

# Industrial (catalytic) processes und reactions

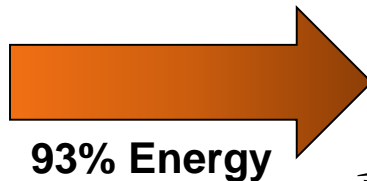
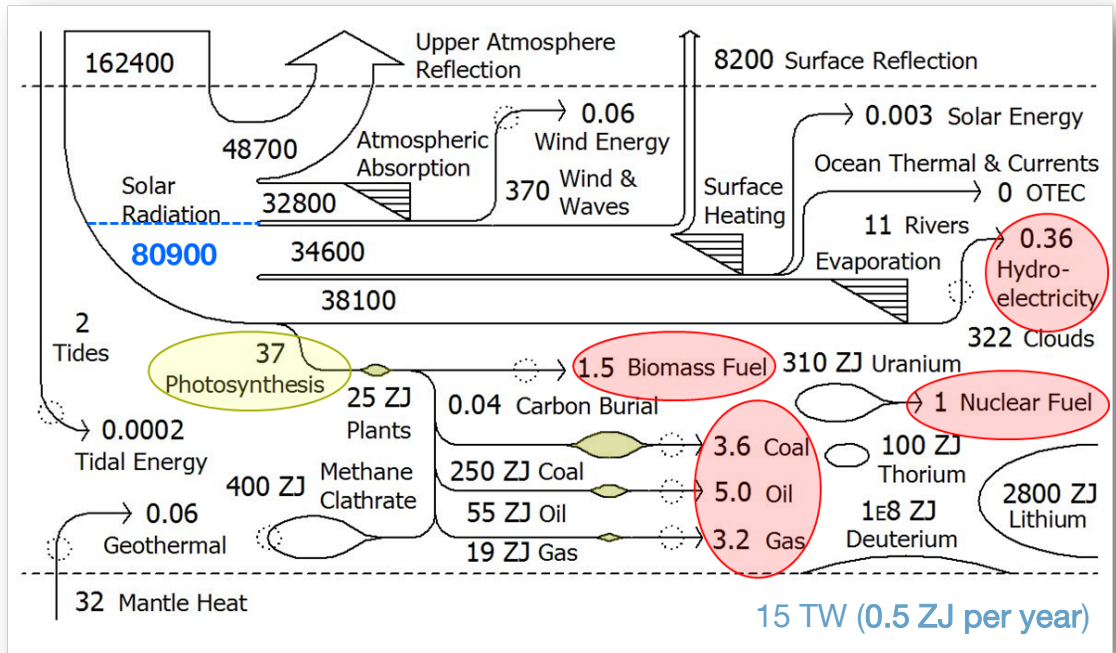
- Introduction
  - Energy situation
  - Catalysis - role, importance
- Refining chemistry
  - Overall refining chemistry
  - Catalytic cracking
  - Catalytic reforming
  - Hydrotreating
  - Synthetic fuels
- Synthesis gas and hydrogen production
  - Steam reforming
  - Partial oxidation
  - CO<sub>2</sub> reforming

# Energy situation

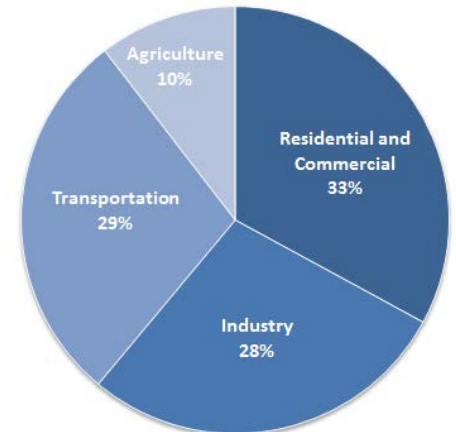
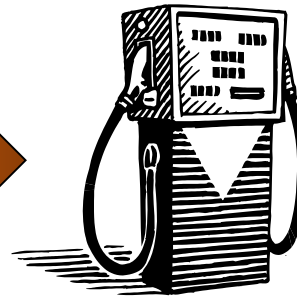
# How are we using carbon?



**7% Chemicals**



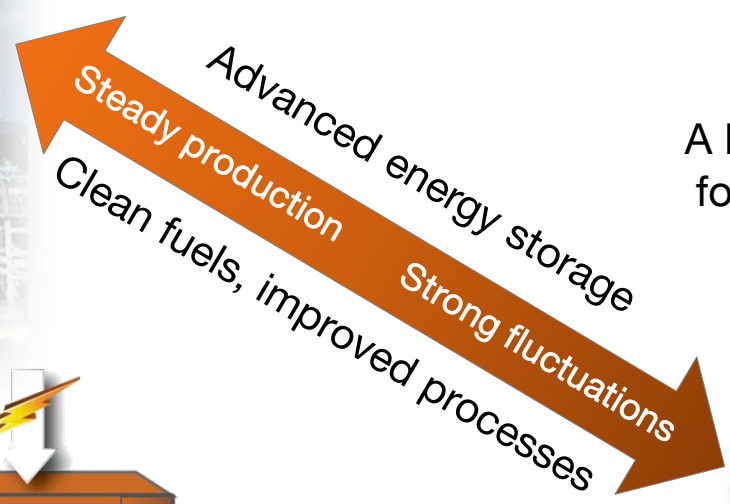
**93% Energy**



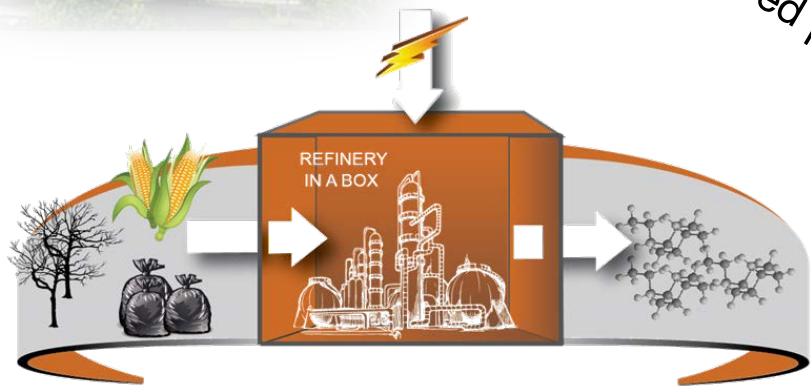
# Catalysis in evolving energy scenarios

More than 80% of all conversions in refinery are catalyzed.

For the present and foreseeable future, the major source of energy ... is found in chemical bonds.  
Opportunities for Catalysis in the 21<sup>st</sup> Century, BESAC 2002



A large fraction of the energy from fossil fuels can be substituted by renewable sources.



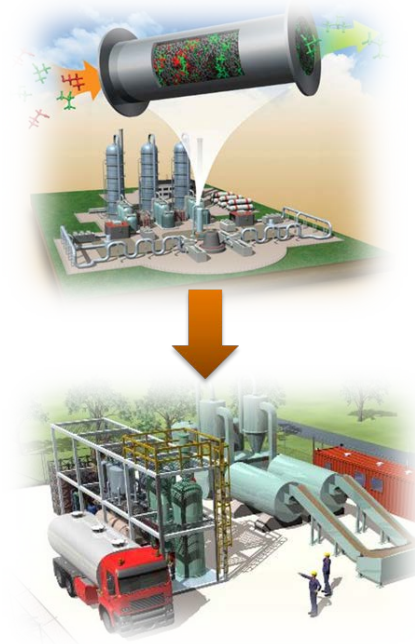
# Fuels present a complex challenge for clean energy goals

## What we do today

- Large refineries ( $> 12\text{GW}$ ,  $1.7 \cdot 10^5$  BOE/day )
- Fossil carbon sources
- Large carbon footprint

## What we need for the future

- “Plants commensurate with carbon and hydrogen availability ( $< 20$  MW, 300 BOE/day)
- Renewable and recycled (hydro)carbon sources
  - for 300 BOE/day ~ 85 ton biomass, organic waste of 125,000 people



Transportation sector is responsible for 27% greenhouse gas footprint

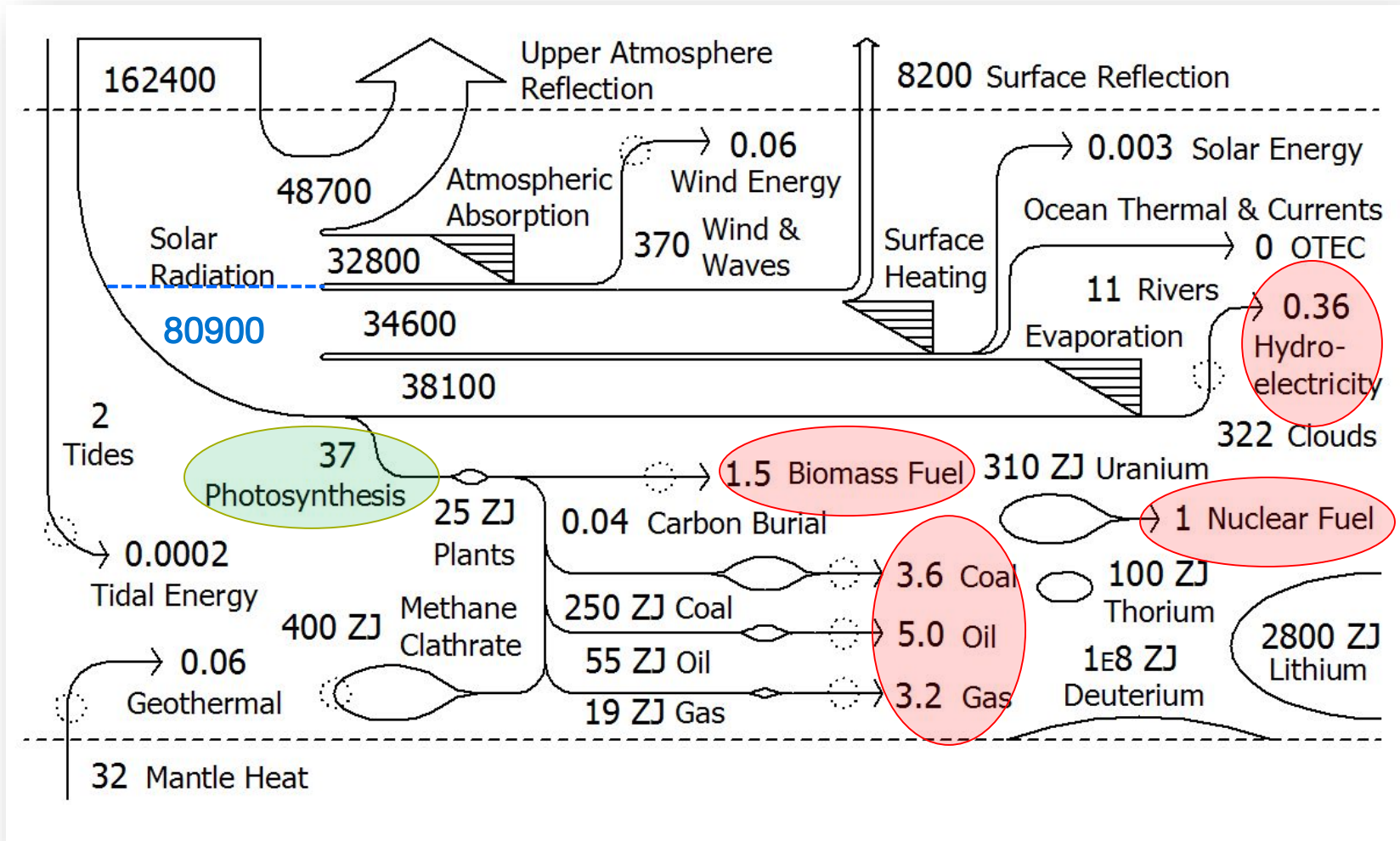
1 MW electric power produces sufficient  $\text{H}_2$  to produce 85 barrels from HTL oil or 19 barrels from biomass per day

