AUTOMOTIVE SERIES

THERMAL ENERGY MANAGEMENT IN VEHICLES

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Thermal Energy Management in Vehicles

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Contents

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Nomenclature

List of Abbreviations

AC	accumulator
A/C	air-conditioning
ACAC	air-cooled charge air cooler
BDC	bottom dead center
BEV	battery electric vehicle
BMEP	brake mean effective pressure
BMS	battery management system
BPHEX	Brazed Plate Heat Exchanger
BTM	battery thermal management
BTMS	battery thermal management system
BOL	beginning of life
CAC	charge air cooler
CC	cooler core
CFC	chlorofluorocarbon
COP	coefficient of performance
CP	compressor
DN	direct normal
DOC	diesel oxidation catalyst
DP	damper
DPF	diesel particulate filter
ECV	externally controlled valve
EG	ethylene glycol
EGR	exhaust gas recirculation
EGRC	exhaust gas recirculation cooler
EHRS	exhaust heat recovery system
EM	electric motor
EOL	end of life
EREV	extended range electric vehicle
EV	electric vehicle
EXV	electronic expansion valve
HC	hydrocarbon
HEV	hybrid electric vehicle
HP	high pressure
FC	fuel cell

FCEV	fuel cell electric vehicle
FMEP	friction mean effective pressure
GWP	global warming potential
HC	heater core
HVAC	heating, ventilation, and air-conditioning
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HHV	high heating value
ICD	internal condenser
ICE	internal combustion engine
ICT	information and communications technology
ICV	internally controlled valve
IEV	internal evaporator
IMEP	indicated mean effective pressure
IR	infrared
LHV	low heating value
LP	low pressure
LT	low temperature
MEP	mean effective pressure
NEDC	new European driving cycle
NTU	number of transfer units
ORC	organic Rankine cycle
OCR	oil circulation ratio
OCV	open circuit voltage
OHEX	outdoor heat exchanger
OT	orifice tube
PCM	phase change material
PE	power electronics
PHEV	plug-in hybrid electric vehicle
PMV	predicted mean vote
PPD	predicted percent dissatisfied
PTC	positive temperature coefficient
PVB	polyvinyl butyral
RC	Rankine cycle
RMS	root mean square
SCR	selective catalytic reduction
SHGC	solar heat gain coefficient
SHR	sensible heat ratio
SOC	state of charge
SOH	state of health
TDC	top dead center
TIM	thermal interface material
TXV	thermostatic expansion valve
WCAC	water-cooled charge air cooler
WCD	water-cooled condenser
WLTP	worldwide harmonized light vehicles test procedure
ZEV	zero emission vehicle

Nomenclature

a	specific Gibbs free energy [J kg^{-1}]
A	area [m^2]
AU	conductance [W K^{-1}]
B	bore [m]
c	specific heat [J kg^{-1} K^{-1}]
C	speed, velocity [m s^{-1}]
C	heat capacity [J K^{-1}]
C	clearance factor [–]
C	concentration [–]
e	specific total energy [J kg^{-1}]
e	thickness [m]
e	amount of excess air [–]
E	total energy [J]
E	emissive power [W m^{-2}]
f	fuel–air ratio [–]
F	force [N]
F	view factor [–]
g	gravitational acceleration [m s^{-2}]
g	specific Helmoltz free energy [J kg^{-1}]
G	irradiation [W m^{-2}]
h	specific enthalpy [J kg^{-1}]
h	convective heat transfer coefficient [W m^{-2}K^{-1}]
H	enthalpy [J]
H	height [m]
i	working cycle frequency [–]
I	irradiance [W m^{-2}]
I	electric current [A]
k	spring constant [N m^{-1}]
k	thermal conductivity [W m^{-1}K^{-1}]
L	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
MM	molar mass [kg kmol^{-1}]
n	number [–]
N	rotational speed [Hz]
P	pressure [Pa]
q	heat flux [W m^{-2}]
$\dot{Q}$	rate of heat transfer [W]
r	ratio [–]
R	heat transfer resistance [K W^{-1}]
RH	relative humidity [–]
rpm	rotational speed [rpm]
T	temperature [°C or K]
s	specific entropy [J kg^{-1} K^{-1}]
S	entropy [J K^{-1}]
S	stroke [m]

t	time [s]
T	torque [N m]
u	specific internal energy [J kg^{-1}]
U	internal energy [J]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
v	specific volume [m^{3} kg^{-1}]
V	volume [m^{3}]
$\dot{V}$	volume flow rate [m^{3} s^{-1}]
Vol	volume [m^{3}]
w	specific work [J kg^{-1}]
W	work [J]
$\dot{W}$	power [W]
x	displacement, distance [m]
x	quality [−]
X	ratio [−]
X	concentration [ppm]
z	elevation, altitude [m]

