Conditions for the Deployment of Alternative Drivetrains

A global energy system perspective

Martin Densing, Hal Turton, Georg Bäuml

Paul Scherrer Institute (Switzerland), VOLKSWAGEN AG

Framework

- **Project:** in cooperation with car manufacturer Volkswagen

- **Goal:** to understand how the development of the global energy system influences the transport sector, focusing on
  - **personal car technologies**, and the corresponding
  - **fuelling options**, up to 2050

- **Approach:** **Scenario Analysis** with a detailed energy system model (GMM)
  → **sensitivity** of the energy system and technology choice to some **key uncertainties**: direction and magnitude of impact
  → identification of **robust trends**
  → **‘what-if’** assumptions about future, no forecast

PAUL SCHERRER INSTITUT

Contents

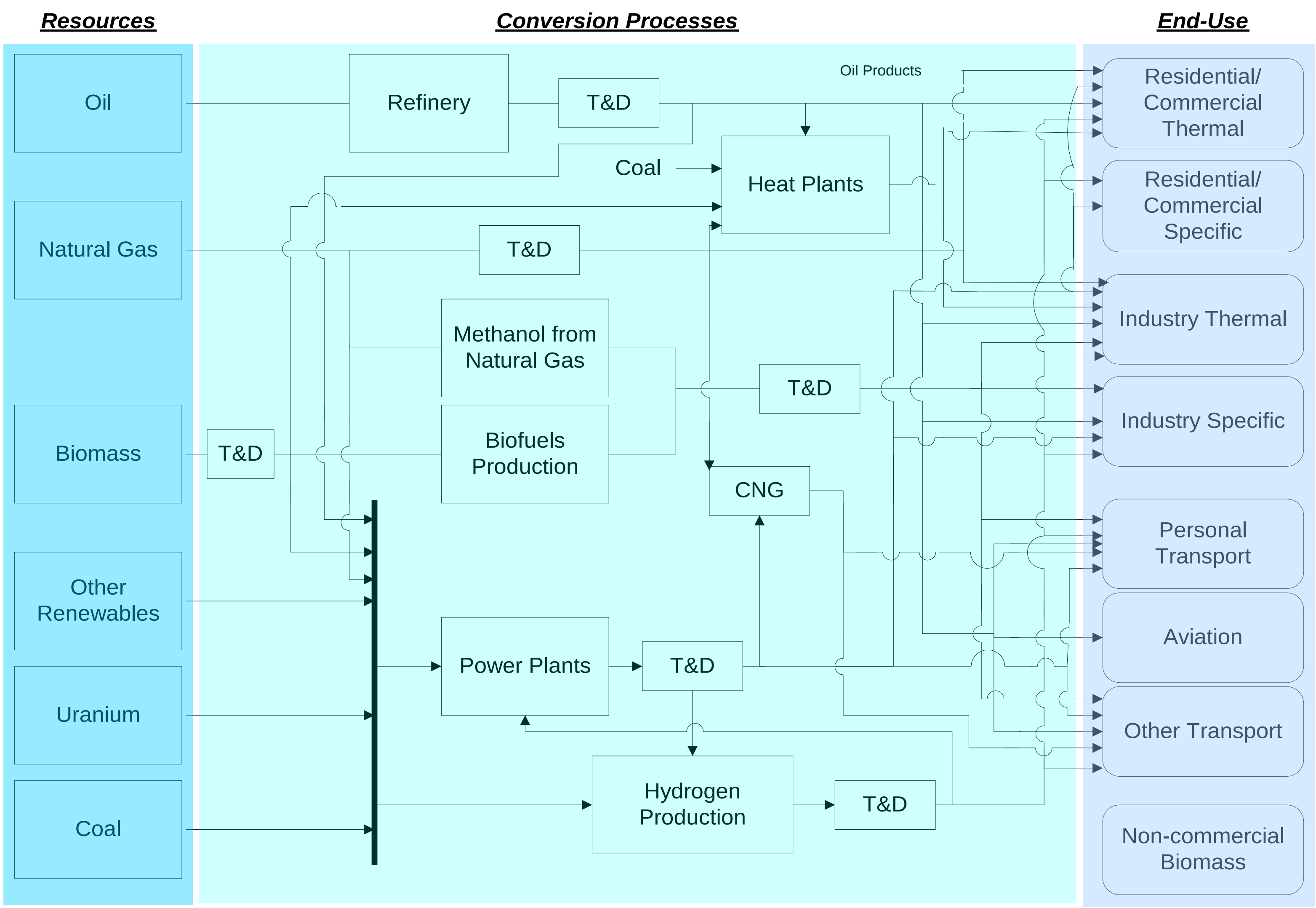
- Introduction of the Energy System Model (GMM)
- Overview of Selected Uncertainties for the Scenario Analyses
- Some Results of the Scenario Analyses
  - for Personal Car Sector
  - for Other Sectors of the Energy System

Modeling Framework of Global Energy System

GMM (Global Multi-Regional MARKAL Model)

- Bottom-up model: detailed representation of resources, technologies, energy flows, and technological change/learning
- Cost-optimization model: yields least-cost solutions for the global energy system under given sets of assumptions and constraints
    - Solution is globally optimal allocation of society's resources
    - Costs and "prices" in GMM represent cost of production, or the scarcity value based on the cost of substitutes (not "real-world" market prices, e.g. for oil)
- Long-term perspective: project reports results until 2050, but results until 2100 are available,
    - addressing long-term energy issues, e.g., resource depletion, climate change policy, economic development and technology learning
- End-Use-Demand inputs: based on IPCC-SRES B2-scenario („middle-of-the-road"); exogenously given
- Endogenous Technology Learning (ETL): unit costs of key technology components decrease with increasing experience (cumulative installations); e.g. battery costs, fuel cell costs

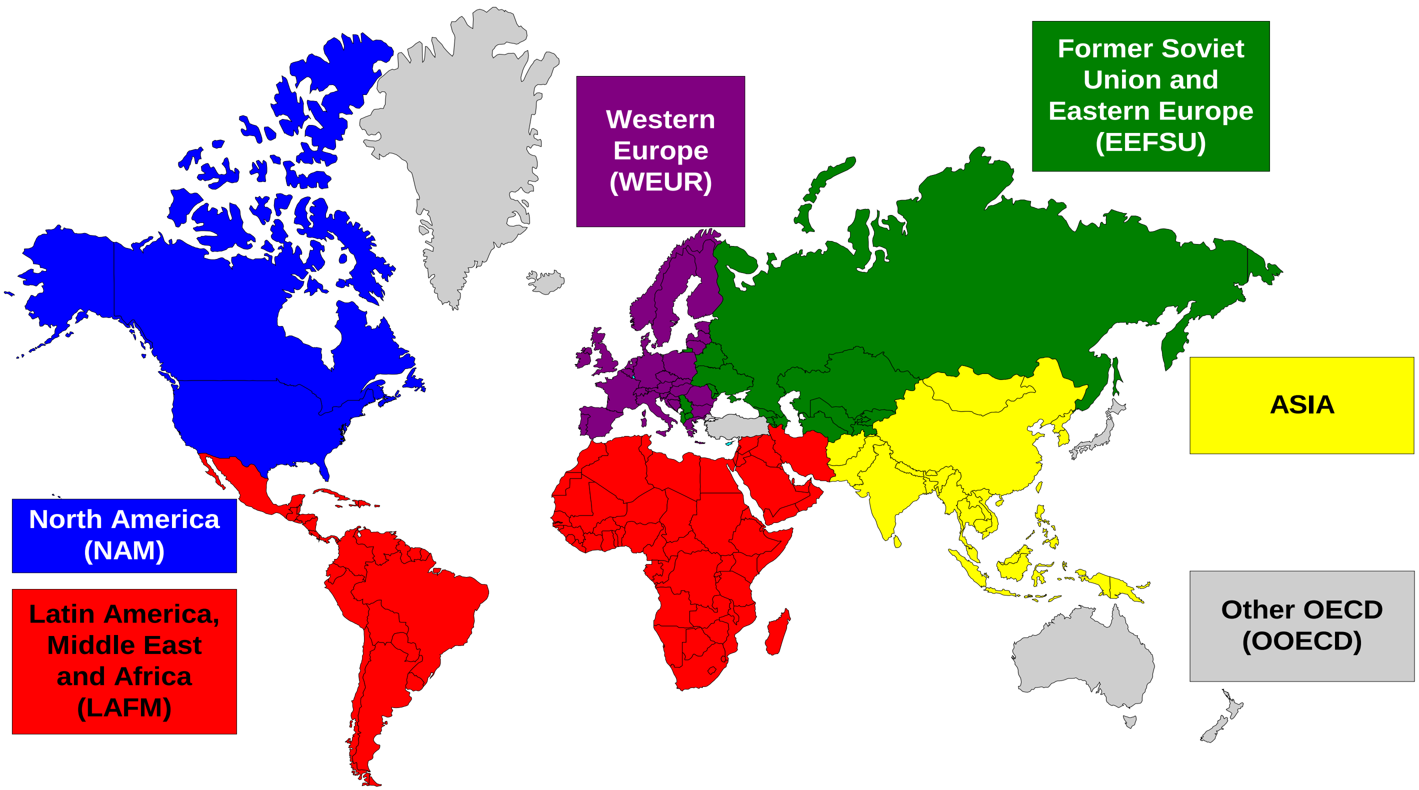
Energy System in GMM (simplified)



approx. 400 technologies per world region

T&D: Transport and Distribution

World-Regions of GMM

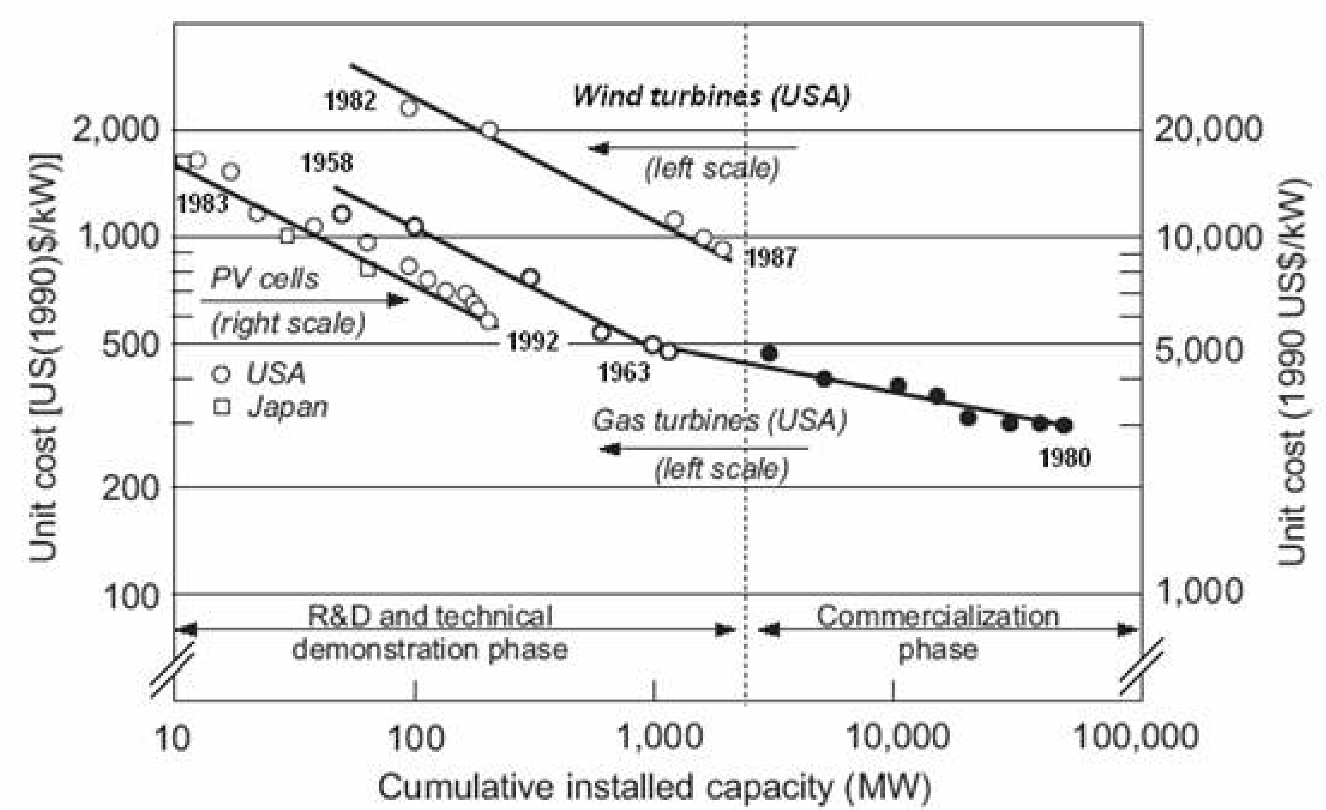


- For each region:
  - **Technology parameters:** Costs, efficiencies, size, growth constraints etc.
  - **Demands:** E.g. km-demand growth for personal car transport
  - **Policies**, **resources**, **renewable potential**, etc.
- Inter-regional trade of energy carriers (limited by transaction costs)
- Inter-regional technology diffusion of key components

WEUR := EU27 + Switzerland + Norway

Endogenous Technology Learning

Empirically, unit production costs depend on cumulative capacity:



$$\rightarrow \quad \frac{\Delta u_t}{u_t} = -b\frac{\Delta c_t}{c_t}$$

Source: IIASA-WEC 1995, Figure 4-7

Key components: Electric battery (in Battery Electric Vehicle, Hybrid Vehicles), Hydrogen FC, Gasifier,...