Carbon-footprint

Land-footprint

Water-footprint

# Exergy flow of planet earth (TW)

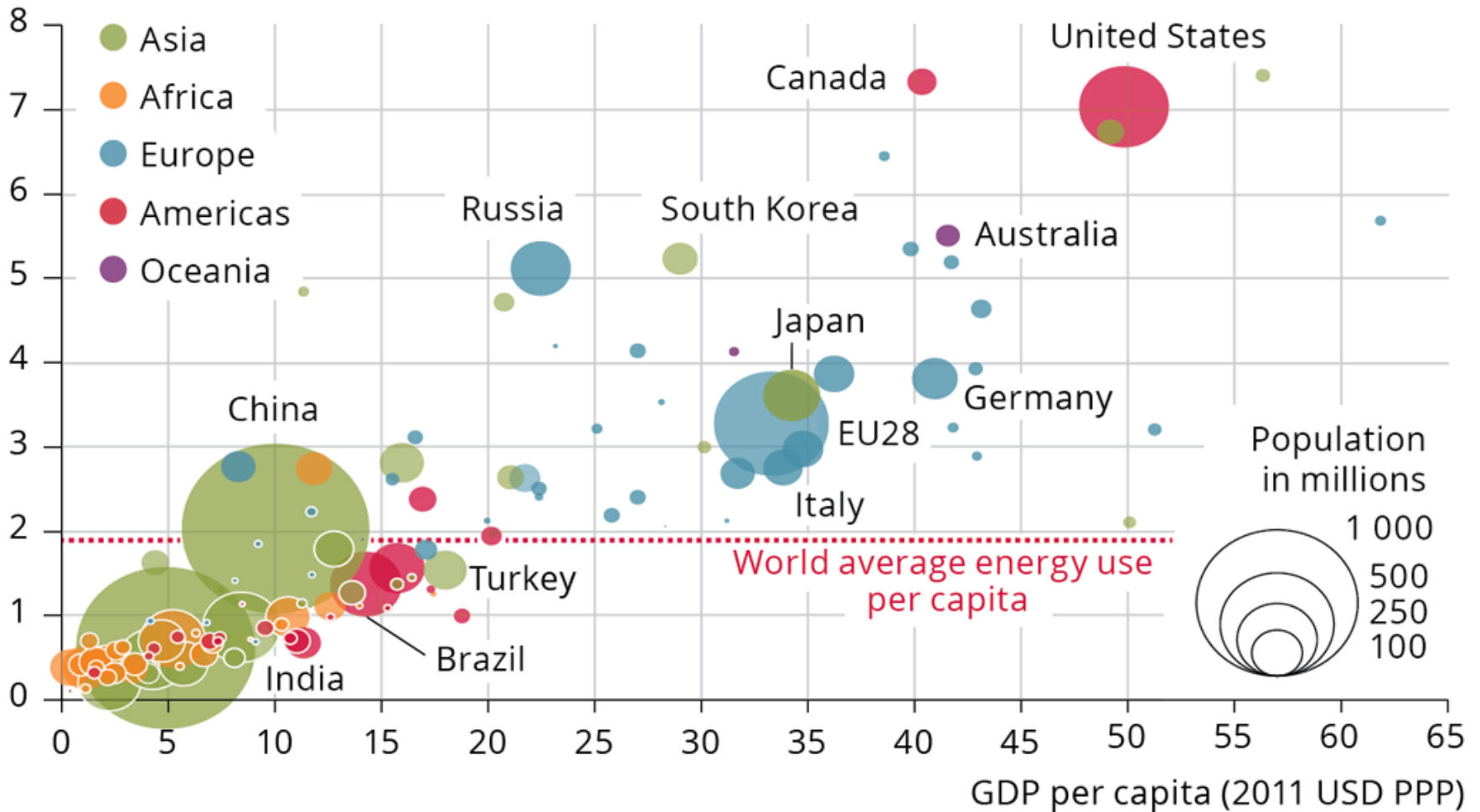


**Current global exergy usage rate ~ 15 TW (0.5 ZJ per year)**

**Influx energy vs. annual consumption  $80900/15 = 5400$**

# Energy demand is correlated to wealth

Energy use in tonnes of oil equivalent per capita



# Shared aspirations lead to shifts



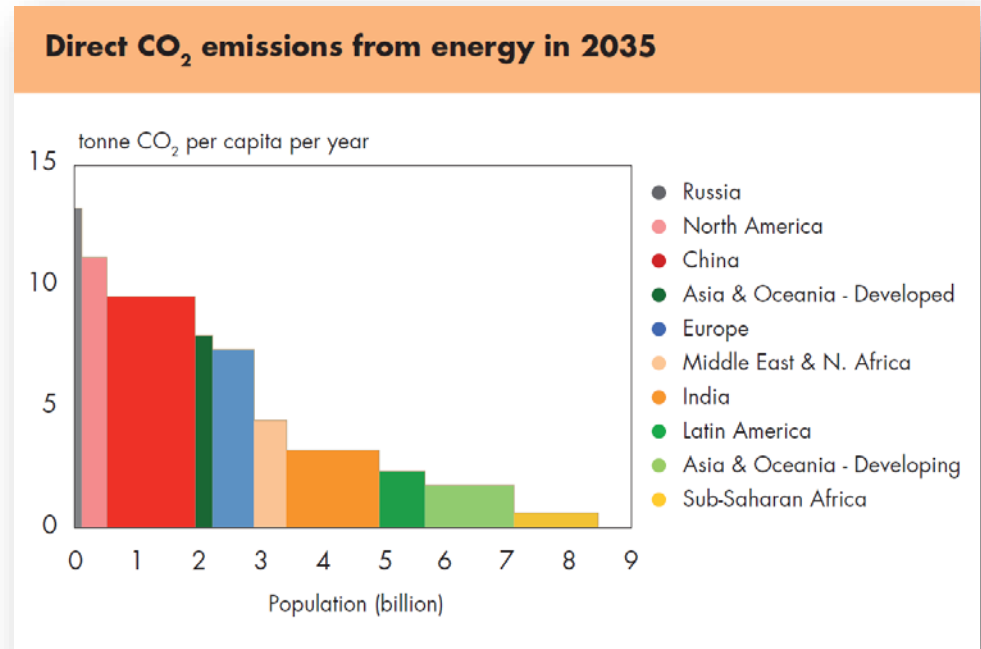
**India** 0.7 TW (1.1 B)  
0.7 kW/person



**China** 2.1 TW (1.3 B)  
1.6 kW/person



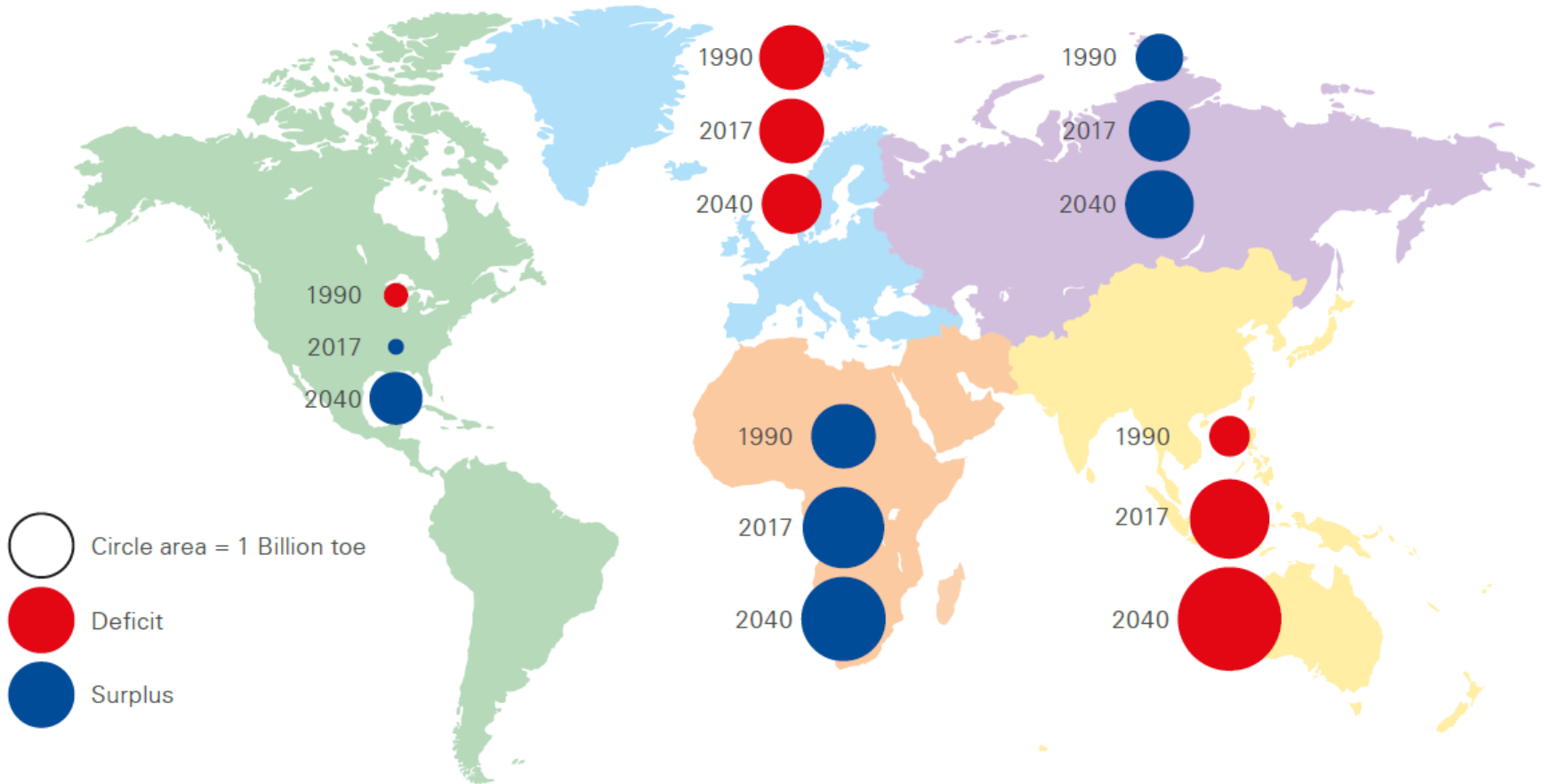
**U.S.** 3.4 TW (0.3 B)  
11.4 kW/person





# Energy self sufficiency

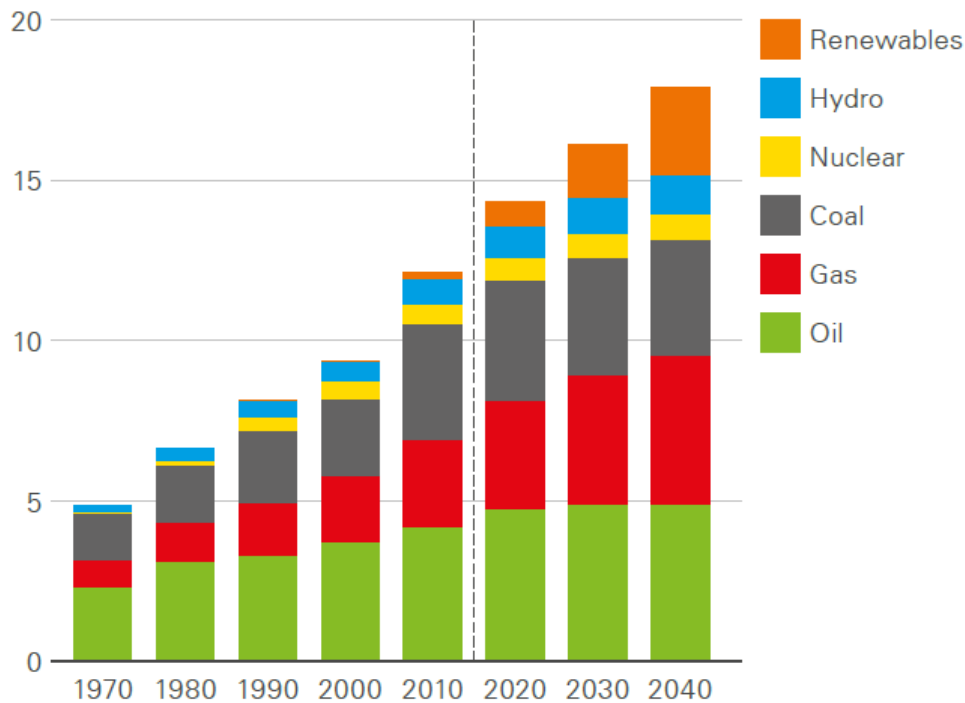
Energy balance of traded fuels (oil, gas, coal)



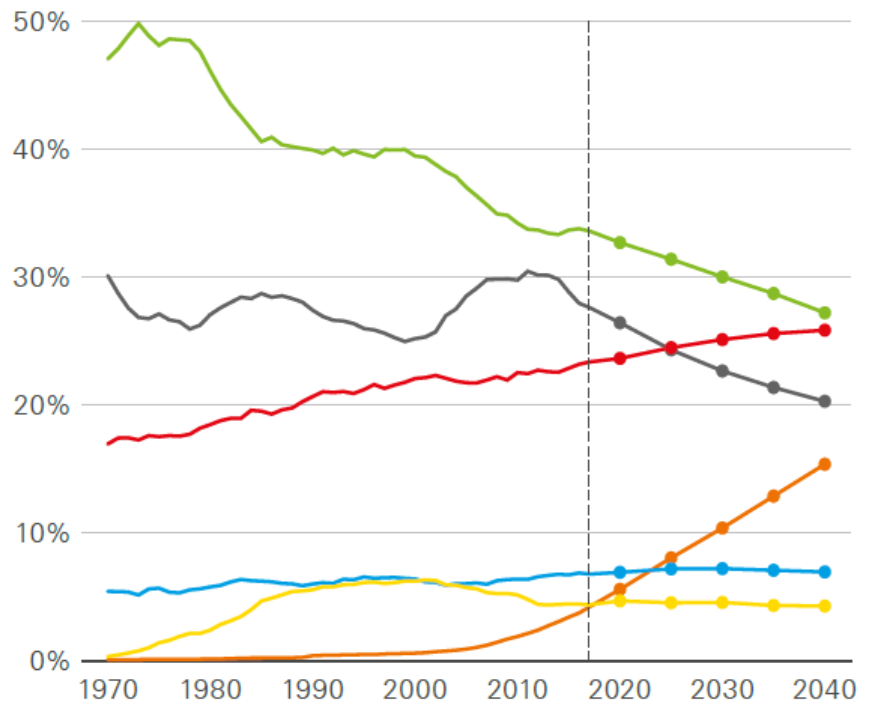
# Energy - world consumption moves to lower carbon

