_b	Mass of batteries
n	Number of cells in a battery OR a fuel cell stack OR the number of moles of substance
N	Avogadro's number, 6.022×10^{23}, OR revolutions per second
P	Power OR pressure
P_{adb}	Power from the battery needed to overcome the wind resistance on a vehicle
P_{adw}	Power at the wheels needed to overcome the wind resistance on a vehicle
P_{hc}	Power needed to overcome the gravitational force of a vehicle down a hill
$P_{mot\text{-}in}$	Electrical power supplied to an electric motor
$P_{mot\text{-}out}$	Mechanical power given out by an electric motor
P_{rr}	Power needed to overcome the rolling resistance of a vehicle
P_{te}	Power supplied at the wheels of a vehicle
q	Sheer stress
Q	Charge (e.g. in a capacitor)
r	Radius, of wheel, axle, OR the rotor of a motor, etc.
R	Electrical resistance OR the molar gas constant $8.314\,\mathrm{J\,K^{-1}\,mol^{-1}}$
r_i, r_o	Inner and outer radius of a hollow tube
R_a	Armature resistance of a motor or generator
R_L	Resistance of a load
S	Entropy
SE	Specific energy
T	Temperature OR Torque OR the discharge time of a battery in hours
T_1, T_2	Temperatures at different stages in a process
T_f	Frictional torque (e.g. in an electric motor)
t_{ON}, t_{OFF}	On and off times for a chopper circuit
v	Velocity

V	Voltage
W	Work done
z	Number of electrons transferred in a reaction
δ	Deflection
δt	Time step in an iterative process
Δ	Change in ..., e.g. ΔH = change in enthalpy
ε	Electrical permittivity
η	Efficiency
η_c	Efficiency of a DC/DC converter
η_{fc}	Efficiency of a fuel cell
η_g	Efficiency of a gearbox
η_m	Efficiency of an electric motor
η_o	Overall efficiency of a drive system
θ	Angle of deflection or bend
λ	Stoichiometric ratio
μ_{rr}	Coefficient of rolling resistance
ρ	Density
σ	Bending stress
Φ	Total magnetic flux
ψ	Angle of slope or hill
ω	Angular velocity