- Learning-by-doing: Unit cost u_t driven by cumulative capacity c_t
- Clustering: Key components can be part of several technologies → Sum of global cumulative capacity in all technologies determines u_t

- Exp.: Battery Storage (kWh): starts at 2010: 300$; 15% decrease by doubling capacity; lower bound: 100$

Car Technologies in GMM

ICEVs:

- Liquid Fuel ICEVs: Fuels: Gasoline or Diesel, Ethanol, Methanol blending, FT-Diesel, Biodiesel
- Advanced ICEV: Better efficiency*, no electric motor
- Gas Fuel ICEV: Fuel is CNG; otherwise similar to Liquid Fuel ICEV

Hybrids:

- Liquid Fuel Electric Hybrid (HEV): Cars with ICE and a small auxiliary battery with electric motor. Fuel choices similar to Liquid Fuel ICEV
- Gas Fuel Hybrid: Fuel is CNG; otherwise similar to HEV
- Hydrogen Fuel Cell Vehicle (HFCV, HFV): Cars with a fuel cell, buffer-battery, and electric motor
- Hydrogen Hybrid: Cars with a hydrogen ICE; otherwise similar to HEV
- Plugin-Hybrid Electric Vehicle (PHEV)

Battery-Electric Vehicle (BEV): with large battery (48kWh)

(can substitute other demand technologies in range and power, as all car technologies)

based on MIT Sloan Automotive Laboratory's naturally-aspirated spark ignition (NA-SI) engine (no turbo, no hybrid). Ex. of efficiency measures: friction reduction (engine, tires, aerodynamics), smart cooling, variable engine geometries, reduced weight, intelligent gear shift, no stop-restart.

Short-Range Car

Empirically, mean car travel distance is **short** (work; shopping; future: emission-restricted city centres)

→ Travel demand is split. Assumption: 10% of km-demand satisfied by **Short Range Cars.**

Vehicle Category	Long-Range Market	Short-Range Market
Liquid Fuel ICEV	all variants	gasoline fuelled
Advanced ICEV	all variants	gasoline fuelled
Gas Fuel ICEV	✓	-
Petroleum Electric Hybrid (subcategory of HEV)	✓	✓
Hydrogen Fuel Cell Vehicle (FCV)	✓	✓
Hydrogen Hybrid	✓	-
Gasoline Fuel Cell Vehicle	✓	-
Plug-In-Hybrid Electric Vehicle (PHEV)	✓	✓
Battery-Electric Vehicle (BEV)	✓	✓

Short-Range Car Parameters:

- ~**100 km** actual drive range (identical mileage for all world-regions)
  - short-range hybrids (HEV, plug-in, FCV) become relatively more efficient
  - e.g. plug-in HEV: 75% travel in electric mode (normal version: 50%)
- BEV: significantly smaller battery (18kWh)
- Smaller (cheaper) engine/FC/storage/battery in other vehicles: e.g. Plug-In HEV, FCV

Scenario Analyses

Policy stringency (climate and sectoral) →

	Policies inactive	Policies active • car efficiency targets • biofuel targets • carbon price	Policies active & reduction target (50% CO_2-emission cap relative to year 2000)
moderate oil and gas resources	"No Policy"	a. "Central Case" b. "No CCS" (CCS unavailable)	"Low Emissions"
low oil and gas resources (~50% reduction)	"Low Resources & No Policy"	"Low Resources"	–

↓ Resource pessimism

CCS: Carbon Capture and Storage

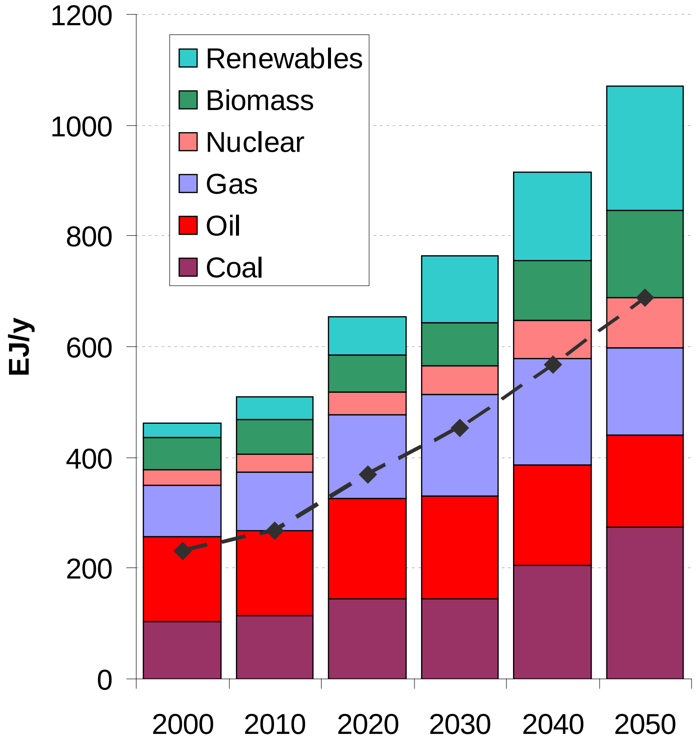
Car Efficiency: E.g. EU-targets (120g CO_2/km for new cars after 2012), regionally varying and extrapolated

Biofuel targets: for the whole transport sector (regional current targets and extrapolated)

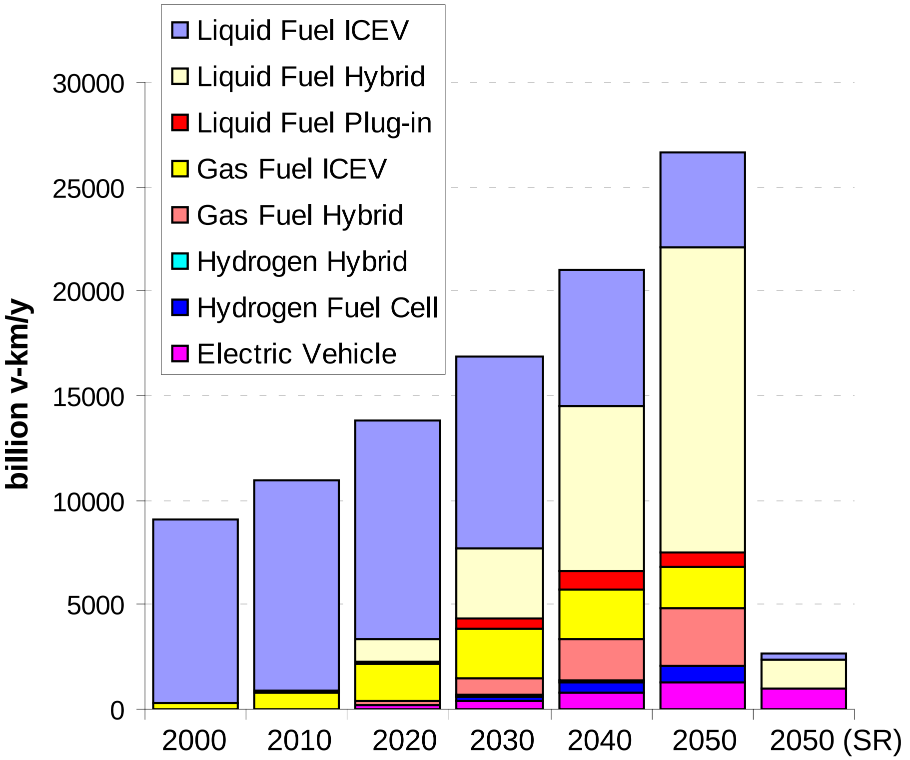
Carbon price: CO_2 price for the energy system, increasing at regionally varying speed with a long-term level of 200$/t$CO_2$

Some Results of “Central” scenario

Global Primary Energy Supply



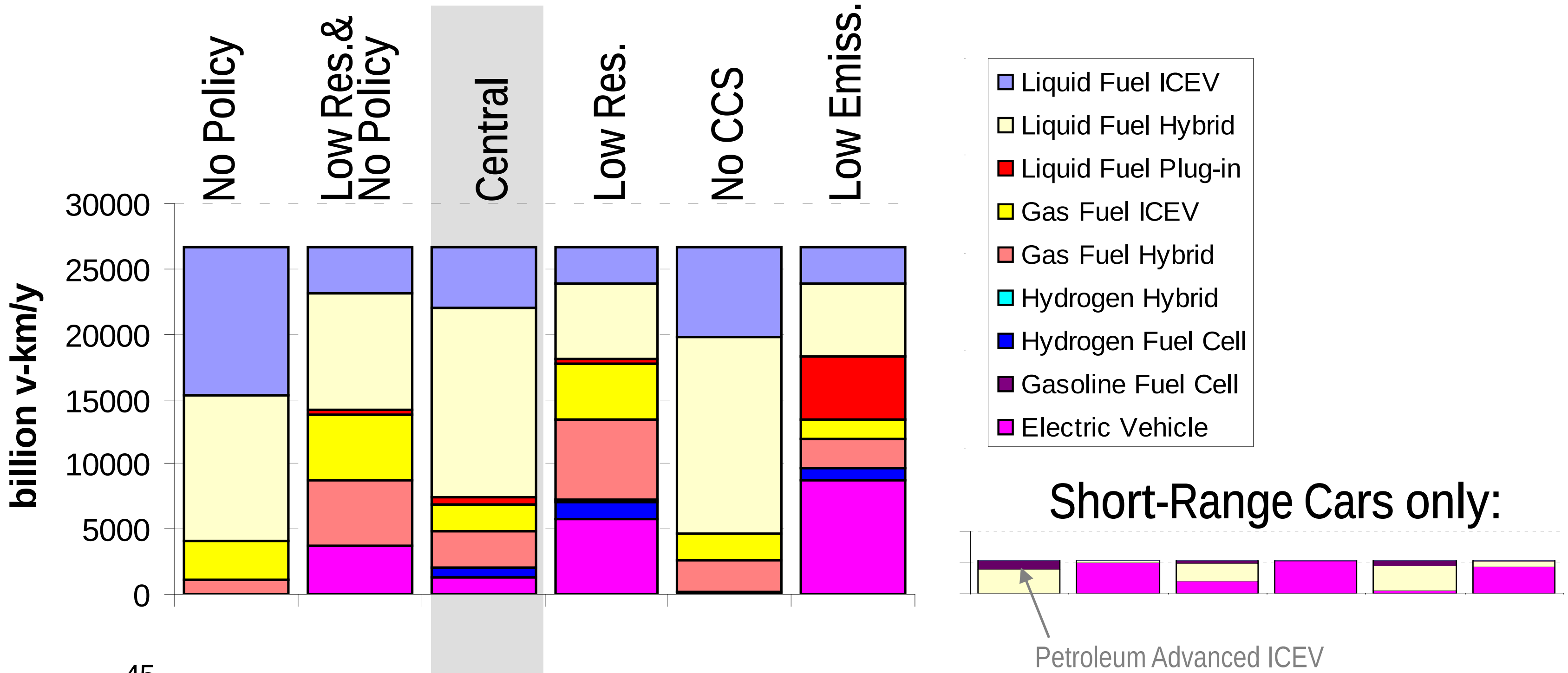
Global Car Technologies

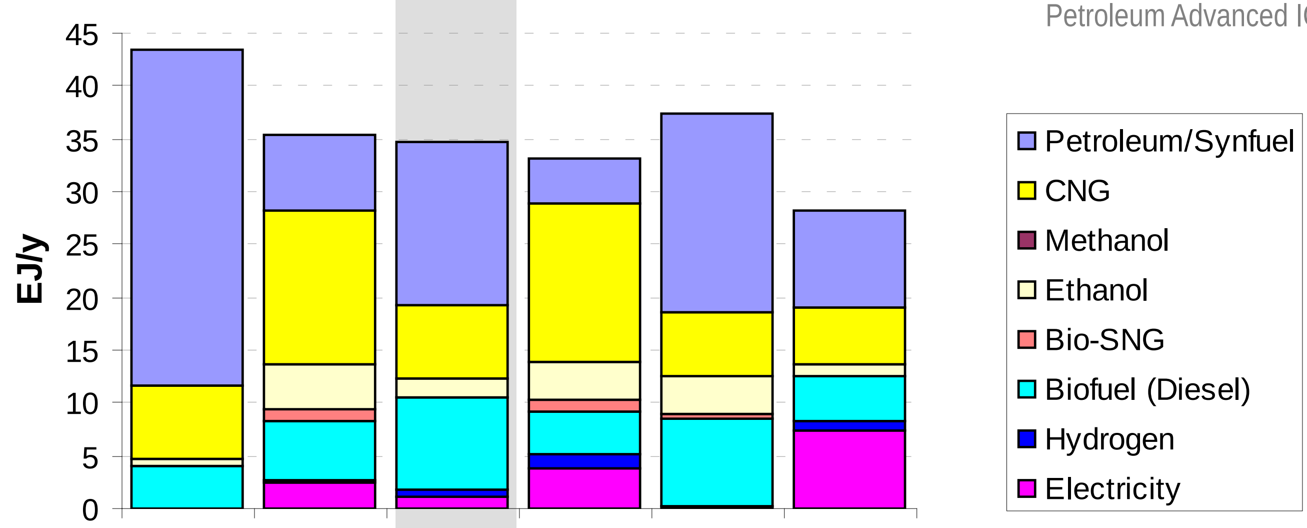


- **Renewables, biomass and coal** (due to CCS) are expanding
- **Developing countries** increase share of energy use (and emissions) (dotted line, Asia + Latin Am. + Middle East + East Europe)