Subscripts

a	acceleration
a	air
adiab	adiabatic
amb	ambient
atm	atmospheric
$\mathit{a}$vg	average
$\mathit{a}$ux	auxiliaries
b	boundary
b	black body
bod	body
c	cold
c	cylinder
c	combustion
c	cutoff
c	convection
cab	cabin
cc	combustion chamber
cd	condenser
cl	cloth
cond	conduction
cond	condensate
cool	coolant
cp	compressor
cr	crank chamber
CV	control volume
d	displacement
d	diffuse

d	discharge
diff	diffusion
dh	diffuse horizontal
dp	dew point
el	electric, electrical
eng	engine
eq	equivalent
ex	exhaust
exf	exfiltration
exp	expander
ev	evaporator
f	saturated liquid
f	fluid
f	fuel
f	fin
f	free
f	final
form	formation
fric	friction
g	gravity
g	saturated vapor
g	gas
gc	gas cooler
gen	generated
gw	glycol water (coolant)
glaz	glazing
h	hydraulic
h	hot
ha	humid air
he	heat engine
i	initial
in	inside, indoor, internal
in	indicated
inf	infiltration
int	internally
k	kinetic
l	liquid
l	leakage
lat	latent
m	maximum
m	mechanical
m	metabolism
m	masses
mech	mechanical
mod	module
n	natural
o	operative
occ	occupant

out	outside, outdoor
p	constant pressure
p	potential
p	piston
plas	plastic
pp	pump
r	radiated
r	refrigerant
rad	radiator
rec	recirculated
ref	reference
rel	relative
rev	reversible
s	isentropic
s	surface
s	swept
s	solar
sa	sol-air
sat	saturated
sens	sensible
sf	secondary fluid
sh	shaft
sk	skin
st	stoichiometric
su	supply
surf	surface
th	thermal
th	theoretical
tot	total
tp	two-phase
turb	turbine
v	constant volume
v	vapor
vent	ventilation
w	water
w	wall
wb	wetbulb
wf	working fluid
wg	waste gate
0	at 0°C
0	clearance
II	second Law of Thermodynamics
∞	freestream

Exponents

$^{\circ}$	ideal gas contribution
^{r}	residual contribution

Greek Symbols

α	absorptivity [–]
β	solar altitude [rad]
γ	specific heat ratio [–]
Δ	difference [–]
ε	emissivity [–]
ε	effectiveness [–]
η	efficiency [–]
θ	specific total energy of flowing fluid [J kg^{-1}]
θ	crank angle [rad]
λ	wavelength [m]
μ	dynamic viscosity [kg $\text{m}^{-1}\text{s}^{-1}$]
ρ	density [kg m^{-3}]
ρ	reflectivity [–]
σ	Stefan–Boltzmann constant [5.67×10^{-8} W $\text{m}^{-2}\text{K}^{-4}$]
Σ	surface tilt angle [rad]
τ	transmissivity [–]
τ	time [s]
ϕ	solar azimuth [rad]
Φ	equivalence ratio [–]
ψ	surface azimuth [rad]
ω	specific humidity [kg kg^{-1}]

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/lemort/thermal

This website includes:

- EES files

Introduction

1 Genesis

The paternity of the automobile is still debated between several inventors among whom are Francesco di Giorgio Martin (1470), Roberto Valturio (1472), or Leonardo da Vinci whose sketches can be found in the Codex Atlantico (1478) and whose drawings are preserved in his engineering notebooks. A study of a self-propelled wagon probably for a theatrical machine, able to move for a short stretch on a stage, is known. For a long time, it was wrongly interpreted as a kind of ancestor of the automobile (Figure 1).