## Primary energy consumption by fuel

Billion toe



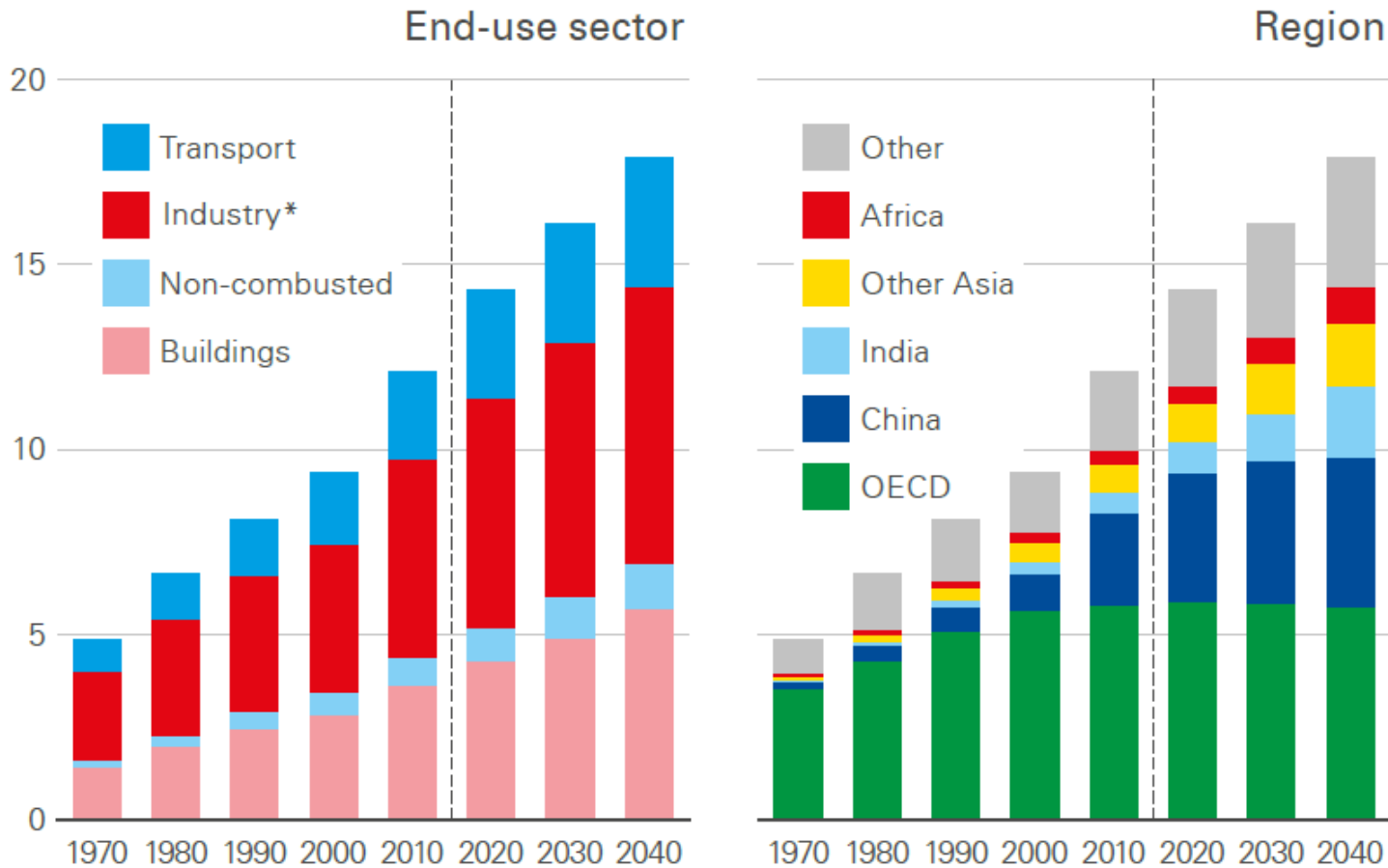
## Shares of primary energy



# Demand patterns suggest robust growth

## Primary energy demand

Billion toe

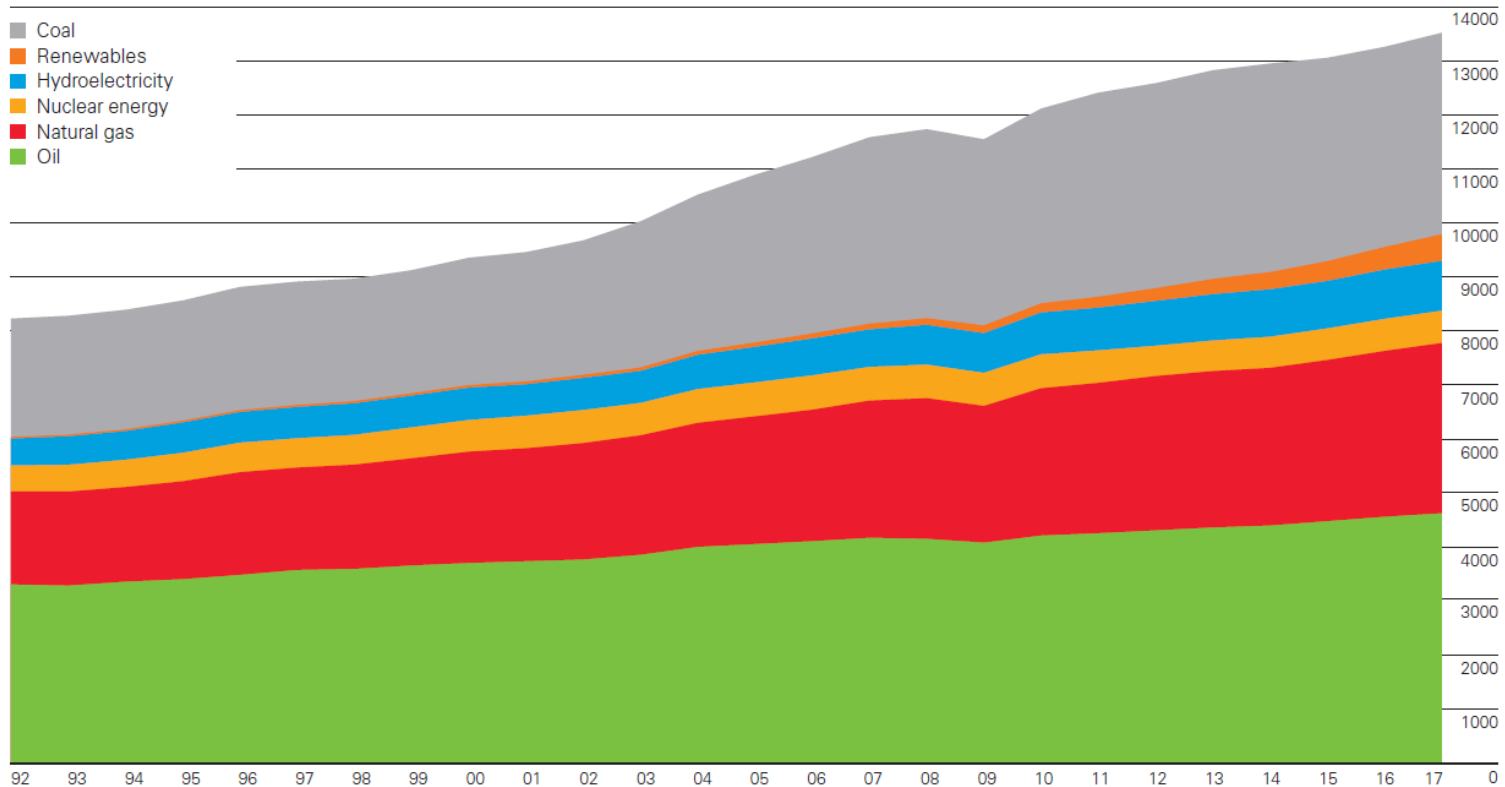


\*Industry excludes non-combusted use of fuels

# World consumption of primary energy carriers

## World consumption

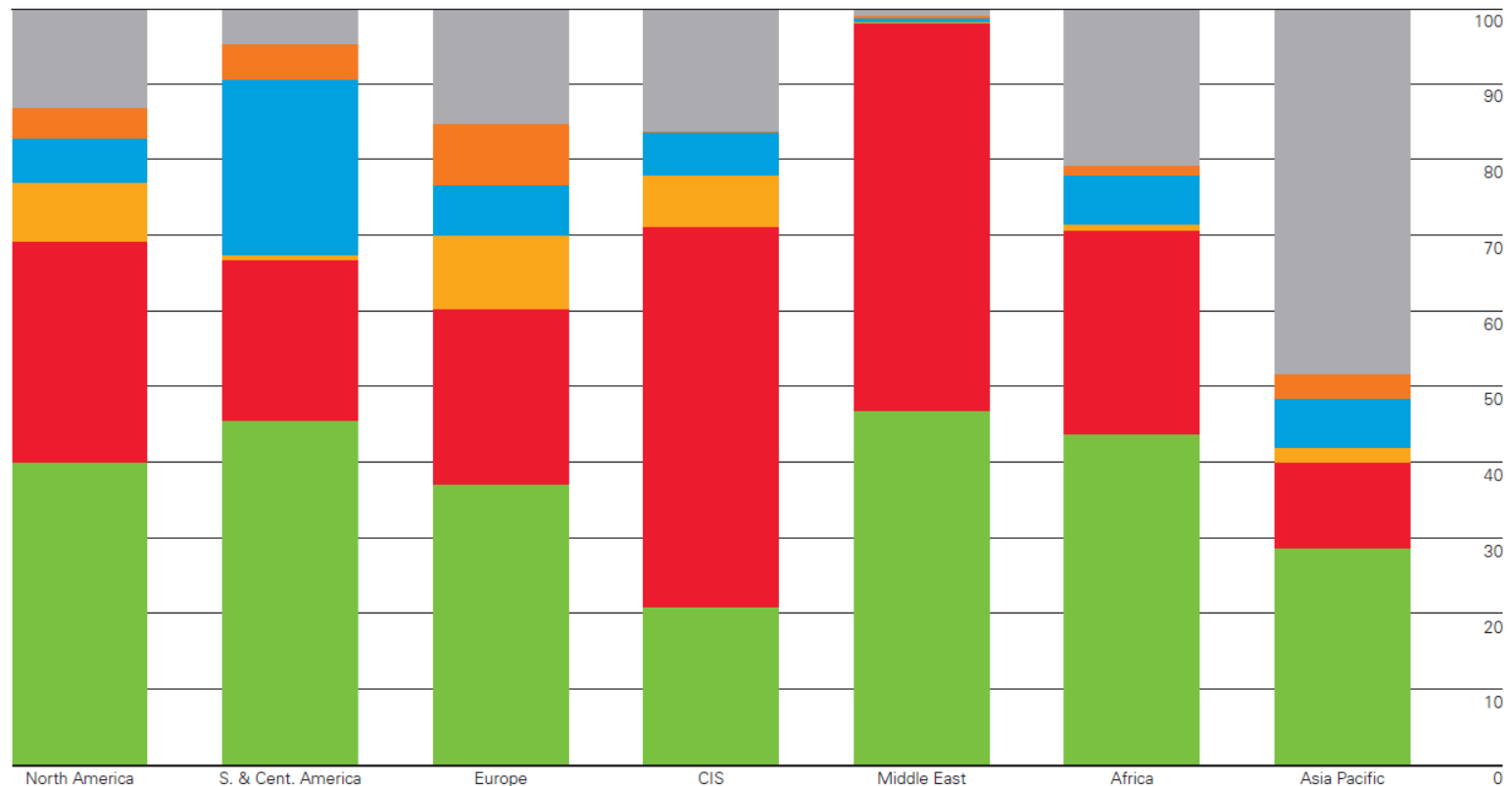
Million tonnes oil equivalent



World primary energy consumption grew by 2.2% in 2017, up from 1.2% in 2016 and the highest since 2013. Growth was below average in Asia Pacific, the Middle East and S. & Cent. America but above average in other regions. All fuels except coal and hydroelectricity grew at above-average rates. Natural gas provided the largest increment to energy consumption at 83 million tonnes of oil equivalent (mtoe), followed by renewable power (69 mtoe) and oil (65 mtoe).