- **Hybrids** dominate in 2050; **natural gas cars** are attractive; **electric and hydrogen vehicles** play a small role (under these assumptions)
- **Short-range market (SR):** battery vehicles are cost-effective; conventional technology is replaced

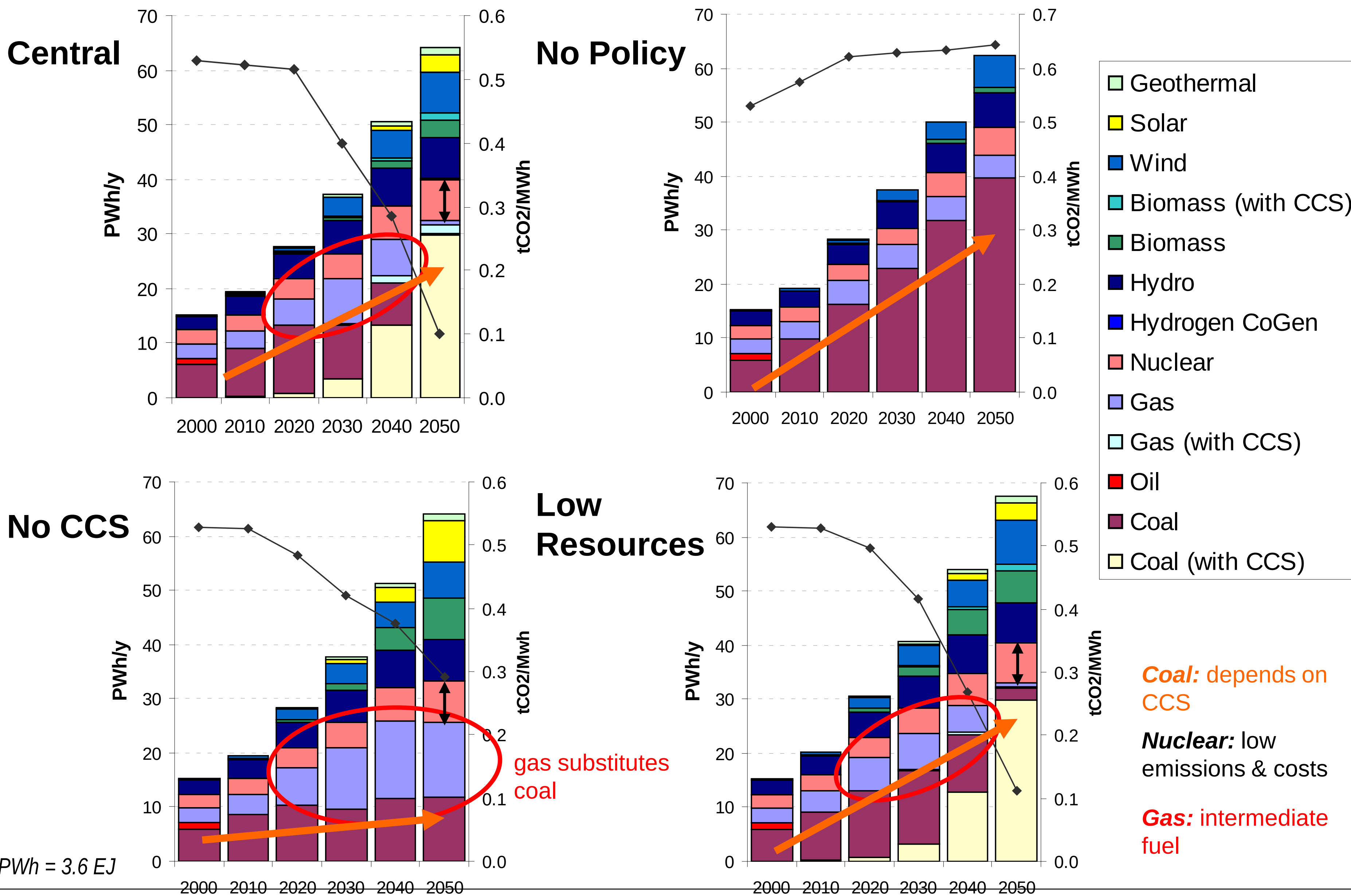
Car Technology and Fuel in year 2050 in Scenarios





Central Case: electricity for cars in 2050 is 0.5% of total generation

Electricity generation under different scenarios



Coal: depends on CCS

Nuclear: low emissions & costs

Gas: intermediate fuel

1 PWh = 3.6 EJ

Overall messages

- **Depletion of cheap oil**
  - is a major driver for many technology developments over the long term (hybrids, CNG vehicles, alternative fuel production)

- **Climate policy**
  - drives **earlier and additional** deployment of hybrids and CNG
  - enables: BEVs, FCVs, biofuels, H_2, more expensive renewables (e.g. solar), nuclear
  - stringent climate policy (50% target) further accelerates deployment of alternative transport technologies

- **CCS availability**
  - crucial for decarbonizing electricity / hydrogen (in both cases, production primarily from coal) → important for supporting new transport technologies
  - one implication is that more rapid deployment of nuclear would have a similar impact

- **Car technology** (under the above “ifs”)
  - HEVs are generally attractive under all cases, short-to-long term
  - CNG vehicles may be interesting in short-medium term
  - BEVs are a mid- to long-term solution for short-range market (but less attractive for long-range)
  - H_2 FCVs are most attractive over the very long-term (beyond 2050)

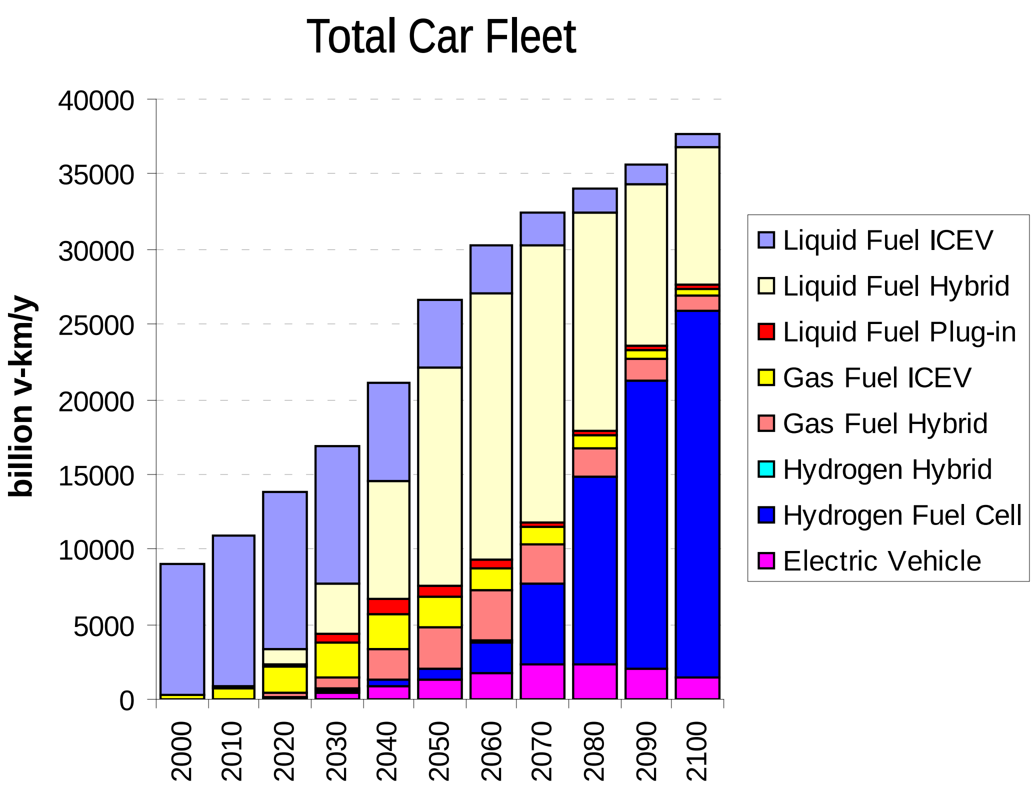
Selected References

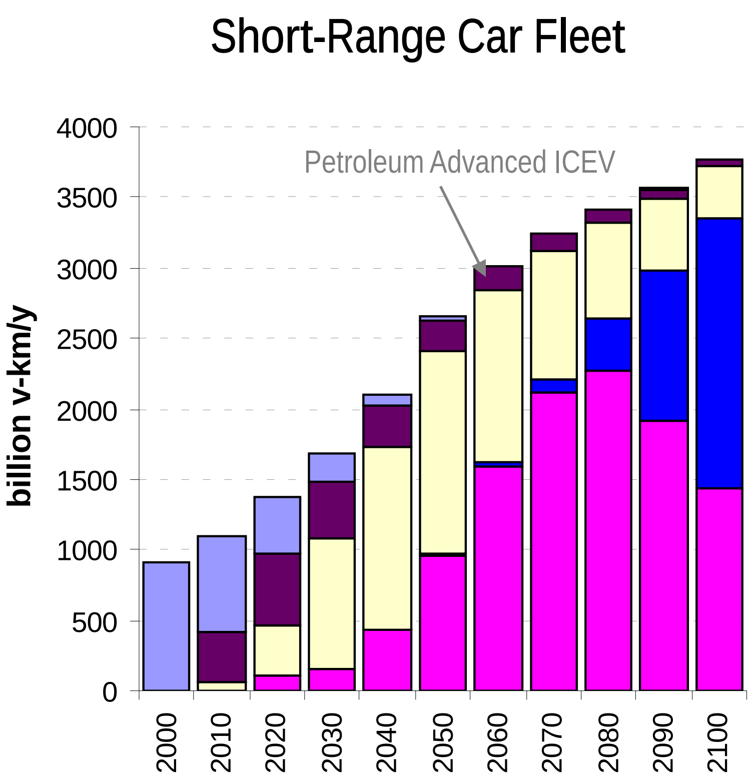
- **Azar et al. (2009):** Global energy scenarios meeting stringent CO_2 constraints – cost effective fuel choices in the transportation sector
- **Hedenus et al. (2010):** Cost-effective energy carriers for transport - the role of the energy supply system in a carbon-constrained world
- **Grahn et al. (2009):** Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO2 targets: connections between transportation and other energy sectors
- **Densing, Turton, Bäuml (2012):** Conditions for the successful deployment of electric vehicles – a global energy system perspective, *The Energy Journal*, in press

…our group seeks a PhD Student and a Post-Doc…

Thank you!