However, thanks to the first functional models of the Belgian Jesuit Ferdinant Verbiest (1623–1688), we can discover the description of a thermodynamic system that allows the movement of the vehicle. In 1672, to put into practice his studies on boilers, he installed one on a small cart. The jet of steam actuated a paddle wheel which drove the wheels through a set of gears.

The drawing in Figure 2 is by the hand of the inventor, as in his description, published in 1685, in Latin, in his treatise “Astronomia Europea.”

The Frenchman Joseph Cugnot presented his “Fardier (or steamer)” developed during the period 1769–1771, a cart propelled by a steam boiler. As shown in Figure 3, it was difficult to brake the steamer, leading to probably the first car accident in history.

Other models followed, but steam propulsion was a stalemate in terms of the relationship between weight and performance. This is how the automobile evolved towards the electric car. The first electric car model was built by Sibrandus Stratingh (1835).

We could not resist quoting Camille Jenatzy’s electric car, “La Jamais contente (or Never-Happy)” (Figure 4). This is the first motor vehicle to reach the $100\,\mathrm{km\,h^{-1}}$ mark.

This electric car, in the shape of a torpedo on wheels, set this record on 29 April 1899 in Achères (France).

The first times of the electric car remained chaotic and inefficient. So, the German Carl Benz built the first automobile in history driven by a thermal engine (1886).

Several revolutions followed that led to changes to steam engines, electric, gasoline, diesel, fuel cell, and electric propulsion again.

Each time, the thermal systems have been adapted or reinvented themselves to meet the new challenges that the automotive industry has encountered. The necessary revolution towards carbon neutrality has accelerated those changes.

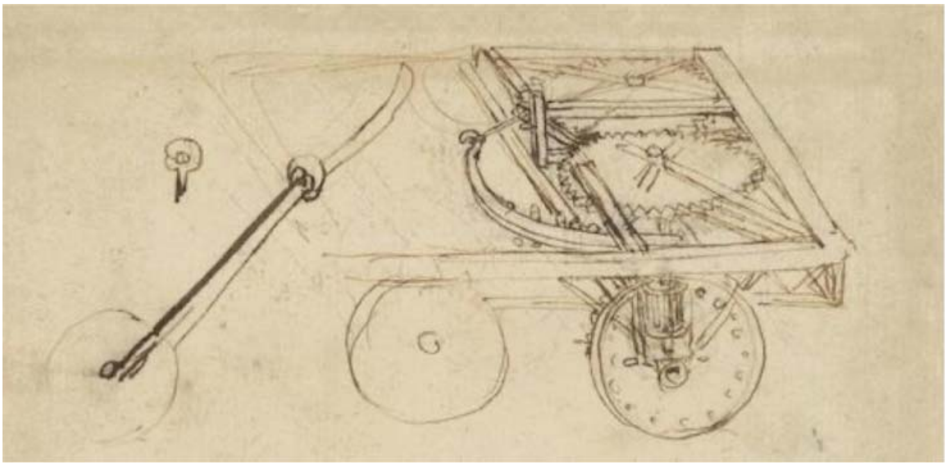

Figure 1 Self-propelled wagon as drawn by da Vinci. Source: Leonardo da Vinci – http://history-computer.com, public domain, https://commons.wikimedia.org/w/index.php?curid=14619567.