# Use of primary energy carriers varies globally

Regional consumption by fuel 2017  
Percentage



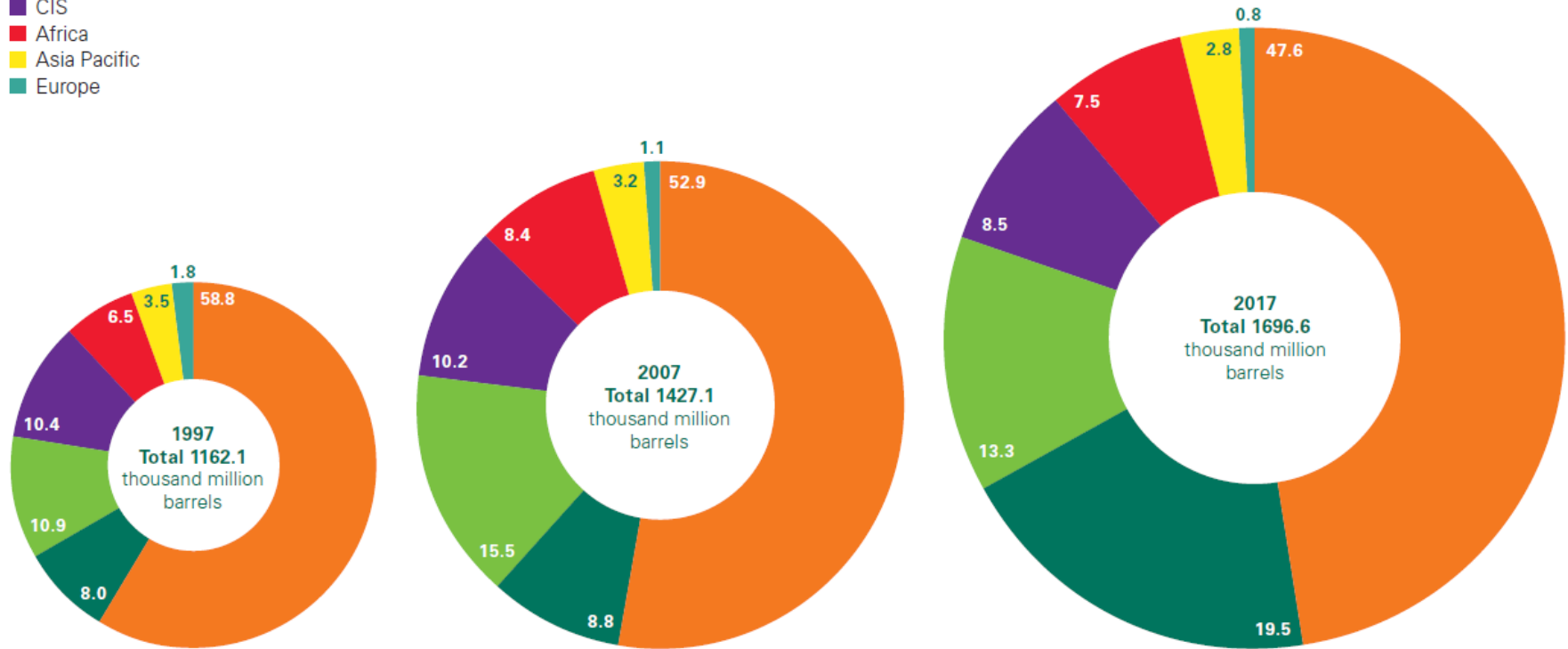
Oil remains the dominant fuel in Africa, Europe and the Americas, while natural gas dominates in CIS and the Middle East, accounting for more than half of the energy mix in both regions. Coal is the dominant fuel in the Asia Pacific region. In 2017 coal's share of primary energy fell to its lowest level in our data series in North America, Europe, CIS and Africa.

# Distribution of proved reserves

## Distribution of proved reserves in 1997, 2007 and 2017

Percentage

- Middle East
- S. & Cent. America
- North America
- CIS
- Africa
- Asia Pacific
- Europe



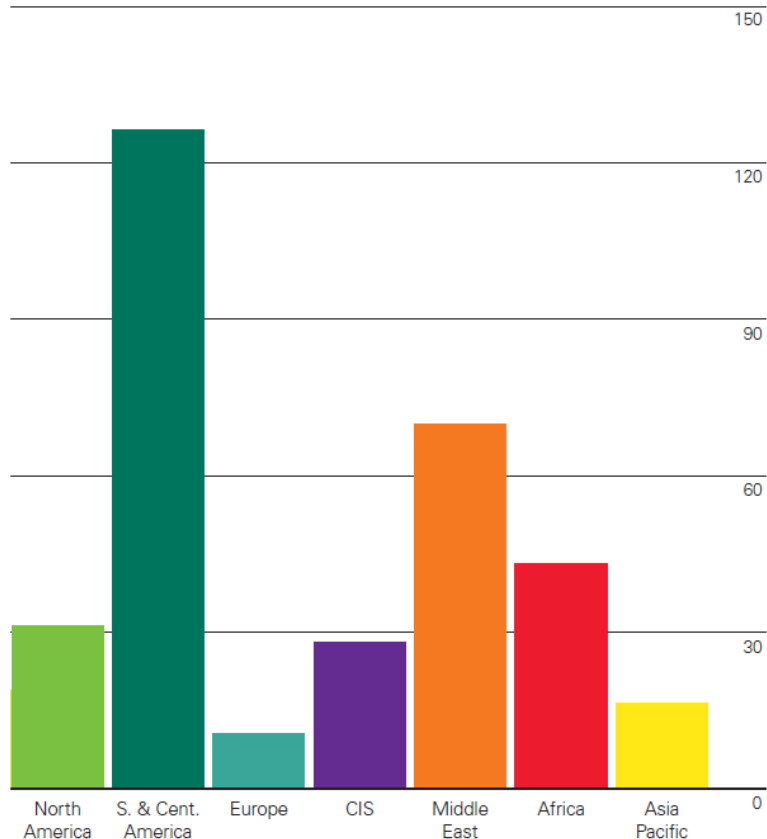
bbl = barrel (volume measurement)  
1 bbl = 159 ltr  
1 t = ca 7.5 bbl  
100.000 bbl/day = 5 mio t/a

# Oil: reserves/production ratios

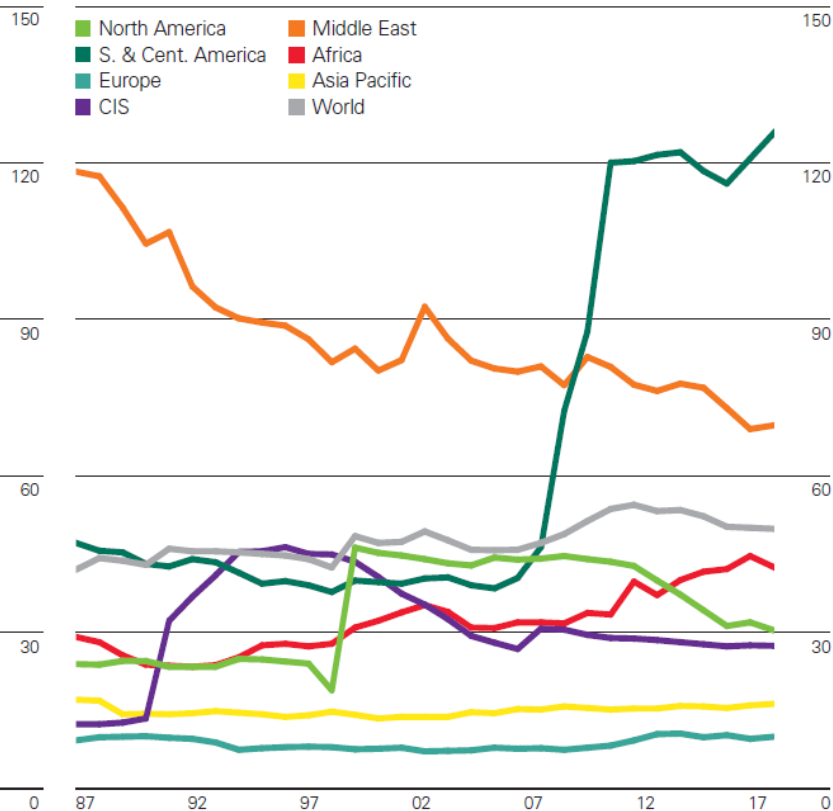
## Reserves-to-production (R/P) ratios

Years

### 2017 by region



### History

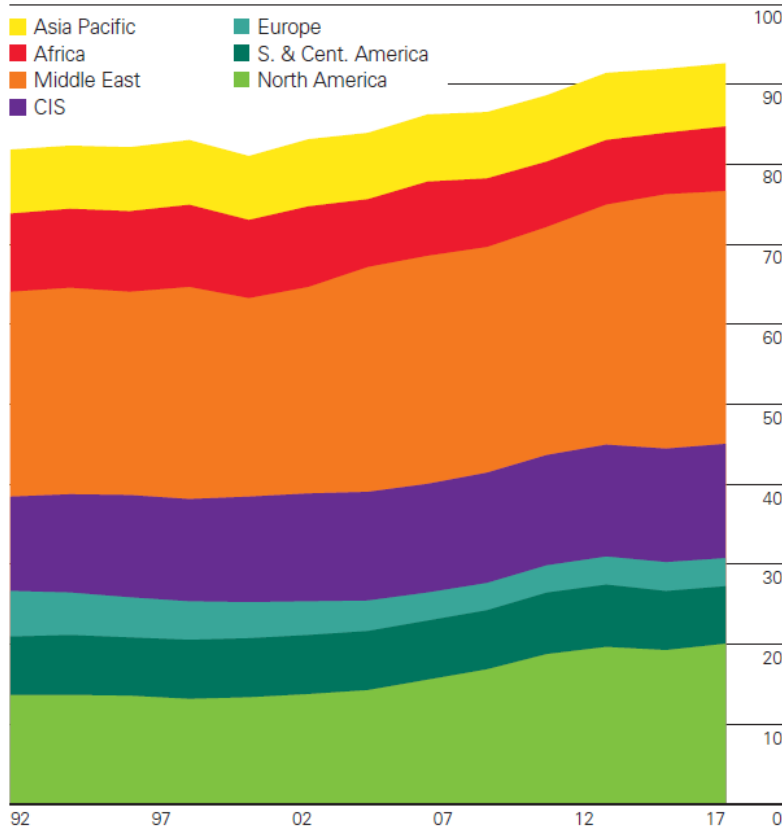


Global proved oil reserves in 2017 fell slightly by 0.5 billion barrels (-0.03%) to 1696.6 billion barrels, which would be sufficient to meet 50.2 years of global production at 2017 levels. Higher reserves in Venezuela (up by 1.4 billion barrels) were outweighed by declines in Canada (-1.6 billion barrels) and smaller declines in a number of other non-OPEC countries. OPEC countries currently hold 71.8% of global proved reserves.  
 Note: Lags in reporting official data mean that 2017 figures for many countries are not yet available.