Long-Term Development of Global Car Sector (Central Scenario)

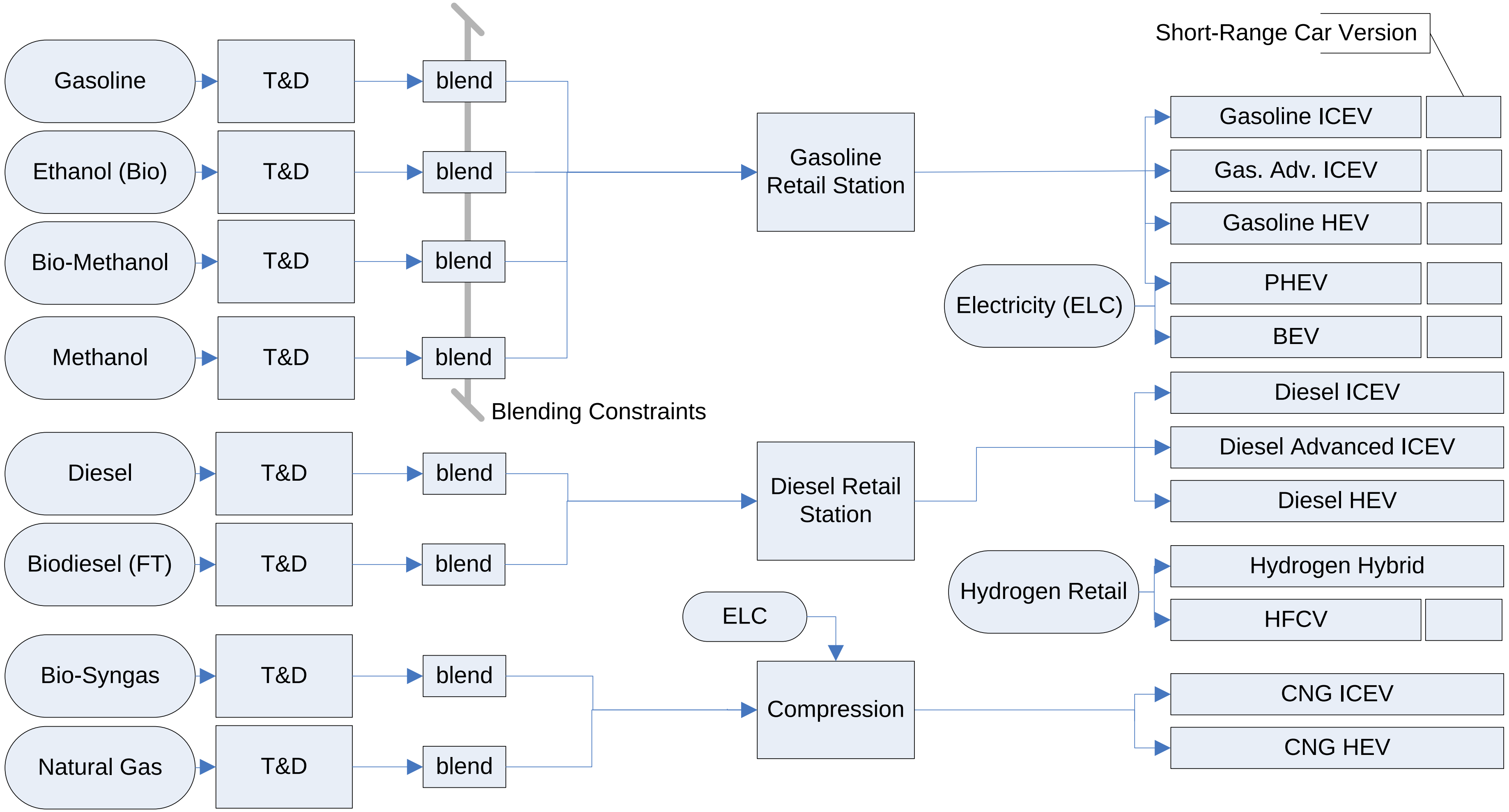




Long-term drivers fo HFCVs:

- technology learning reduces FC stack costs
- H_2 is also used in non-car transport →synergy in infrastructure build-up
- cheap low-carbon H_2 is crucial (CCS availability)
- short-range car sector: BEVs are cost-competitive due to reduced investment costs

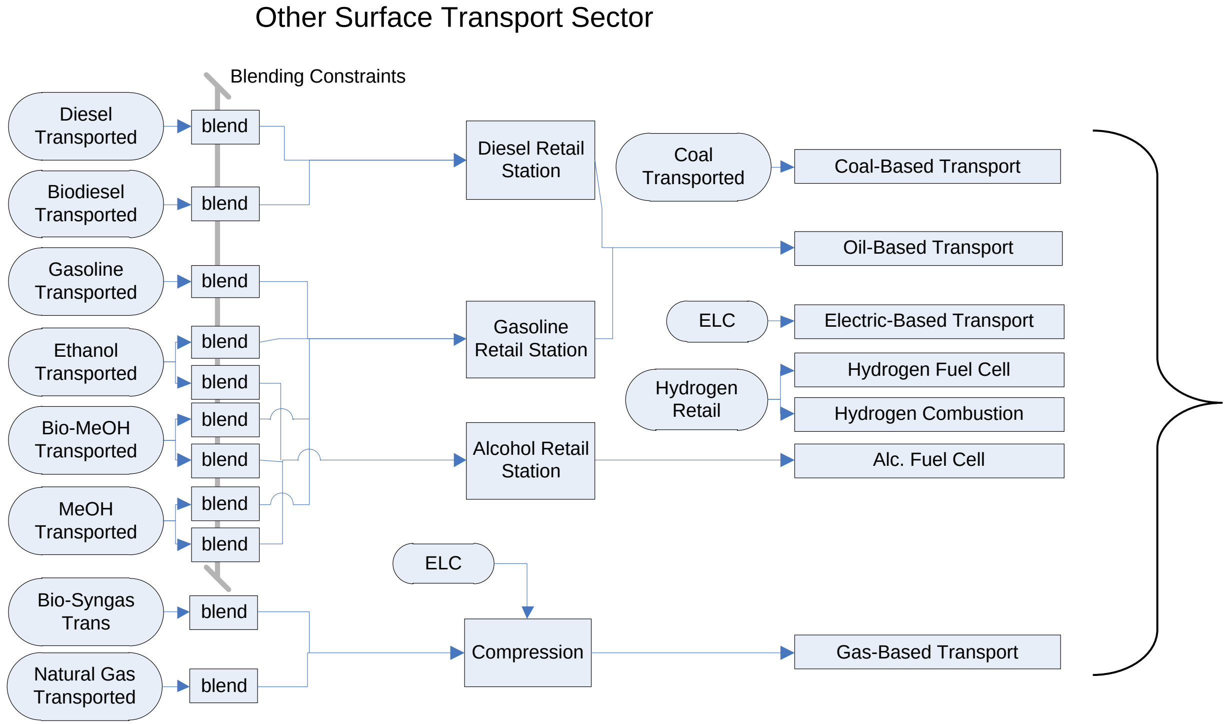
Personal Transport Sector



WEC/PSI (2011): Global Transport Scenarios 2050

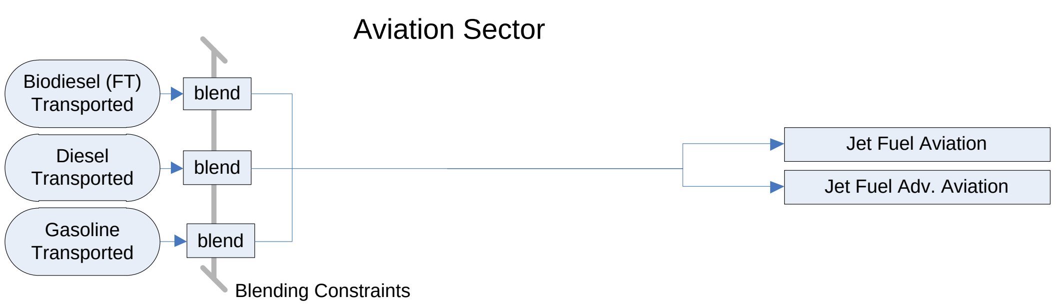
Other Surface Transport and Aviation Sector

Other Surface Transport: Trucks, buses, other commercial road vehicles, 2- and 3-wheelers, rail, ships



technologies categorized by

- fuelling option, and
- engine type



WEC/PSI (2011): Global Transport Scenarios 2050

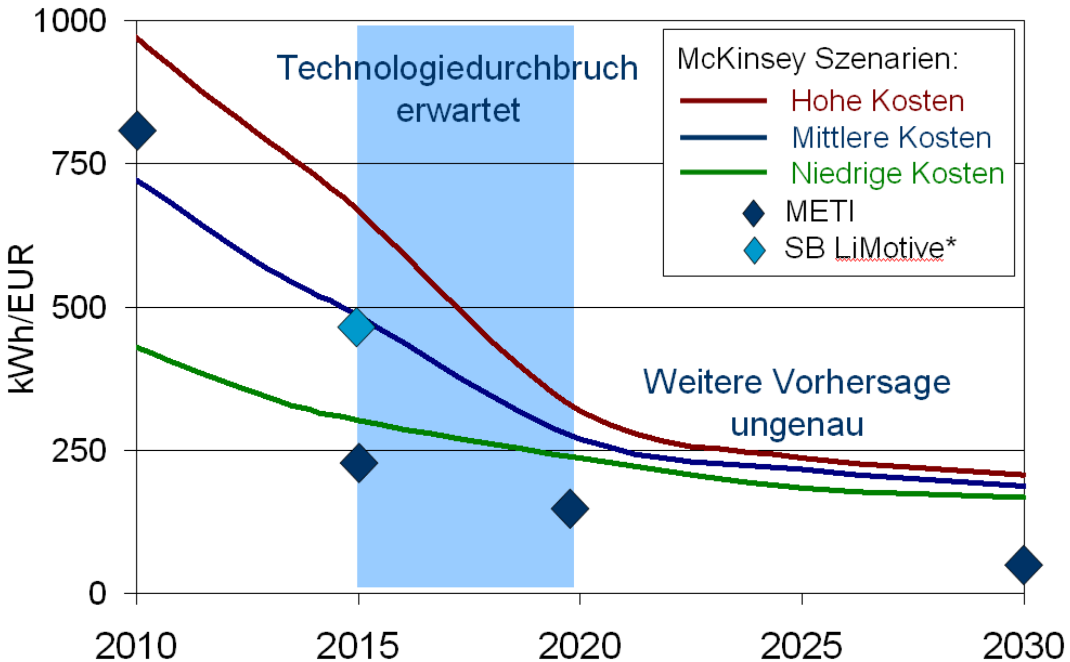
PAUL SCHERRER INSTITUT

Some ETL Parameters

Some endogenous costs of key components in GMM:

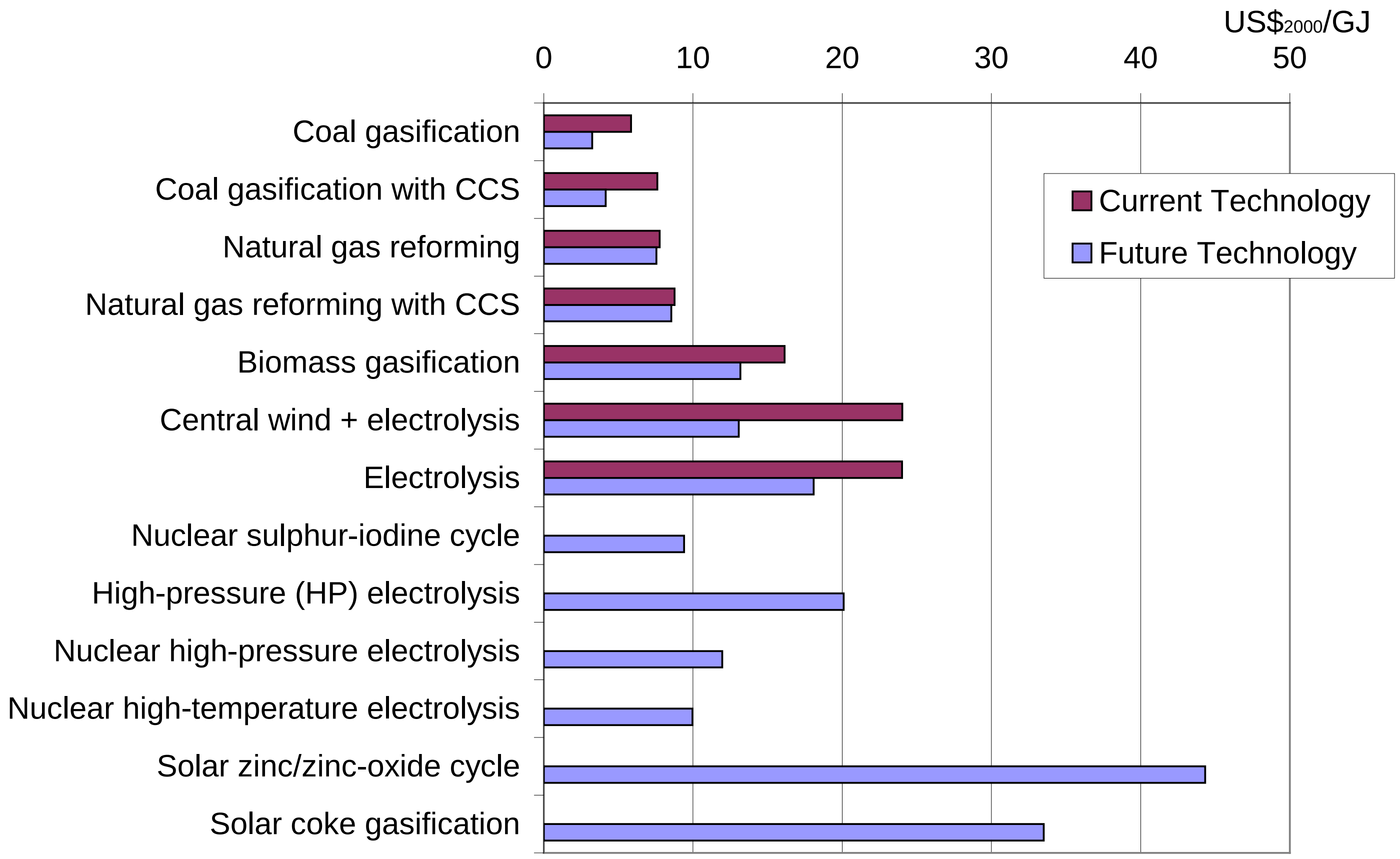
component	initial cost (year)	decline by capacity doubling	floor
Battery Storage (kWh)	300$ (2010)	15%	100$
Mobile Fuel Cell (kW)	250$ (2010)	15%	50$
Solar PV (kW)	5500$ (2000)	18%	1000$