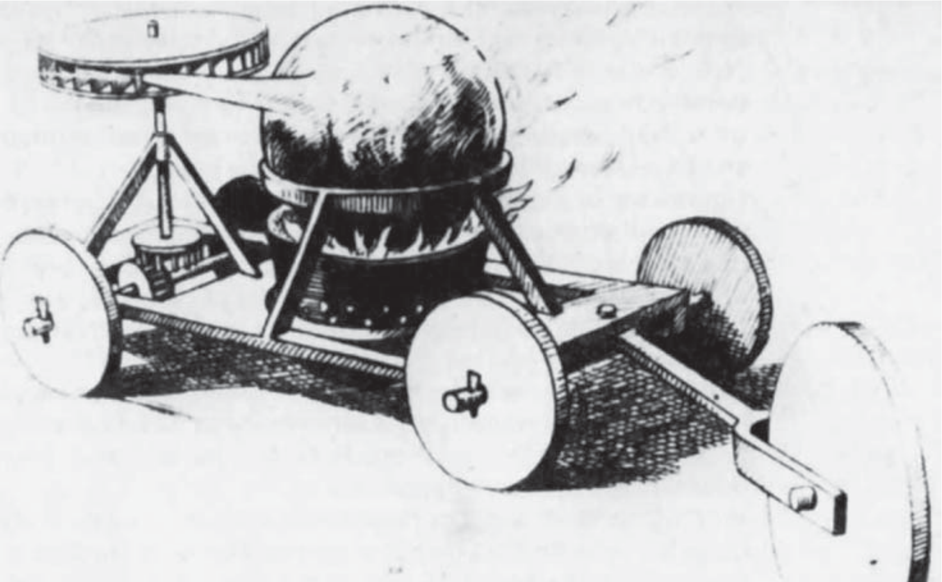

Figure 2 One of the first steam-driven cars by Belgian Ferdinant Verbiest. Source: Unknown author/Wikimedia/Public Domain.

Figure 3 Cugnot's Steamer ("Fardier de Cugnot"), tested in Paris in 1770.

Figure 4 "La Jamais contente (or Never-Happy)". Source: Unknown author/Wikimedia/Public Domain.

2 Vectors of Evolution of Thermal Systems

The vectors of the evolution of the automobile world and of its motorization were successively: a race for speed record, increase in the reliability of the engines, increase in the specific power of the engines, introduction of heating and then of air conditioning of the passenger compartment, reduction of vehicle consumption, regulatory constraints governing the environmental impact of engines, reduction in vehicle weight, conservation of the autonomy of electric vehicles, and finally, an improved comfort for passengers of electric and autonomous vehicles.

With each step, the thermal management of the vehicle has evolved toward more performance and functionality, less weight, and lower cost.

To cope with these new challenges, the number of independent thermal systems has increased initially, their interconnection has evolved, and today, many of these systems are fully connected to ensure optimal energy management.

3 The Regulatory Constraints of Change

Pollution regulations have been important vectors for the evolution of propulsion systems and they asked for the energy sobriety of the auxiliaries (all components and systems not directly contributing to propulsion, such as heating, air-conditioning, battery thermal management systems, etc.)

The evolution of the allowed emission limits, in CO_2 per kilometer, for the four main geographical areas, namely the USA, Europe, Japan, and China, is shown in Figure 5.

European CO_2 pollution standards imposed since 1992 refer to the New European Driving Cycle (NEDC). In addition to CO_2 reduction, the European regulations have imposed limitations on emissions of other pollutants, including NO_x, CO, particulate matter (PM), and $HC + NO_x$.

As an example, Figure 6 gives the allowed emission limits for diesel engines from July 1992 (Euro 1) to September 2015 (Euro 6).

To comply with these emission regulations, car manufacturers and tier one suppliers have developed major new systems such as turbocharger, fuel direct injection, high-pressure and low-pressure

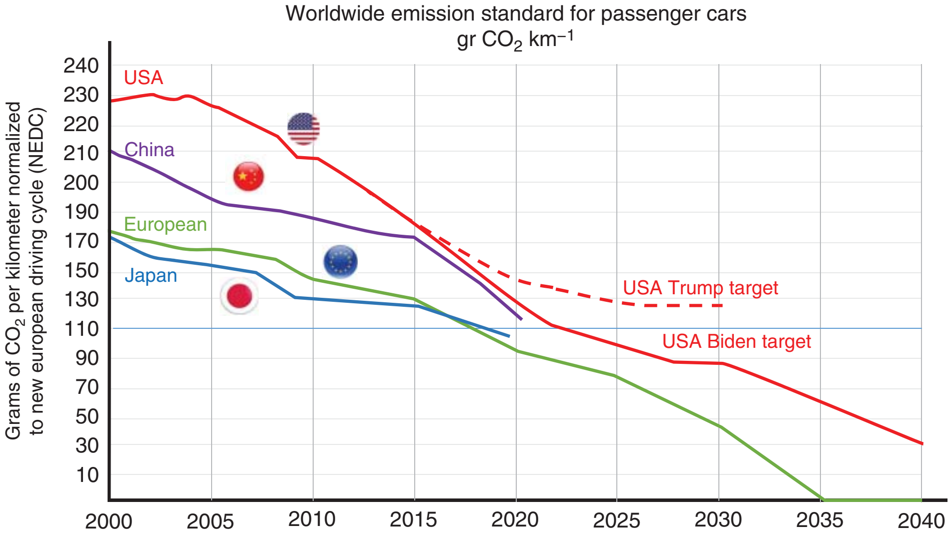

Figure 5 Yearly evolution of the allowed emission limits in CO_2 per kilometer.