# Production and consumption show the energy dependence

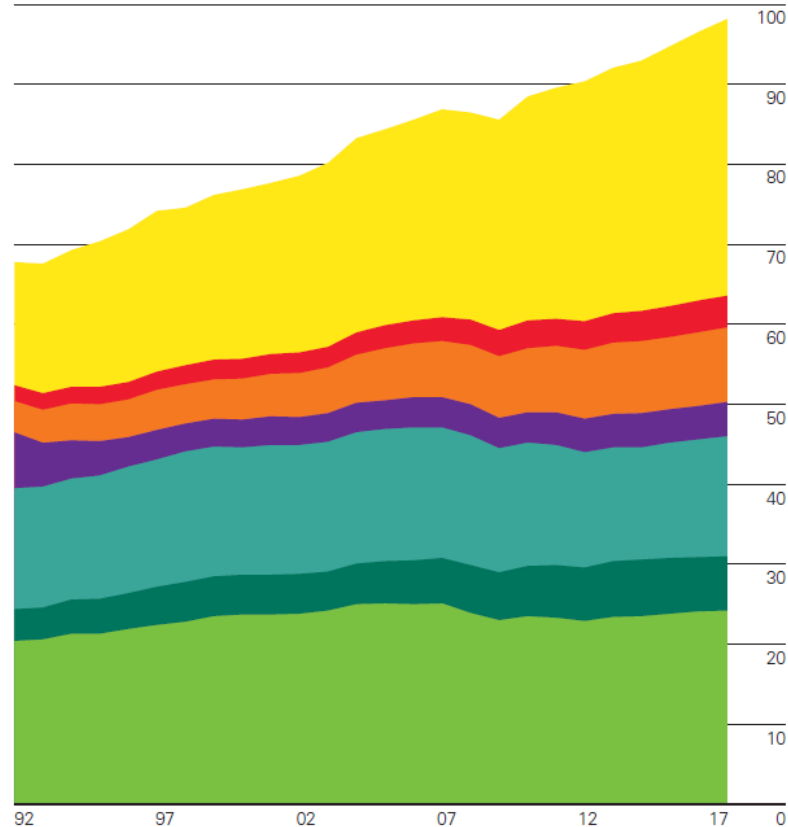
## Oil: Production by region

Million barrels daily



## Oil: Consumption by region

Million barrels daily



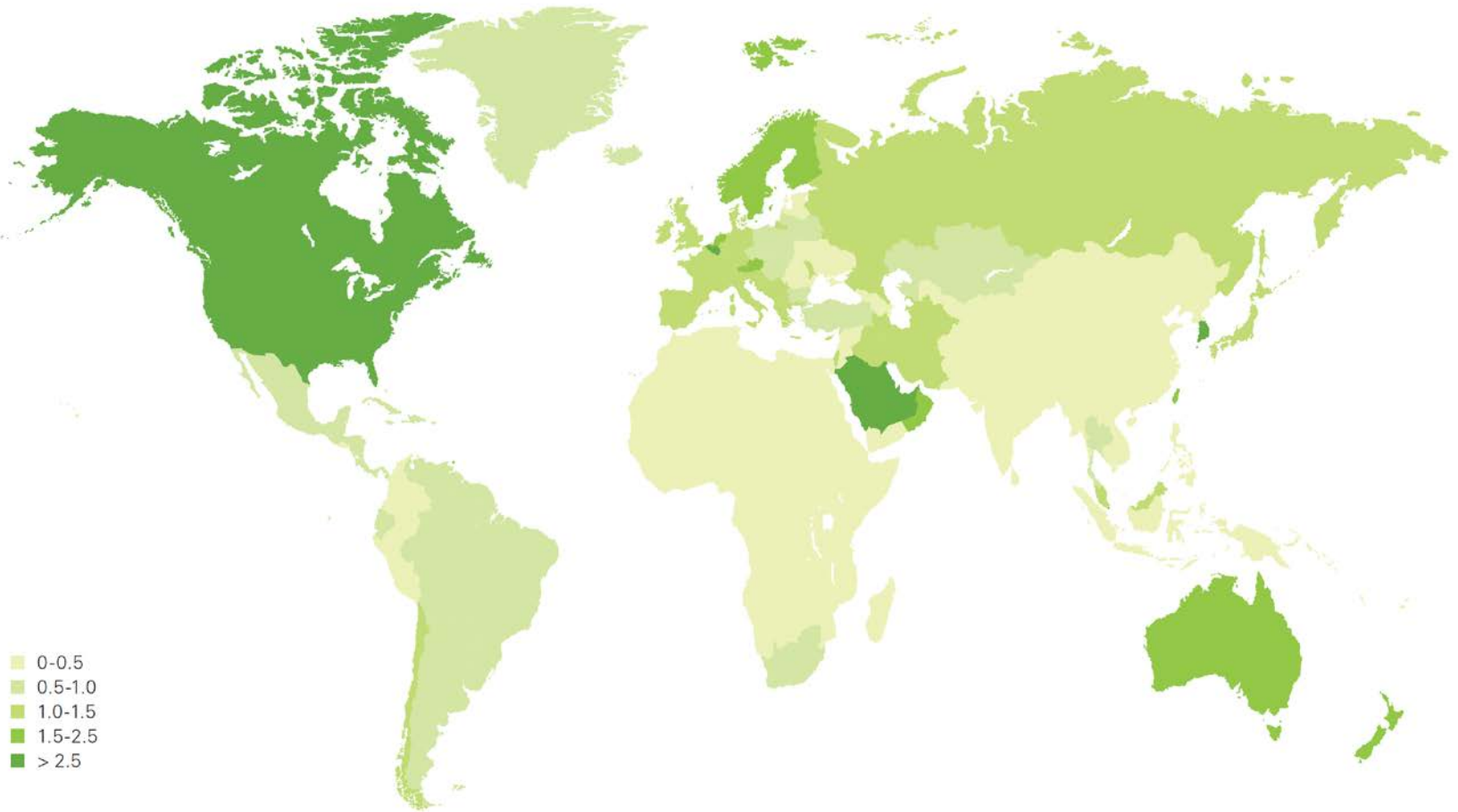
World oil production rose by only 0.6 million b/d in 2017, below average for the second consecutive year. Production fell in the Middle East (-250,000 b/d) and South & Central America (-240,000 Kb/d) but this was outweighed by growth from North America (820,000 b/d) and Africa (390,000 b/d). Global oil consumption growth averaged 1.7 million b/d, above its 10-year average of 1.1 million b/d for the third consecutive year. China (500,000 b/d) and the US (190,000 b/d) were the single largest contributors to growth.



# Oil consumption by area

Oil: Consumption per capita 2017

Tonnes

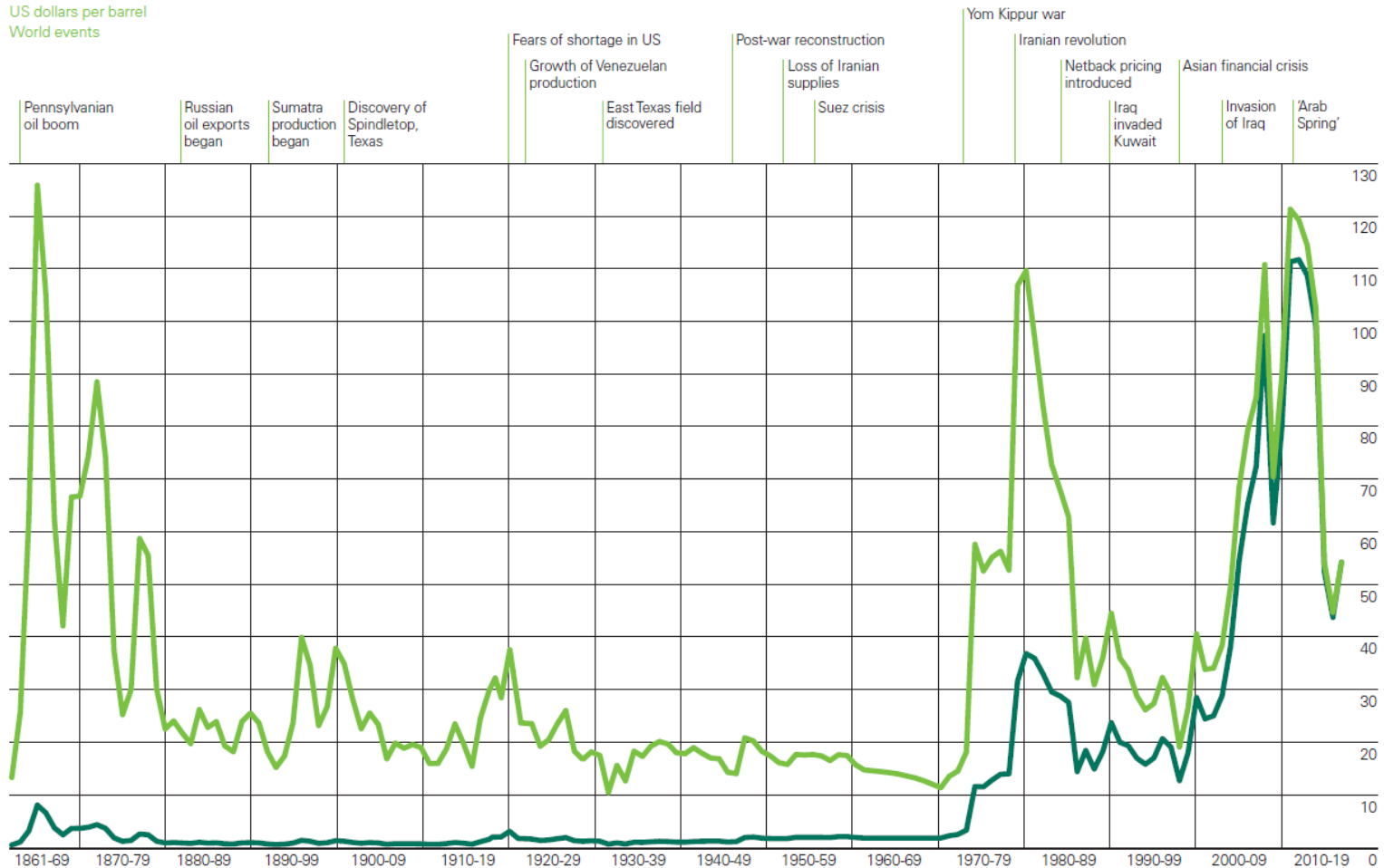


# Crude oil prices since 1861

## Crude oil prices 1861-2017

US dollars per barrel

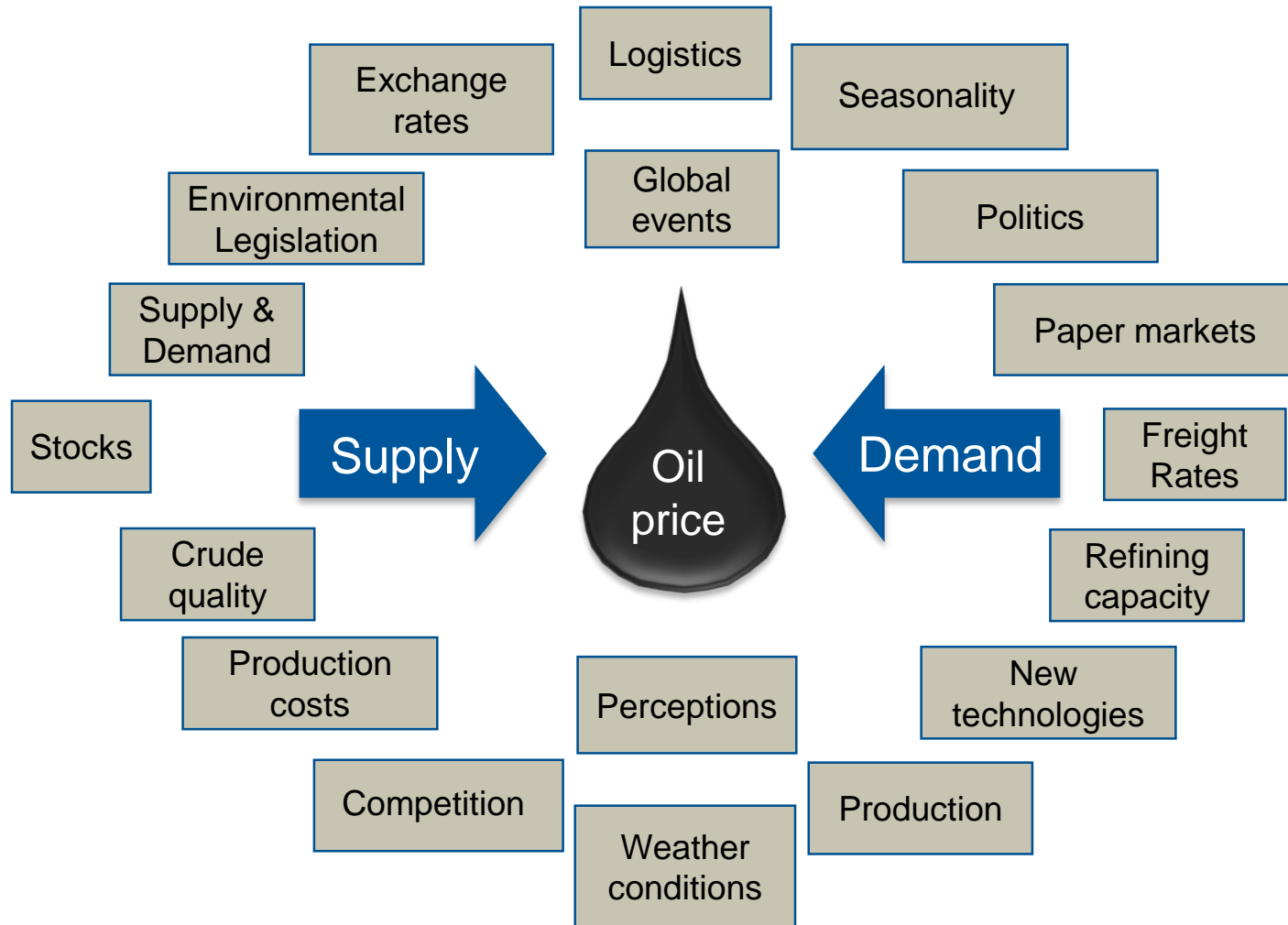
World events



■ \$ 2017 (deflated using the Consumer Price Index for the US)  
 ■ \$ money of the day

1861-1944 US average.  
 1945-1983 Arabian Light posted at Ras Tanura.  
 1984-2017 Brent dated.