Comparison: Exogenous battery costs estimation in industry:



Detailed Technology Options

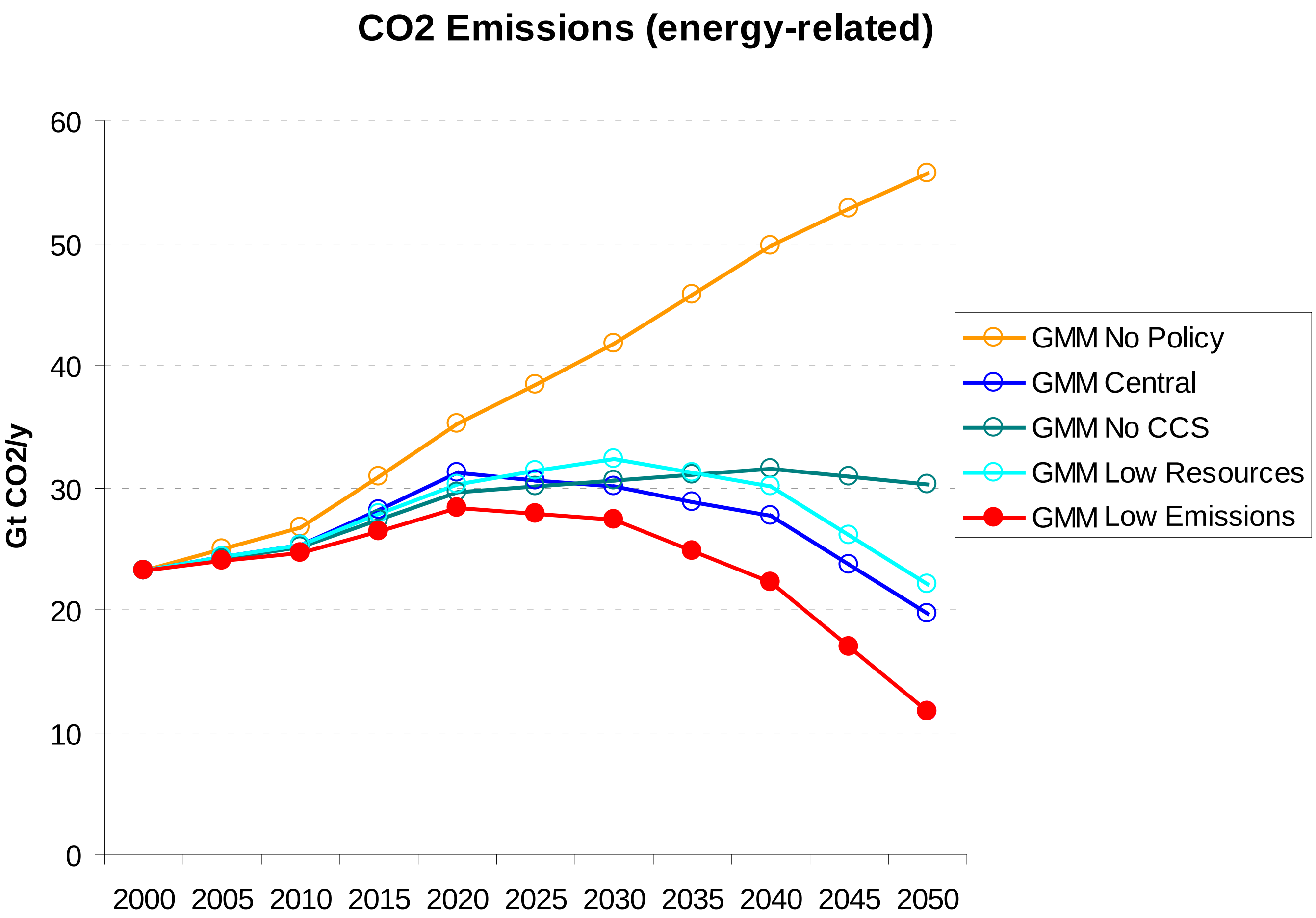
Hydrogen Production Costs in GMM:



Source: adapted from US DoE (2006) and Felder (2007)

Note:
- US Dollar based on year 2000
- investment costs annualised with 5% discount rate
- feedstock costs constant in chart (GMM fuel costs are endogenously varying)

Emissions

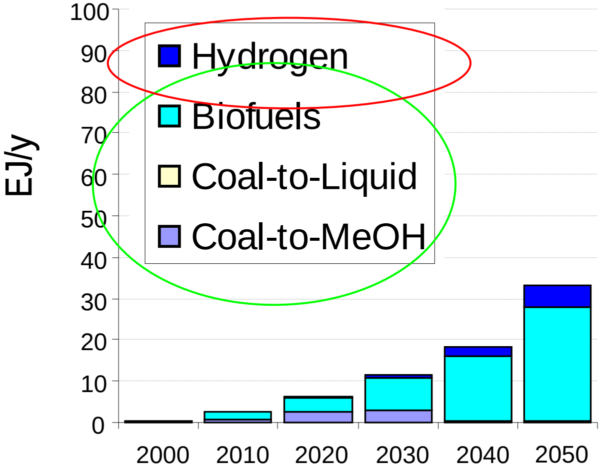


Low oil and gas resources lead to slightly higher CO_2 emissions with climate policy (higher use of coal slightly outweighs improvements in efficiency and increased use of renewables)

Alternative fuel production

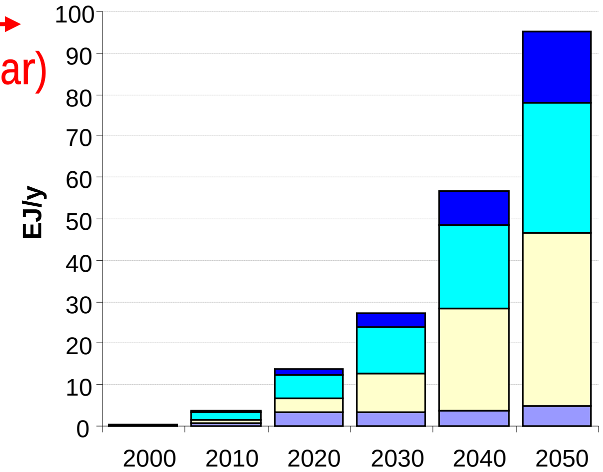
PAUL SCHERRER INSTITUT

Central Case



- more H_2 (from coal, gas, nuclear)
- H_2 can partially replace oil

Low Resources

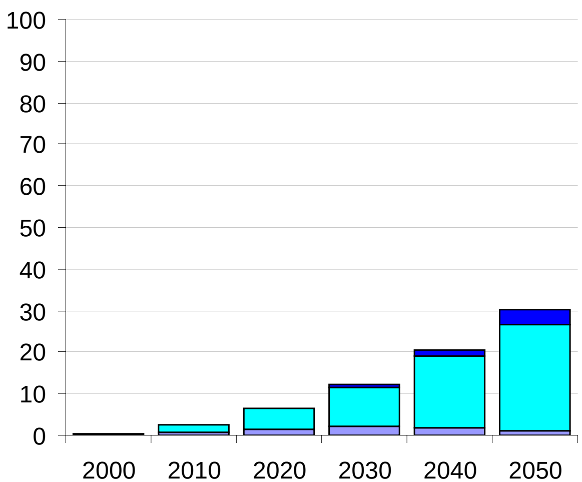


H_2 enabled by:

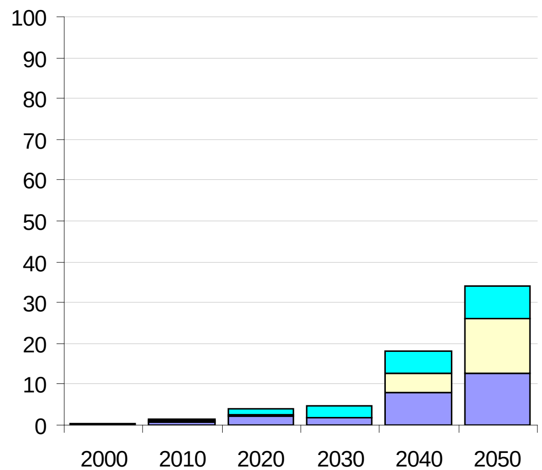
- Climate Policy, or
- Low Resources

H_2 from coal discouraged

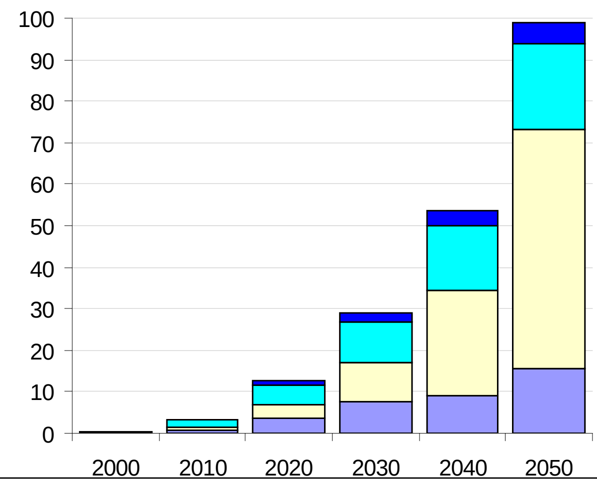
No CCS



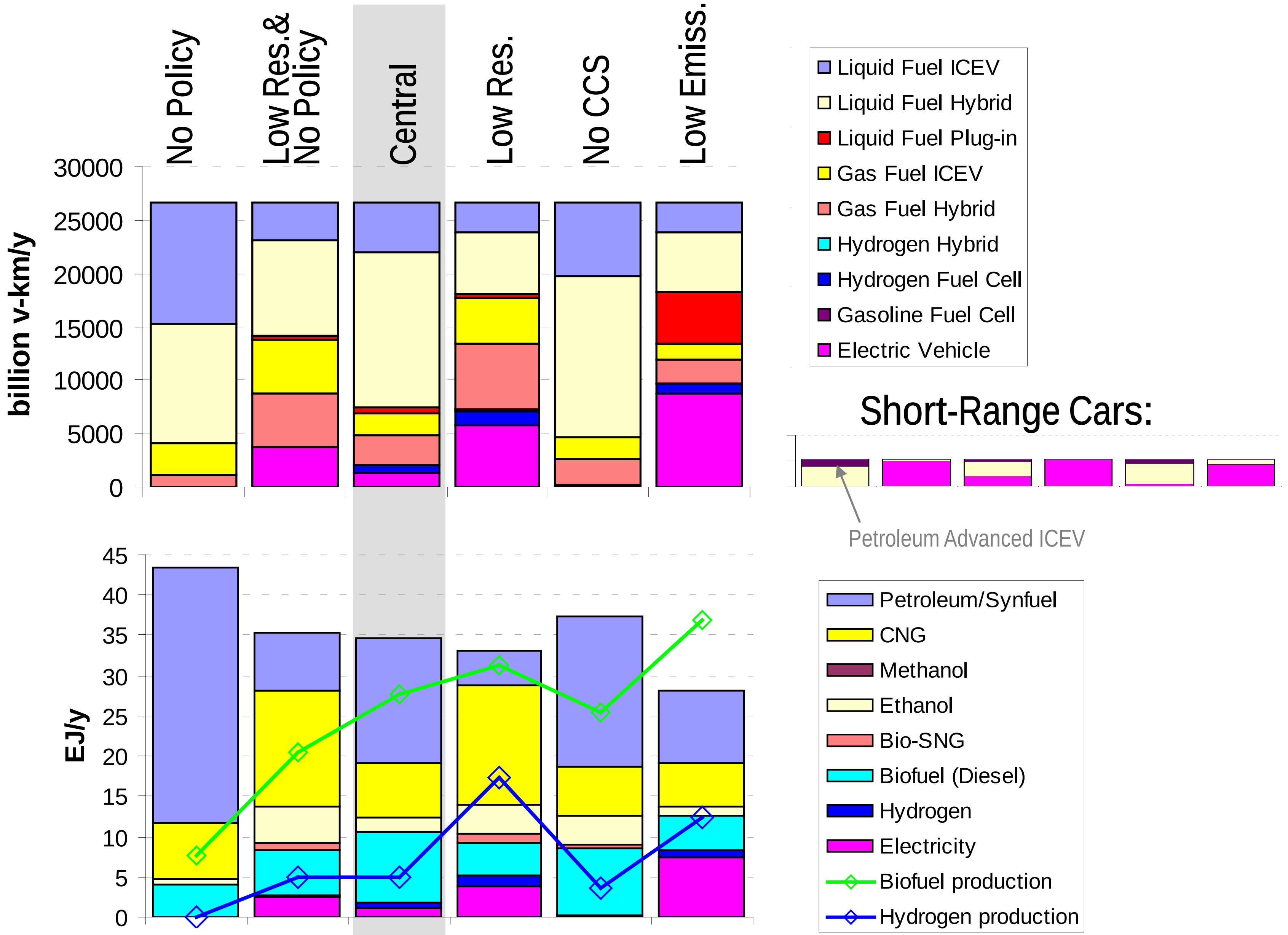
No Policy



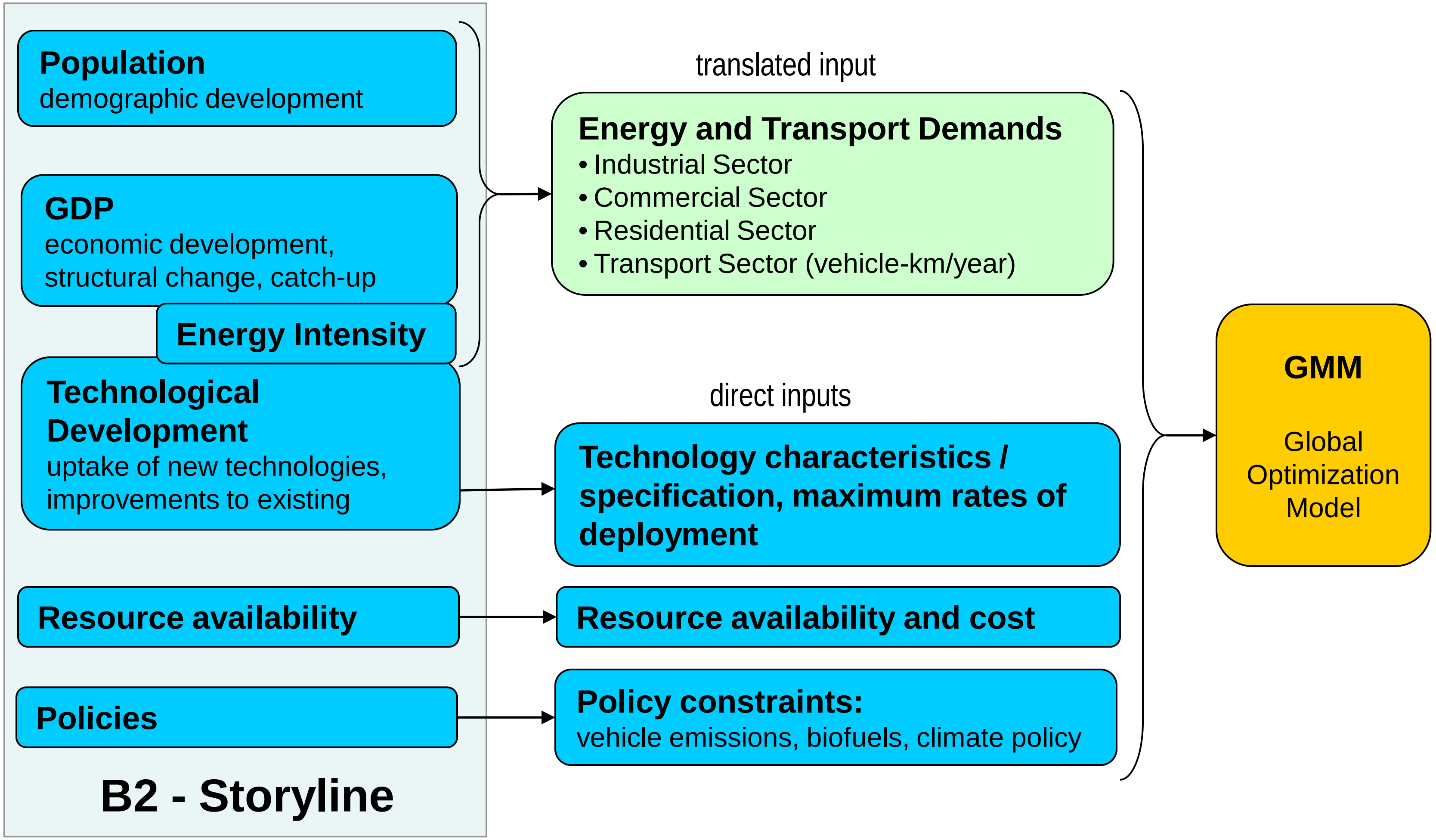
Low Resources + No Policy



Car Technology and Fuel in year 2050



Developing a scenario to analyse energy and transport



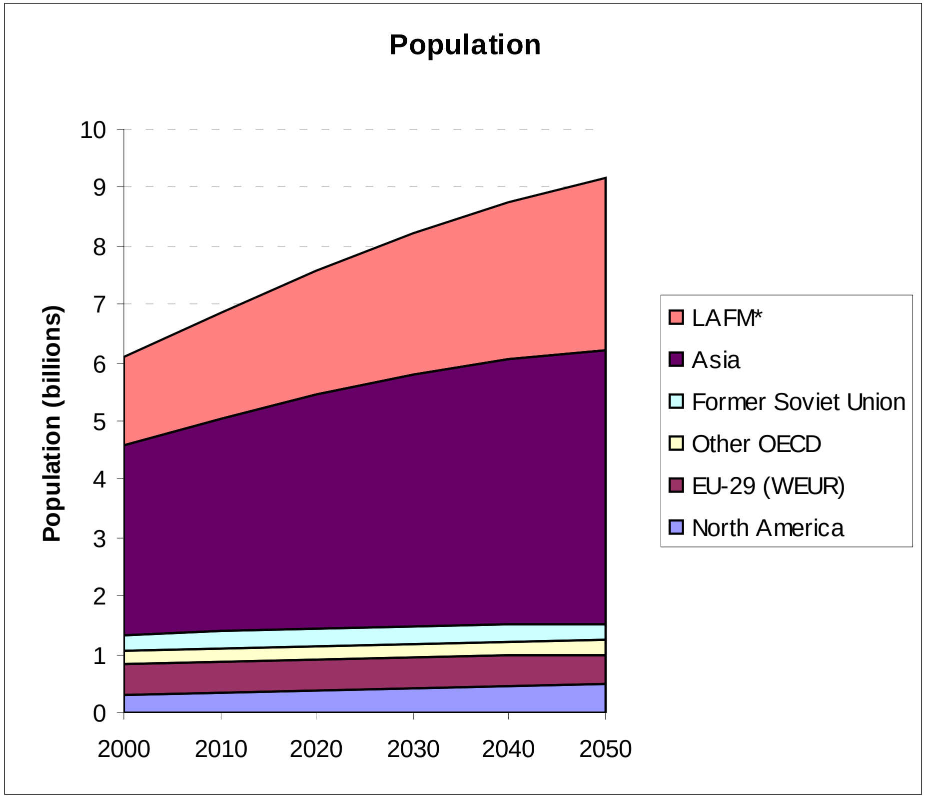
IPCC's B2 scenario has **'dynamics-as-usual'**: e.g. GMM uses

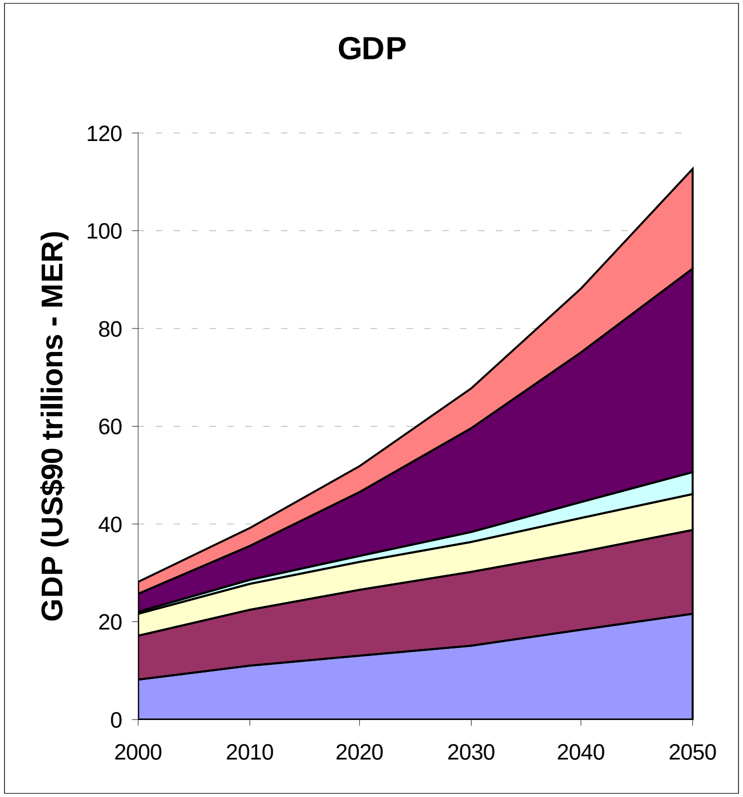
- avg. ann. income growth (1990 – 2050): 2.8%; historical (1950 – 1990): 2.2%
- avg. ann. km-demand growth (2000 – 2050): 2.2% car transport, 2.9% air transport

Central Case: Population and GDP drivers

Energy demands derived from the IPCC's B2 scenario (updated with Global Insight data):

B2 scenario based on 'dynamics-as-usual': future rates of change (e.g. technological change, energy intensity) do not depart substantially from historical experience



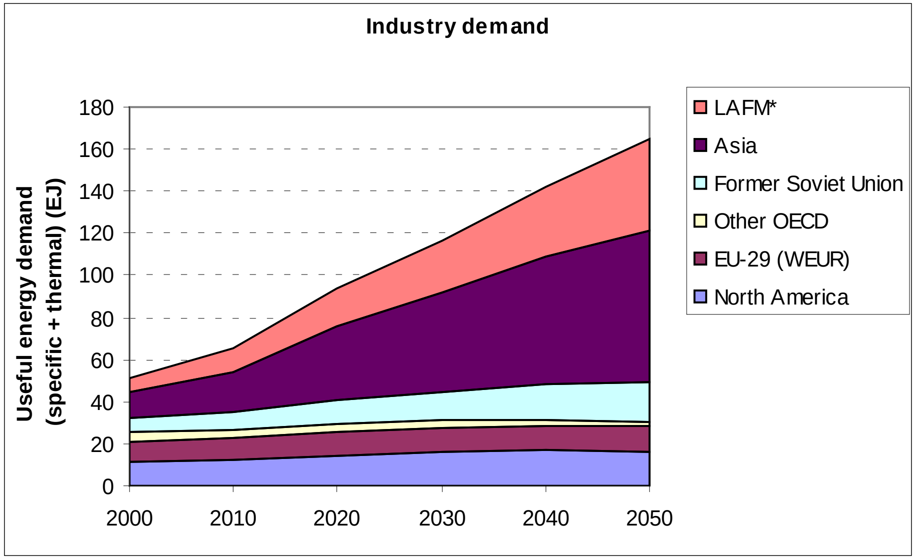


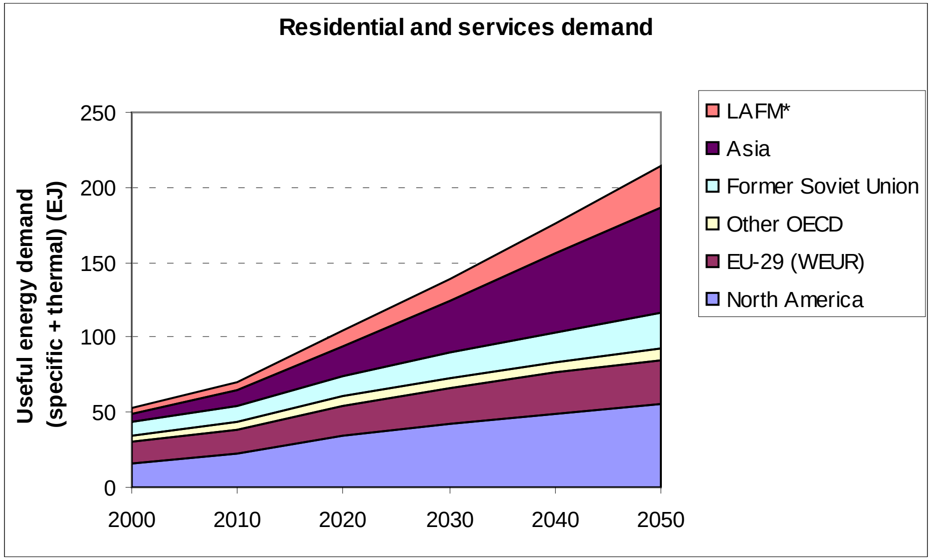
- population stabilizes at about 10 billion by 2100
- largest increase in population and in GDP in the developing world