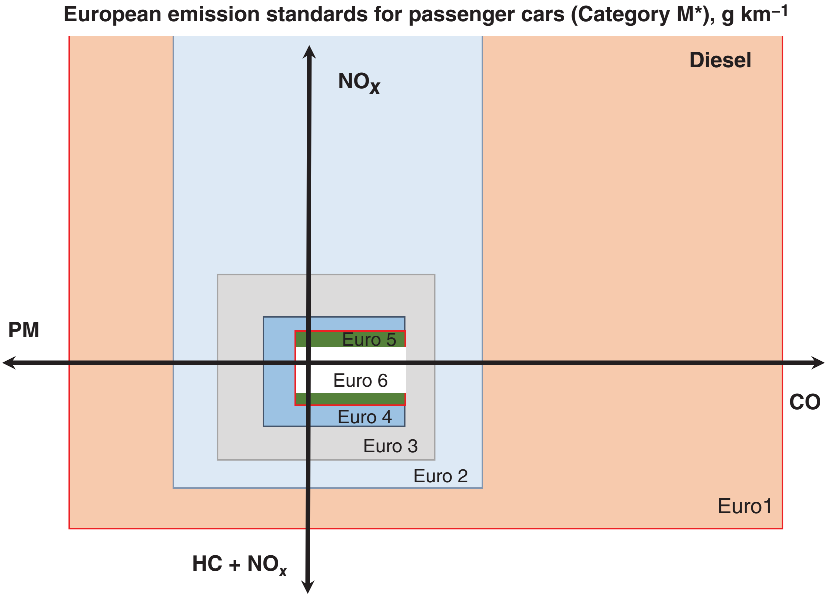

Figure 6 Allowed emission limits for diesel engines from Euro 1 (1992) to Euro 6 (2015) regulations.

exhaust gas recirculation systems (EGR), selective catalytic reduction (SCR), and diesel particulate filter (DFP).

Each of these systems requires optimal operating conditions and specific cooling or heating systems, which have complicated the thermal architecture of the vehicle.

The introduction of electrical motorization created new demands, which included cooling of the battery, fast cooling of the battery during charging, and compensation of the thermal deficit in winter for passenger comfort, and the problem is even more important for fuel cell systems.

The optimization of thermal energy for full electric vehicles is no more an option but a condition to secure vehicle range.

Despite the demands for reduction in the consumption of internal combustion engine vehicles following the oil crises (1973 and 1979) and finally since 1992, the increasingly stringent depollution regulations enacted, the GHG (greenhouse gas) emissions of the transport sector are the only one increasing compared to other sectors responsible of GHG emissions (power generation, industry, buildings, etc.). The index shown in Figure 7 is a relative measurement of the emissions of gases responsible for the greenhouse effect.

In addition, the share of road transport represents 11.9% of GHG emissions. Figure 8 shows the distribution of the GHG emission per sector. The energy sector represents 73.2% of the global emissions.

For this reason and following the Diesel Gate (2008–2015), state and city standards have been tightened, and the NEDC standard has been replaced by the worldwide harmonized light vehicles test procedure (WLTP) standard, which represents more real-time driving of the vehicle by integrating the consumption of accessories.

Furthermore, real driving emissions (RDE) pollution standards were introduced. These standards refer to a fleet of vehicles in real use during their lifetime and not only for a new vehicle.

Figure 9 shows that the reduction of the pollution has accelerated mainly after the Diesel Gate.

Figure 10 shows a schematic illustration of average CO_2 emission levels in the EU between 2014 and 2030, assuming a 3.9% per year and 6.8% per year CO_2 reduction scenario.