# Many factors impact the oil price

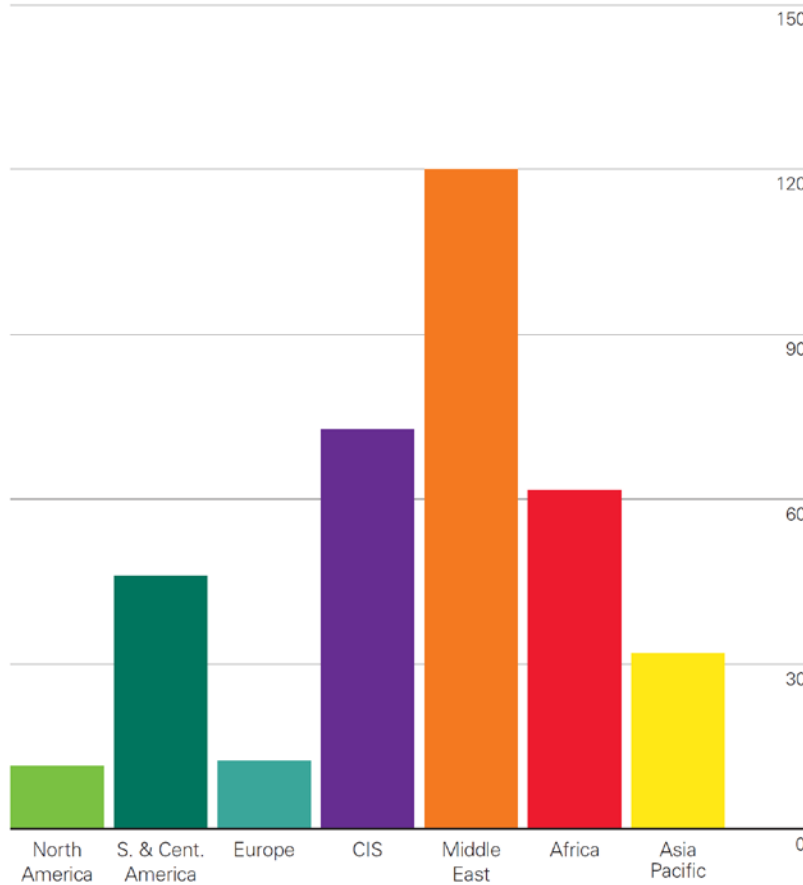


# Gas resources: plentiful but...

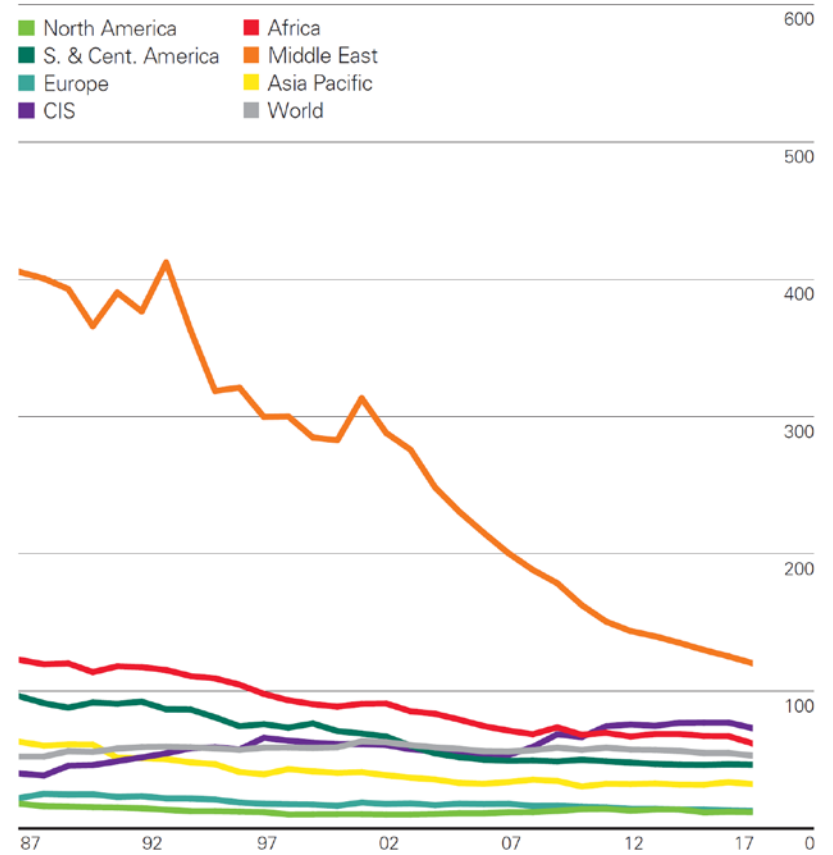
## Reserves-to-production (R/P) ratios

Years

### 2017 by region



### History

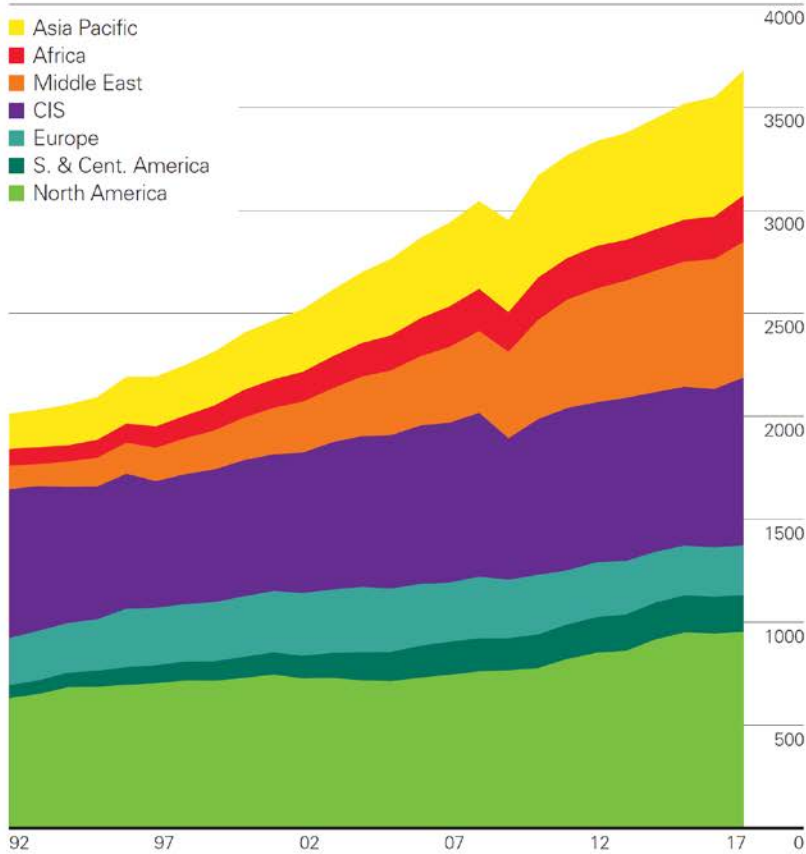


- Transportability and market issues

# Gas production and consumption

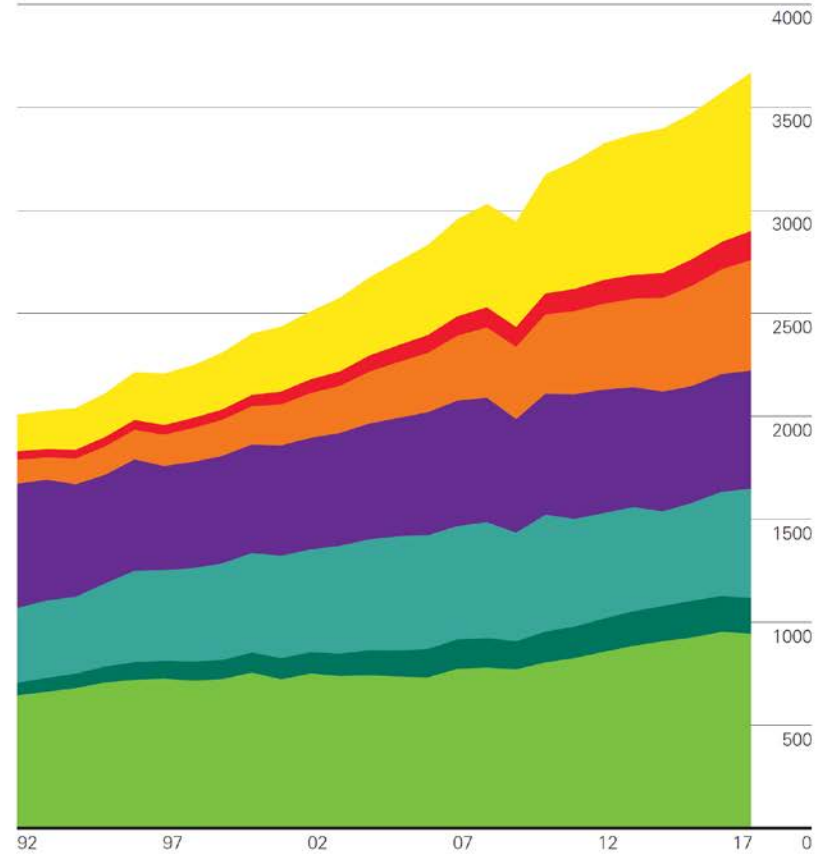
**Natural gas: Production by region**

Billion cubic metres



**Natural gas: Consumption by region**

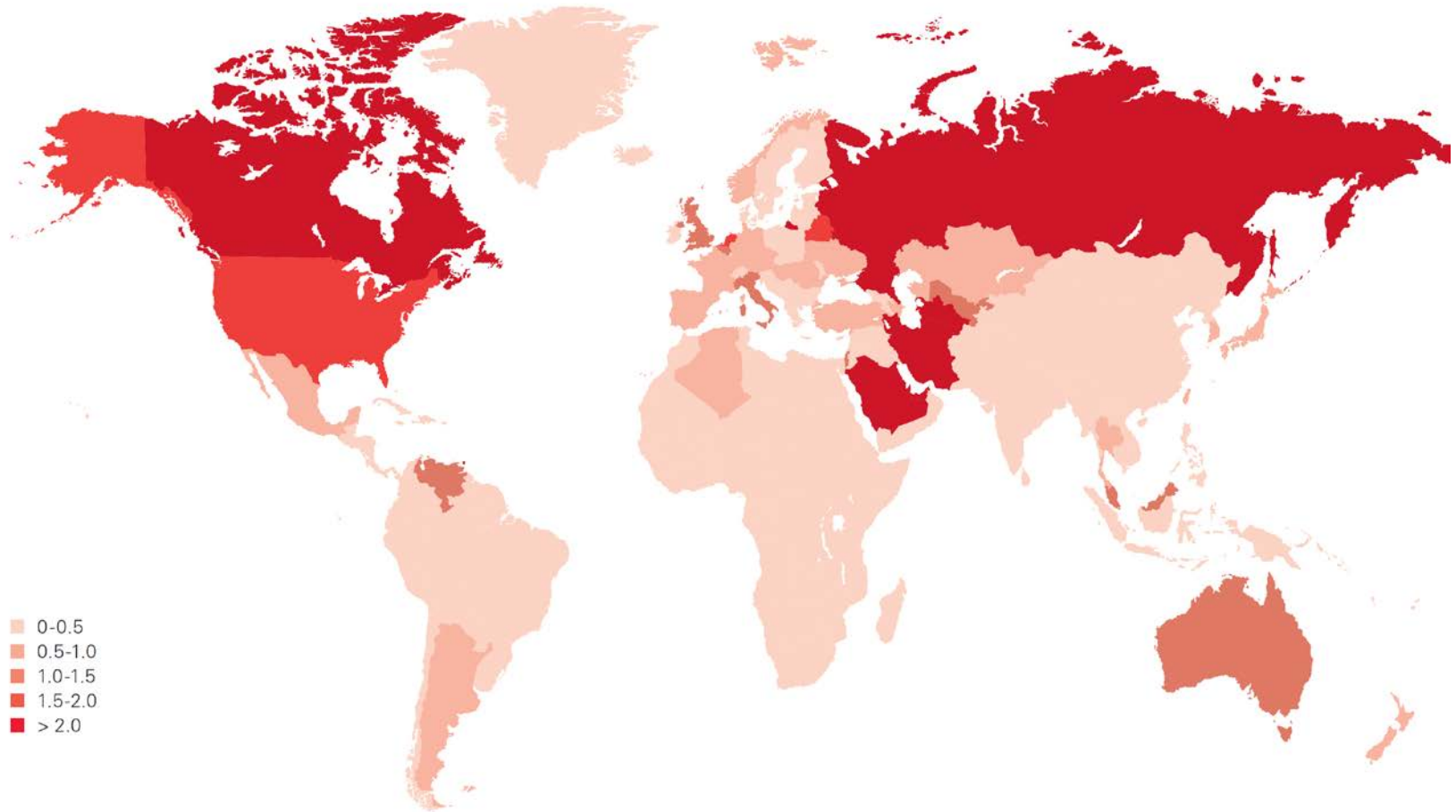
Billion cubic metres



# Gas consumption per capita

## Natural gas: Consumption per capita 2017

Million tonnes oil equivalent

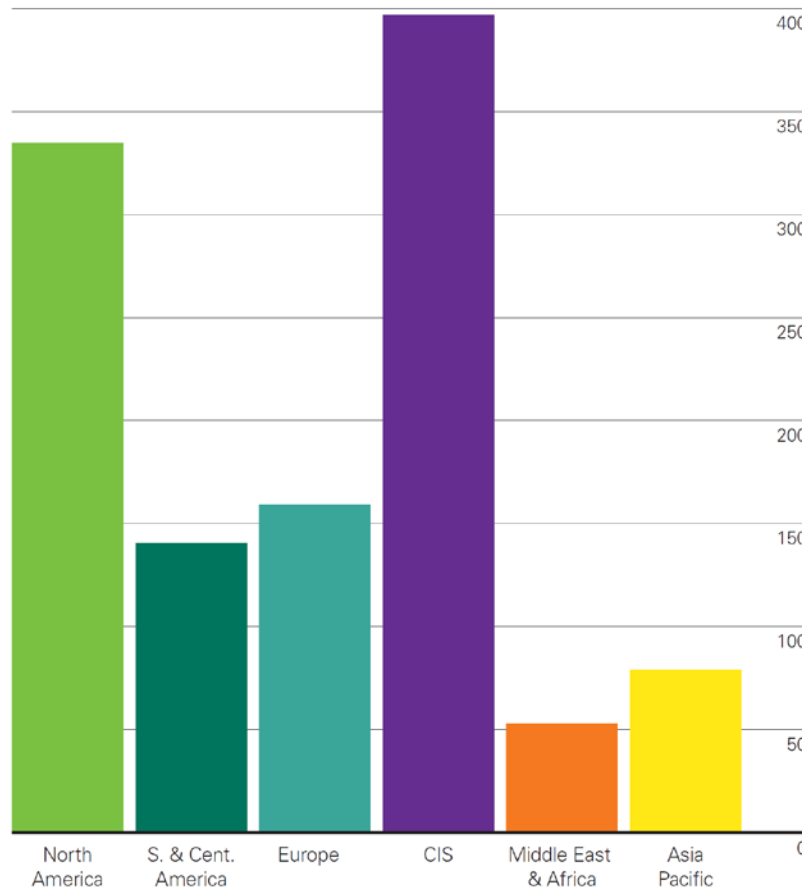


# Coal reserves/production ratio

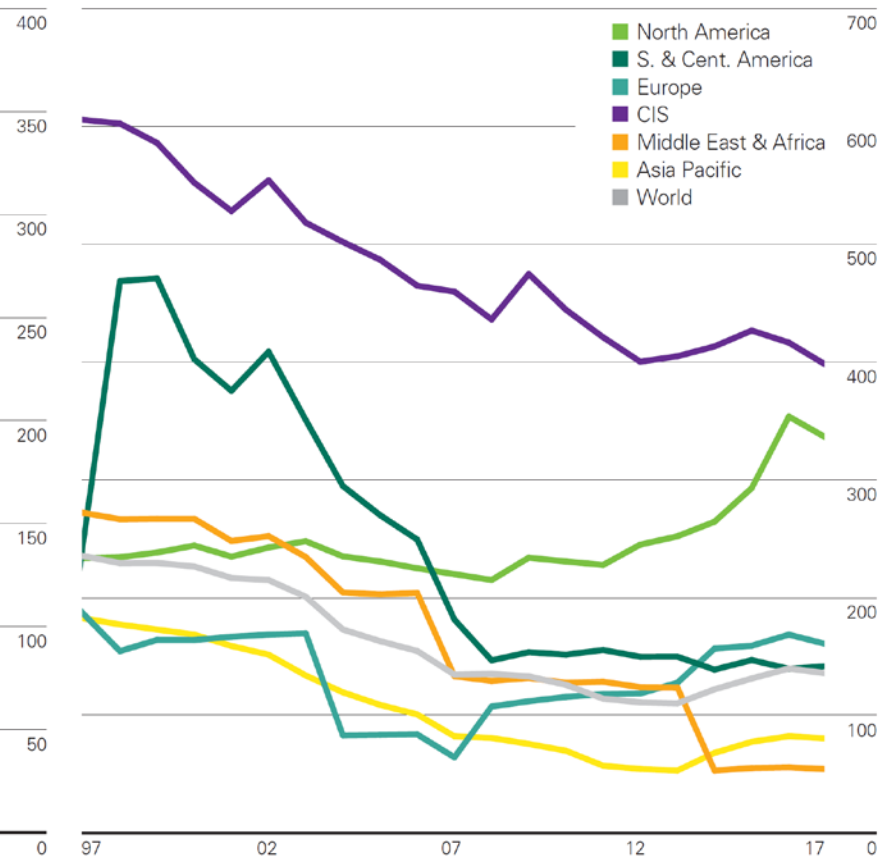
## Reserves-to-production (R/P) ratios

Years

2017 by region



History

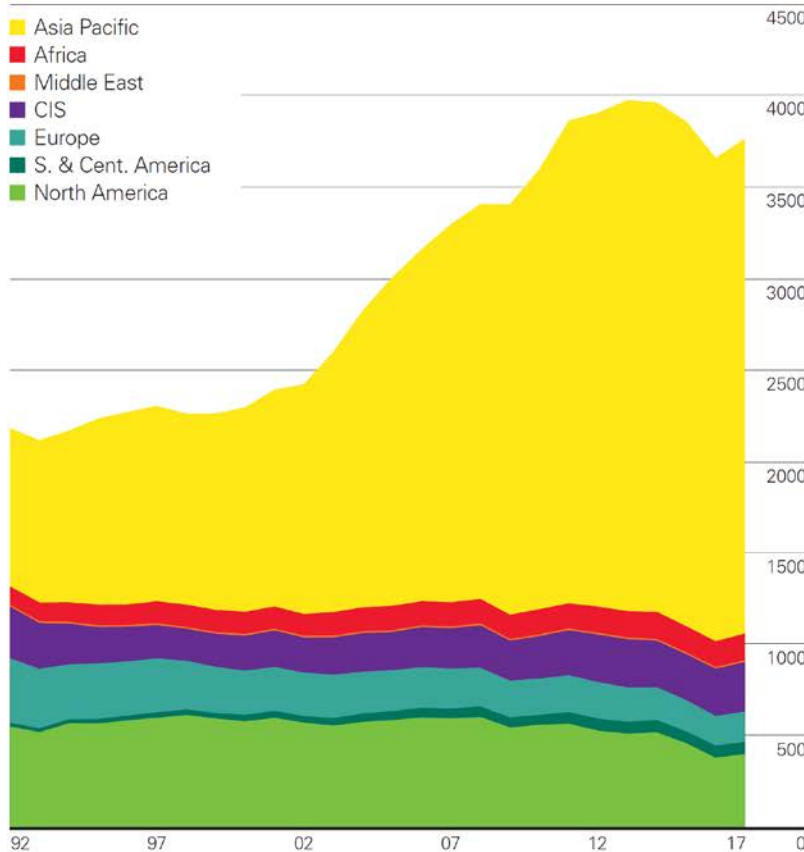


# Coal production and consumption

## Coal: Production by region

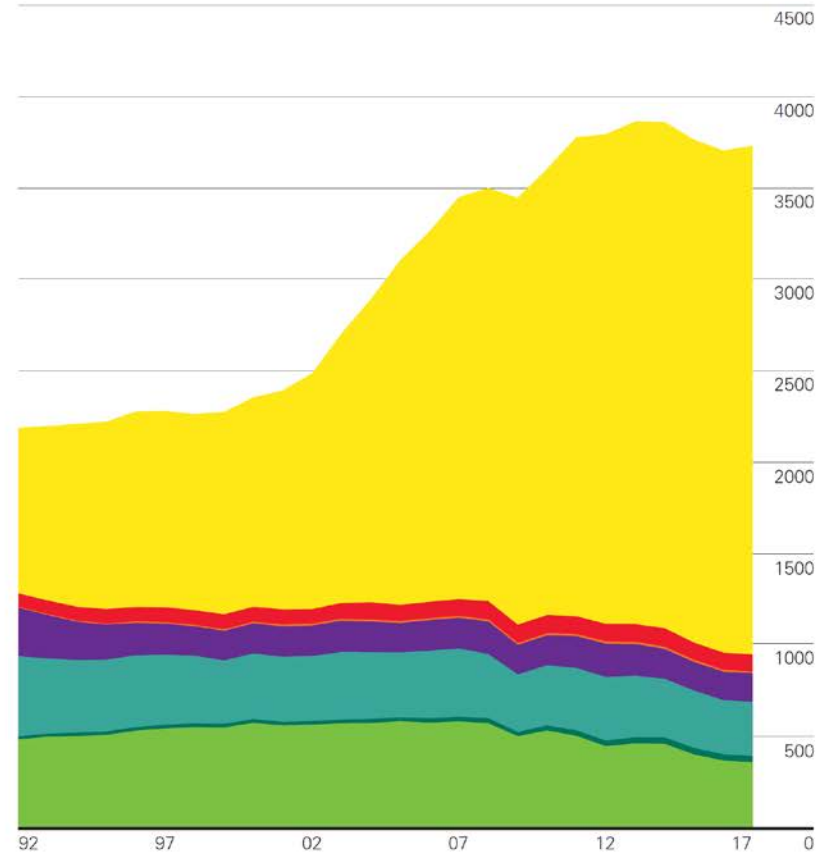
Million tonnes oil equivalent

- Asia Pacific
- Africa
- Middle East
- CIS
- Europe
- S. & Cent. America
- North America



## Coal: Consumption by region

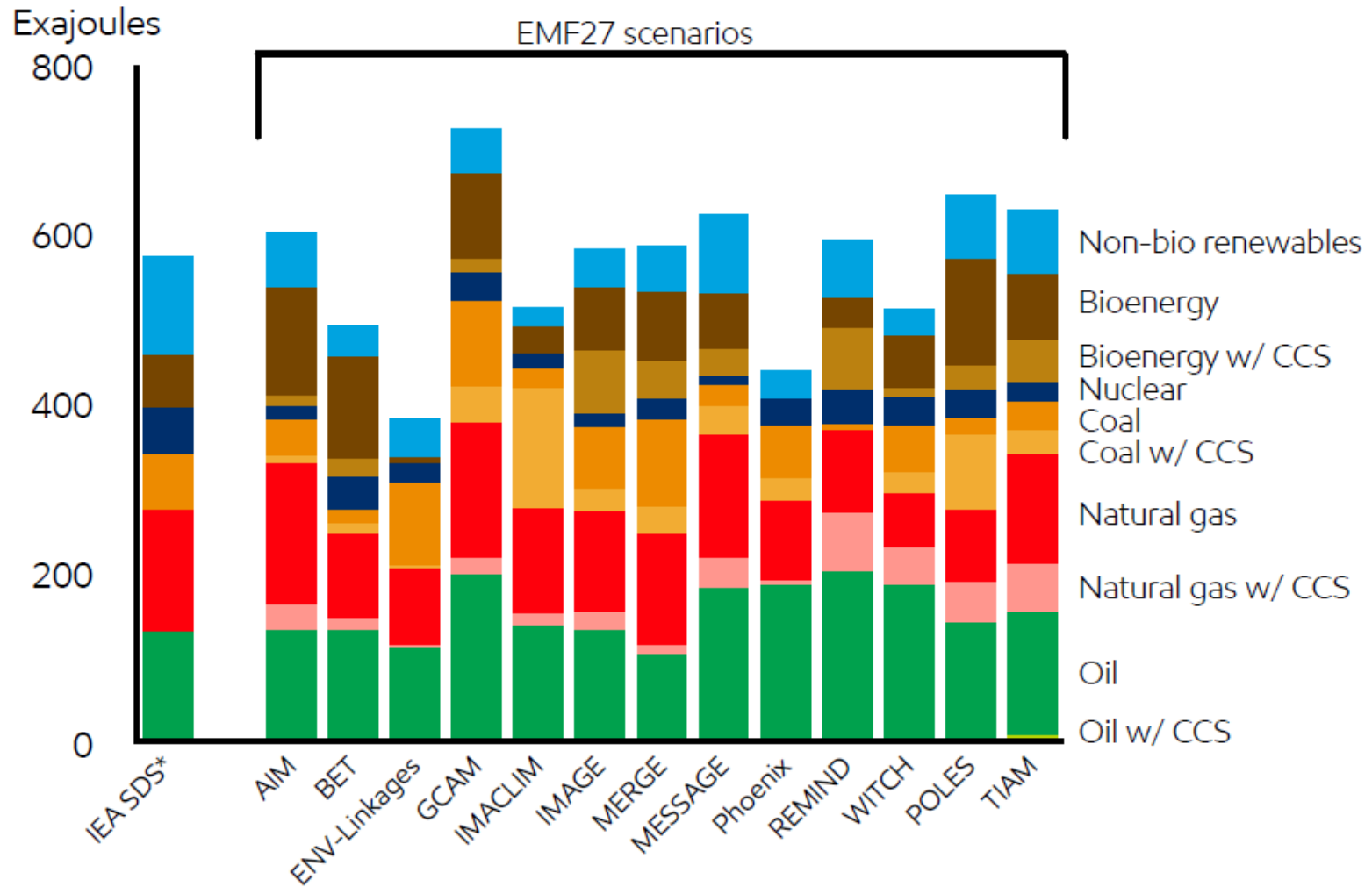
Million tonnes oil equivalent





# Future scenarios vary in a wide range

2040 global demand by model by energy type in the assessed 2°C scenarios and the IEA SDS