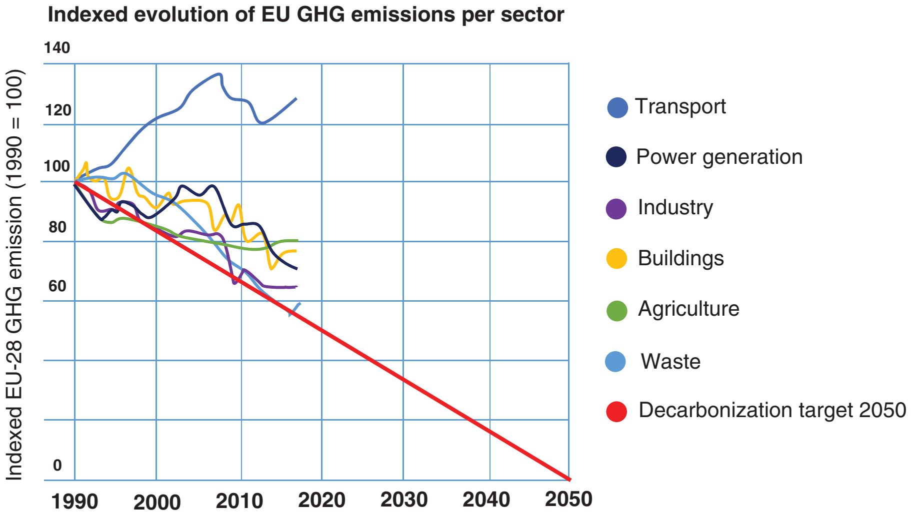

Figure 7 Evolution of the European GHG emissions relative to 1990 per sector. Source: Data from Transport & Environment (1998), UNFCC (1990-2016 data) and EEA's approximated EU greenhouse inventory (2017 data).

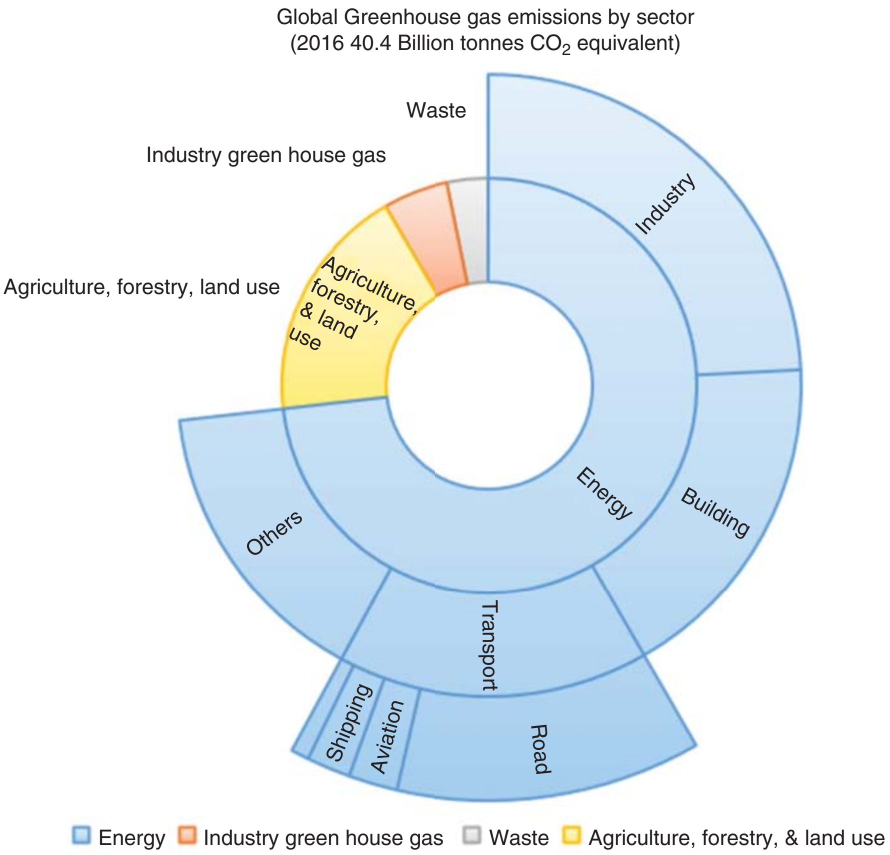

Figure 8 Global greenhouse gas emissions per sector.