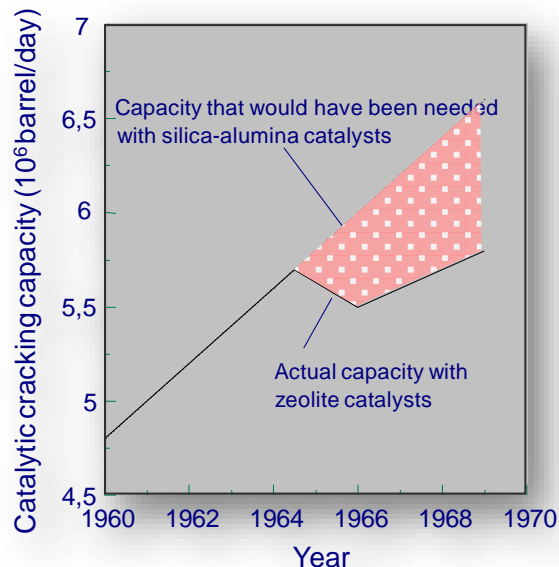
# **Catalysis – role and importance**

# Catalytic processes are the key for sustainability

- High **activity** (lower capacities necessary)
- High **selectivity** (fewer separation steps for product purification)
- High **flexibility** (use in existing units)

Impact of catalysis on the GNP in developed countries	15 – 20 %
World chemicals production in 2006	2.300 Billion \$
World catalyst market in 2007	15,5 Billion \$

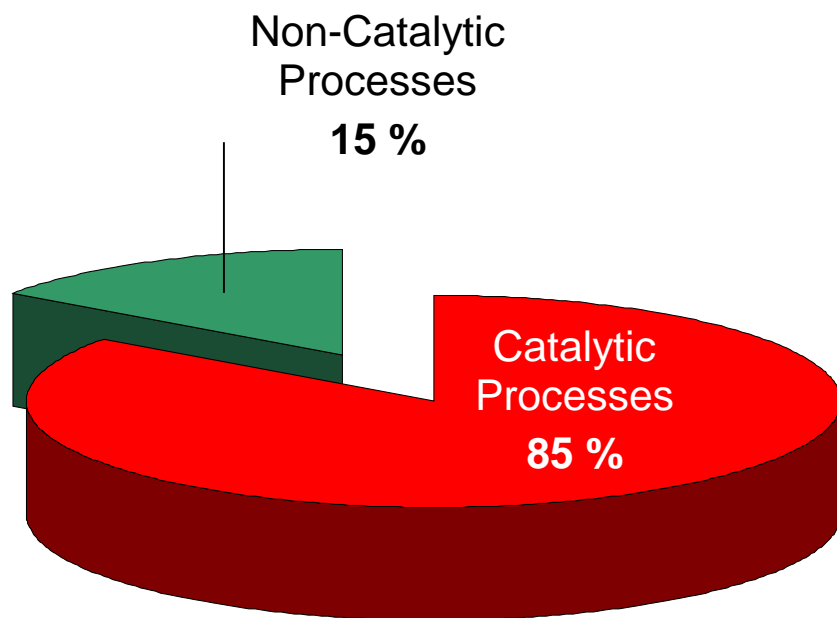
BASF sulfuric acid production 1888 to 1994	25 Mio tons
Catalyst consumption during that time	1.800 tons
	→75 g catalyst/ton



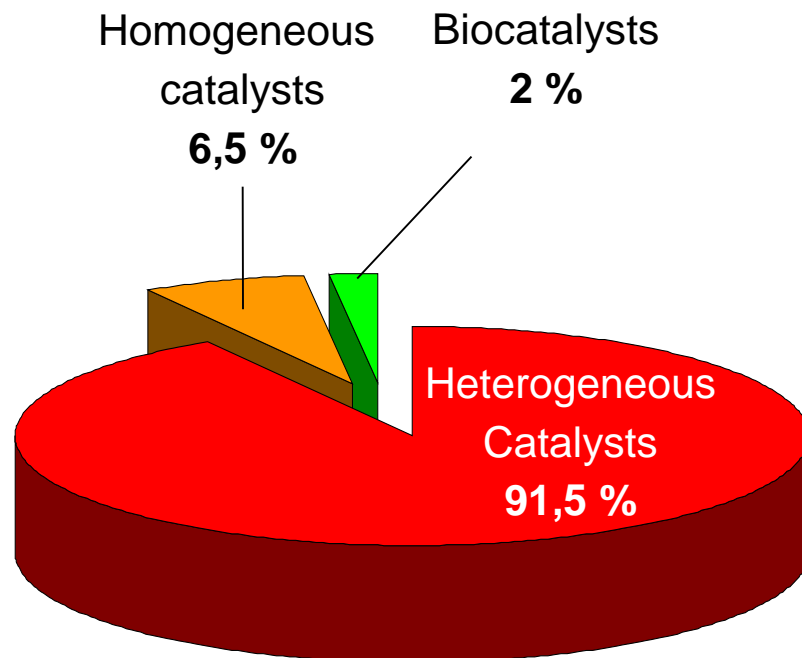
Introduction of zeolites for FCC cracking improved gasoline yield compared to alumosilicate catalysts by 40%.

# Heterogeneous catalysis dominates industrial use

## All processes

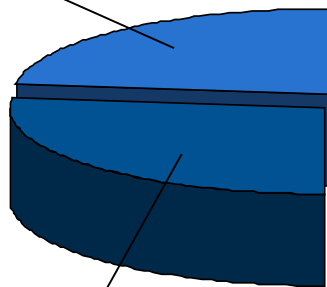


## Catalytic processes



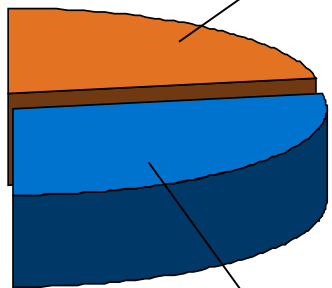
# Global merchant catalyst sales

Environmental – 22%



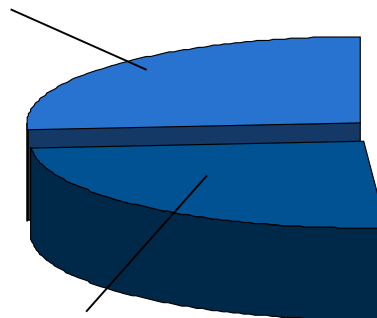
Polymer – 23%

Refinery – 28%



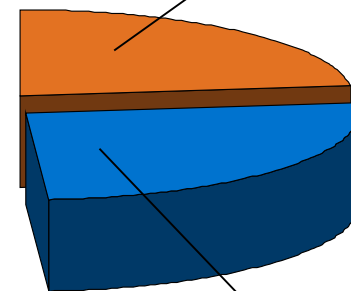
Chemical – 27%

Environmental – 23%



Polymer – 26%

Refinery – 26%



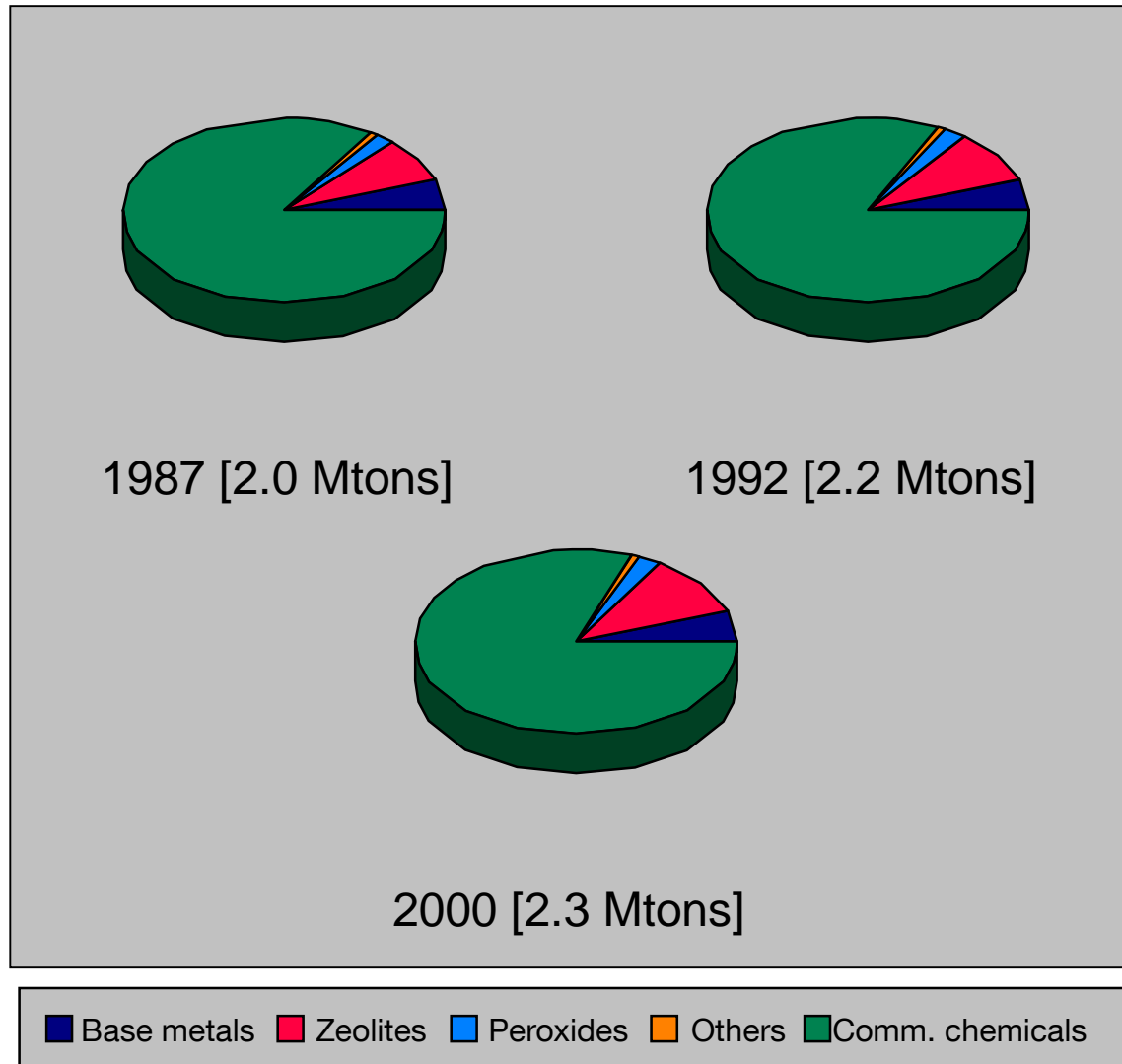
Chemical – 25%

1977 sales = \$ 7.4 billion

Projected 2003 sales = \$ 8.9 billion

Excludes precious metals value in environmental catalysts

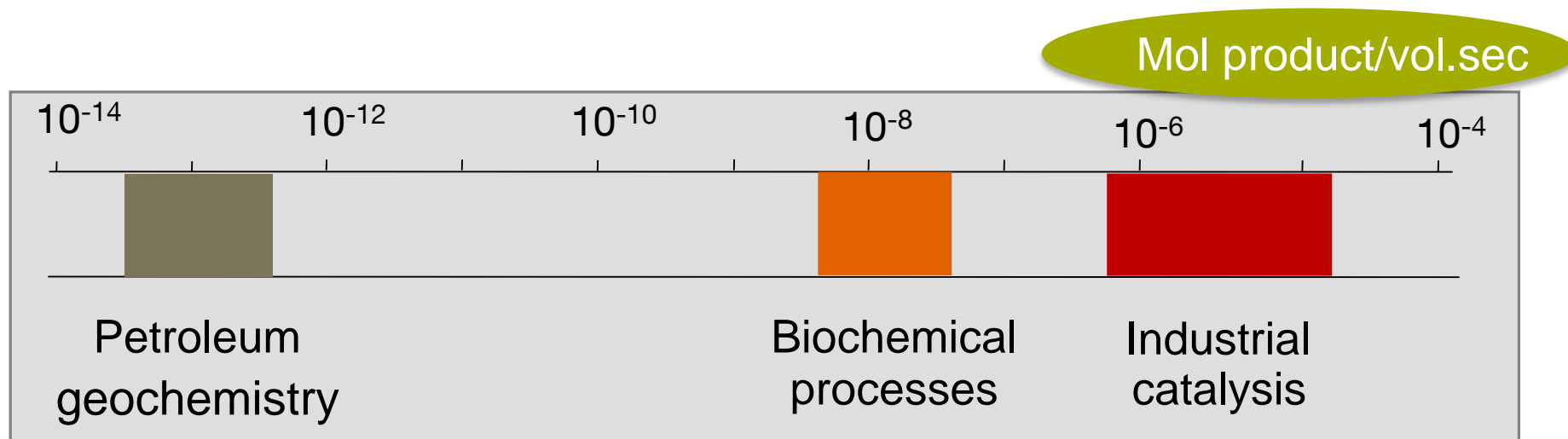
# Catalyst volume used



# Waste in chemical production

<i>Industry</i>	<i>Byproduct [kg/kg]</i>	<i>Product [ton/year]</i>
<b><i>Oil</i></b>	~ 0.1	$10^6 - 10^8$
<b><i>Bulk chemicals</i></b>	1 – 5	$10^4 - 10^6$
<b><i>Fine Chemicals</i></b>	5 – 30	$10^2 - 10^4$
<b><i>Pharmaceuticals</i></b>	50 – 100	$10 - 10^3$

# Rates of chemical processes



- Mismatch or rates between petroleum generation and use.
- Small volume chemicals – *Biochemistry*
- Large volume catalysis – *Heterogeneous Catalysis*