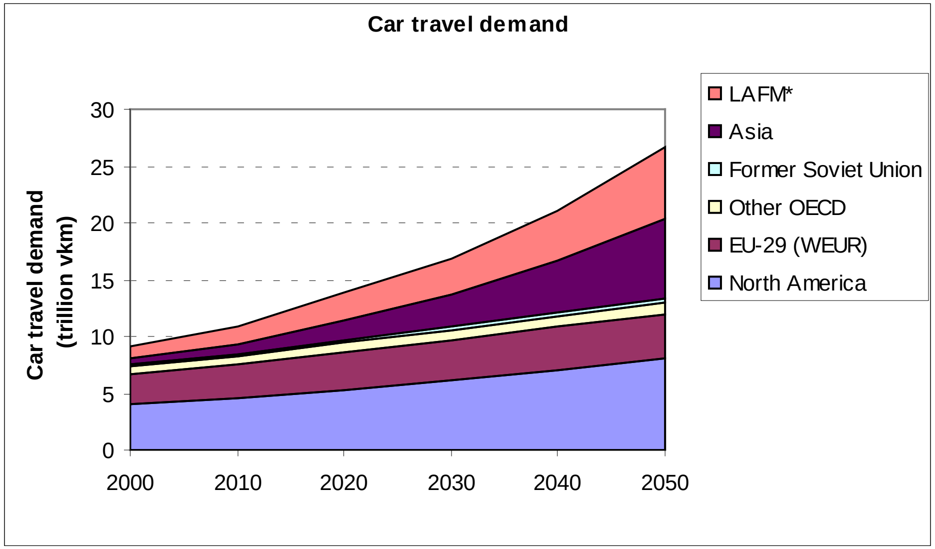
$$\text{energy} = \frac{\text{energy}}{\text{gdp}} \frac{\text{gdp}}{\text{popl.}} \text{popl.}$$

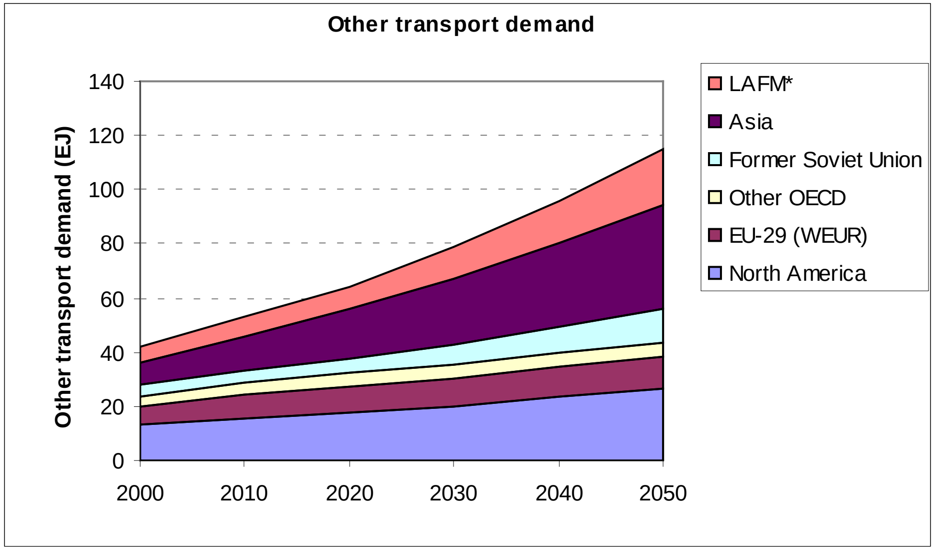
* LAFM: Latin America, Africa, Middle East

Central Case: Energy Demand, Car Travel Demand





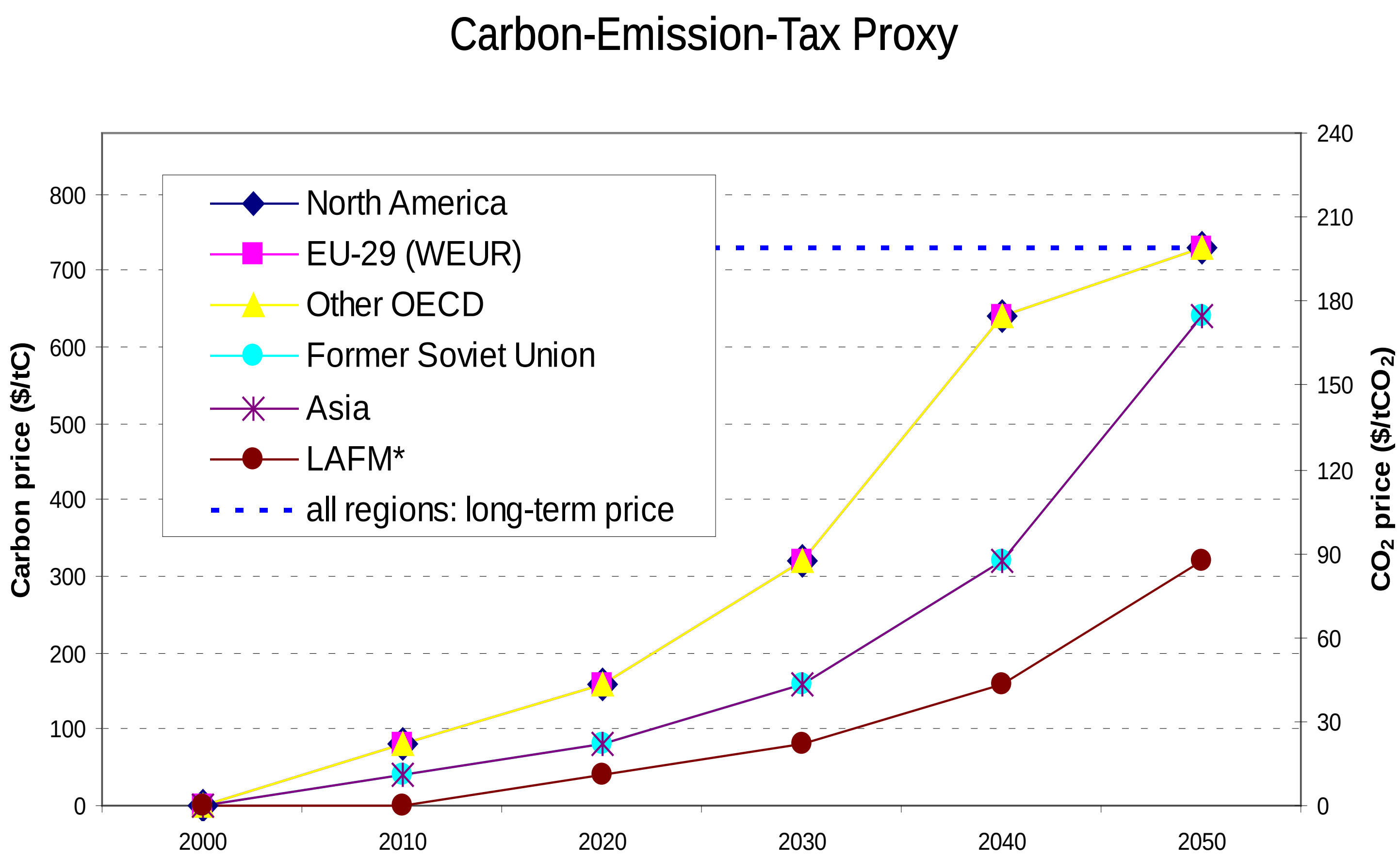




Car travel demand (vehicle-km per year) is calibrated to year 2000 statistics, and projected using the v-km growth rates from the IEA/SMP model*.

*IEA/SMP Model Documentation and Reference Case Projection; L. Fulton (IEA) and G. Eads (CRA); July 2004, p.34

Climate Change Policy

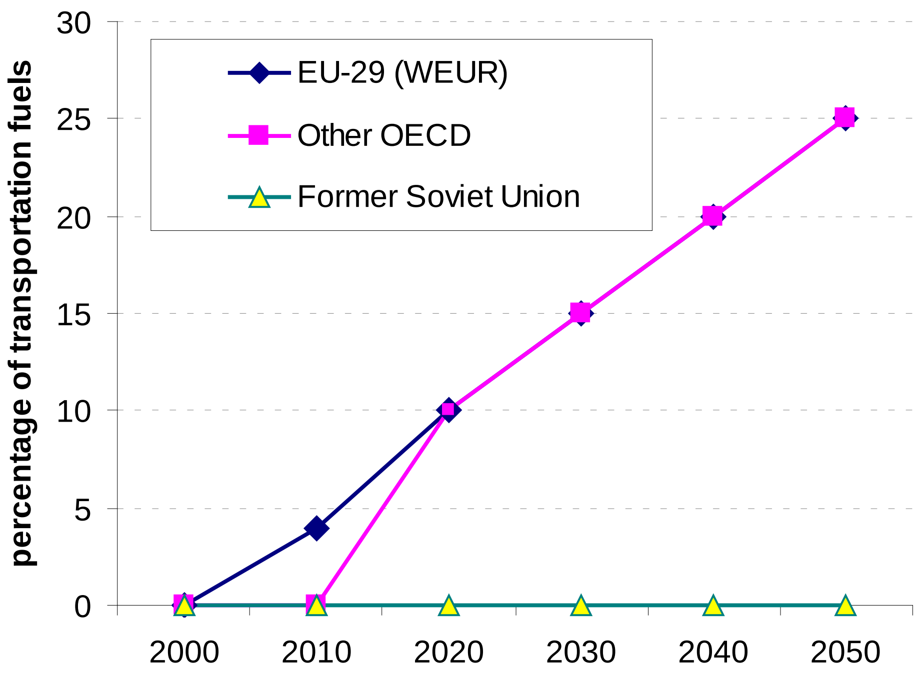


- Biofuels: have no emissions in GMM
- CCS potential until 2100: approx. 2500 Gt CO_2

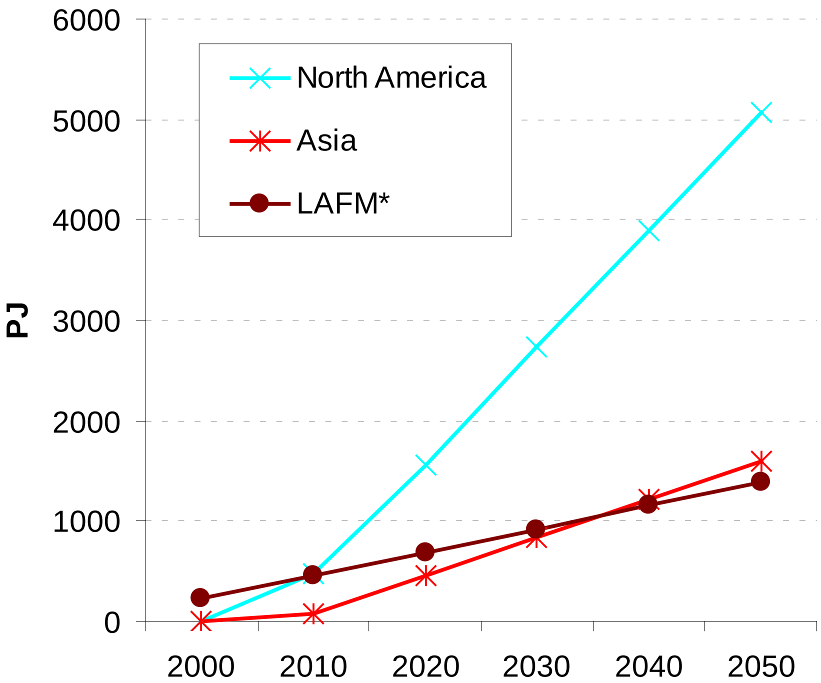
* LAFM: Latin America, Africa, Middle East
"$" refers to US dollar with base year 2000

Biofuel Targets in the Transport Sector

relative targets:



absolute targets:



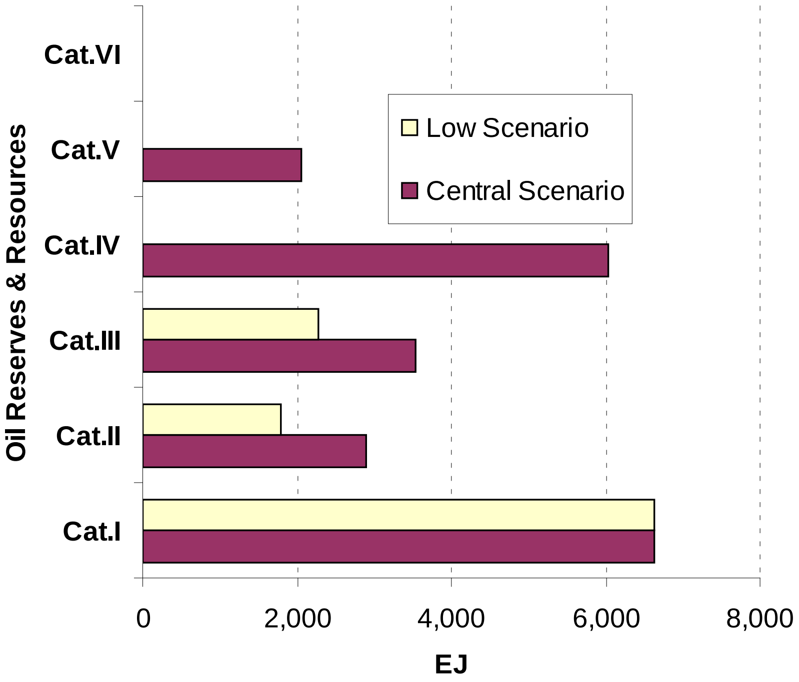
- EU-29: Directive 2009/28/EC until 2020
- North America: USA Energy Independence and Security Act 2007 (until 2022)
- Asia: China NDRC targets (until 2020)
- LAFM: projection of historical production in Brazil

*LAFM: Latin America, Africa, Middle East

Scenarios of Oil & Gas Resource Availability

- **Central Case:** Conventional oil & gas in line with IEA and BGR estimates, Some unconventional oil & gas reserves and resources also included

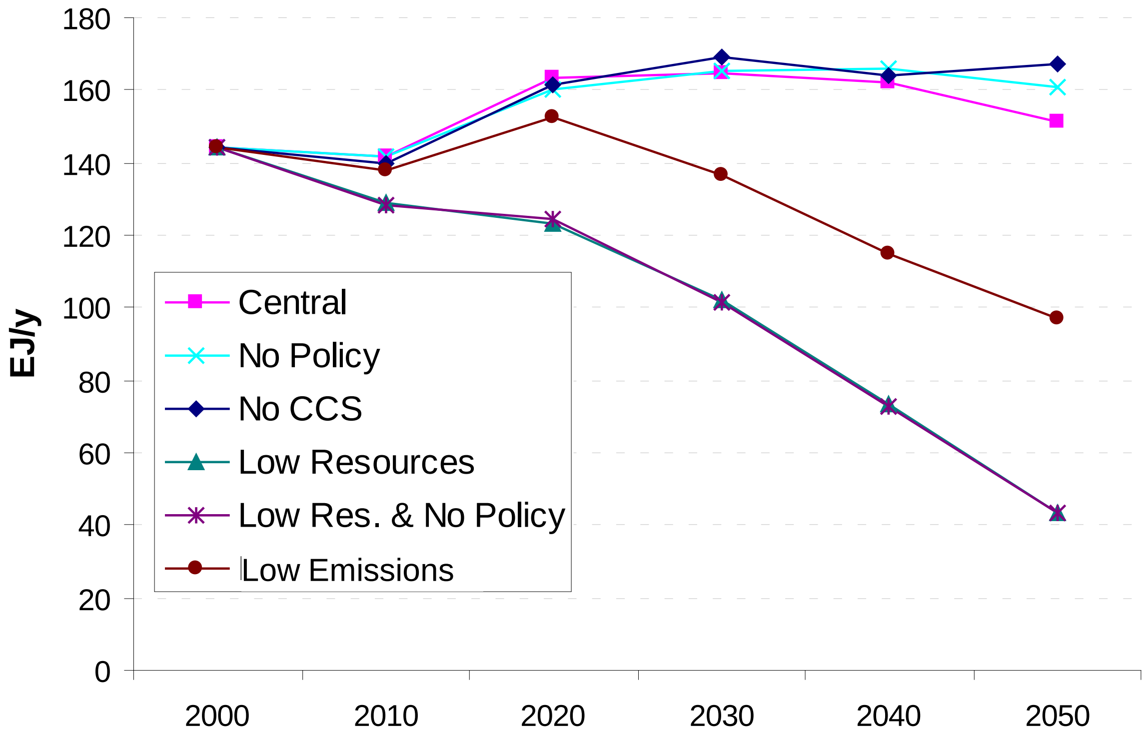
- **Low Resources:** - Gas: unconventional resources are assumed to be unavailable
  - Oil: no unconventional reserves or resources, reduced conventional resources (total approx. 50% less than Central Case, guided by estimates of the EWG, but still higher)



Category I: Proven reserves (discovered and high probability that they can be extracted)
Category II: Estimated additional reserves (additional volumes that are thought to exist and to be extractable, but with higher costs)
Category III: Additional speculative resources (resources are occurrences with less-certain geological assurance and/or with doubtful economic feasibility)
Category IV: Enhanced recovery of existing reserves (e.g. by solvents, steam injection)
Category V: Unconventional reserves (oil shales, tar sands, bitumen, and heavy oils)
Category VI: Unconventional resources

Rogner 1997: An Assessment of World Hydrocarbon Resources. Annu. Rev. Energy Environ. 1997. 22:217-62

Production of Oil under different scenarios



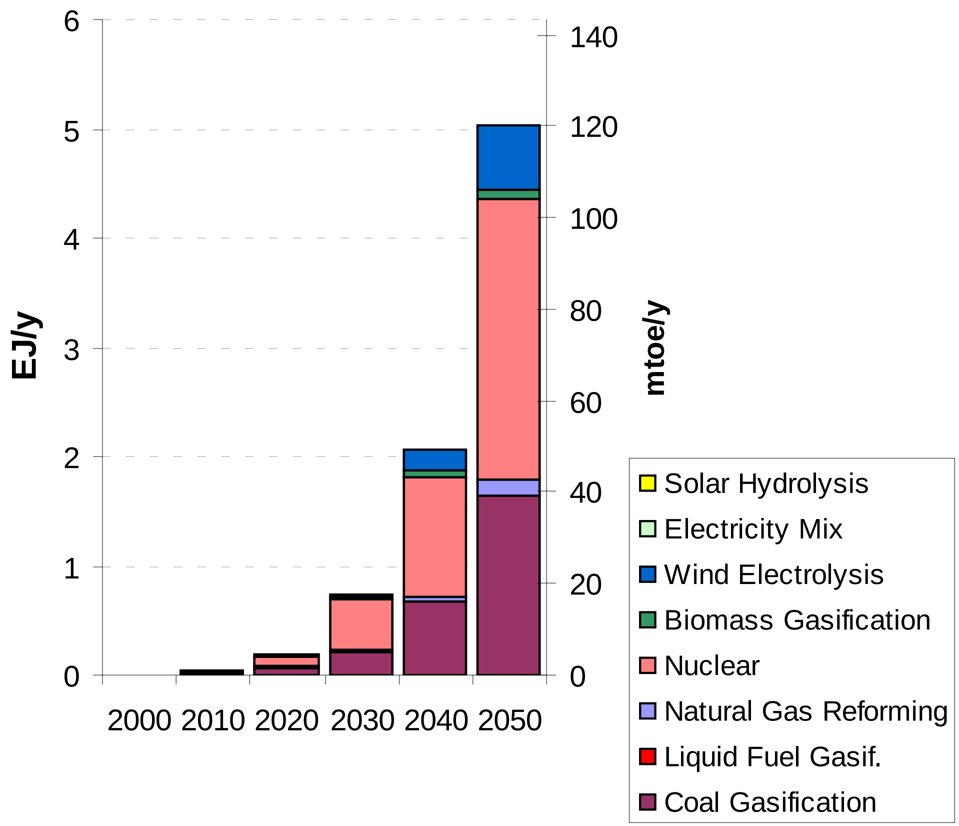
No policy assumes the same resources as **Central** case, but without any policy measures

- The applied policy measures have a minor impact on production before 2040/2050. (increase in aviation*, decrease in car transport)
- Oil production **peaks in 2030 or before in all scenarios** (depletion of cheap reserves and resources)
  - In Low Resources Scenario (around ~1500 billion bbl), production is already declining from 2000.

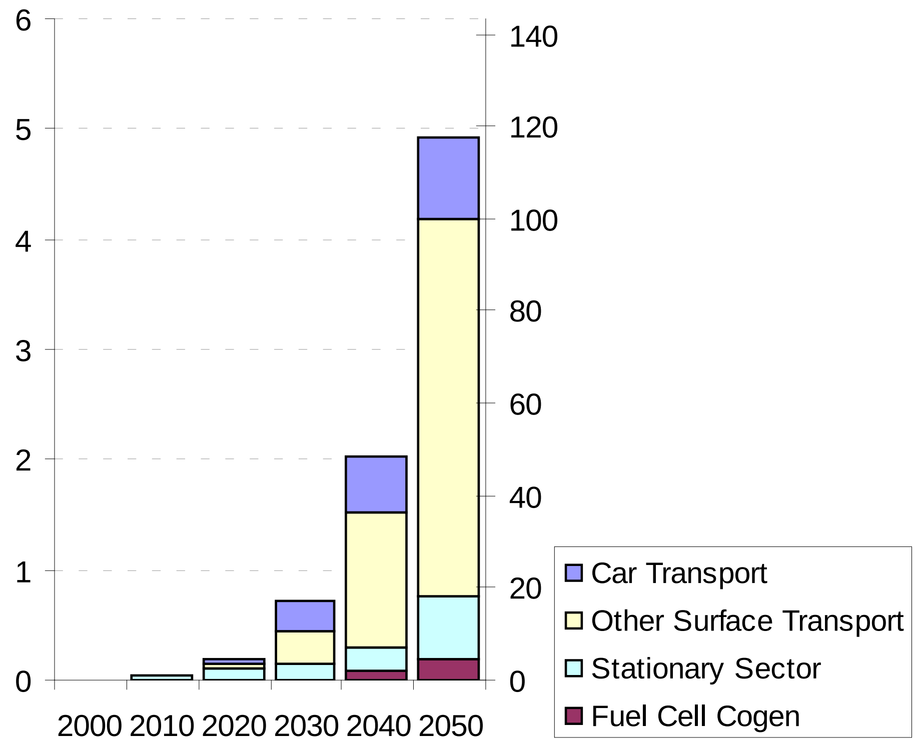
* *some studies see potential for biofuel: Air Transport Action Group,* Beginner's Guide to Aviation Biofuels*, 2009* , 50% will be reached by 2040

Hydrogen in the Energy System (Central Scenario)

Production of H_2



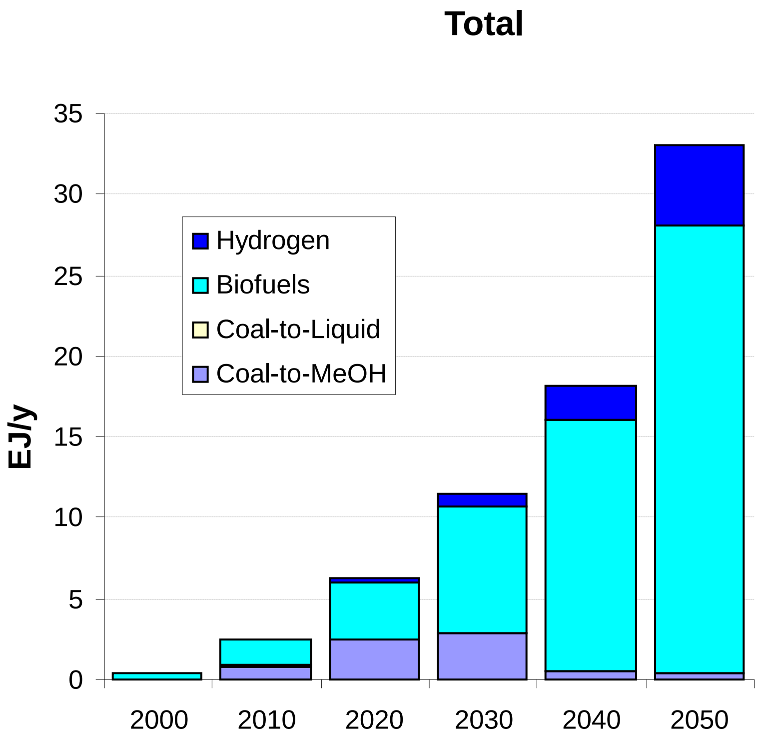
Consumption of H_2

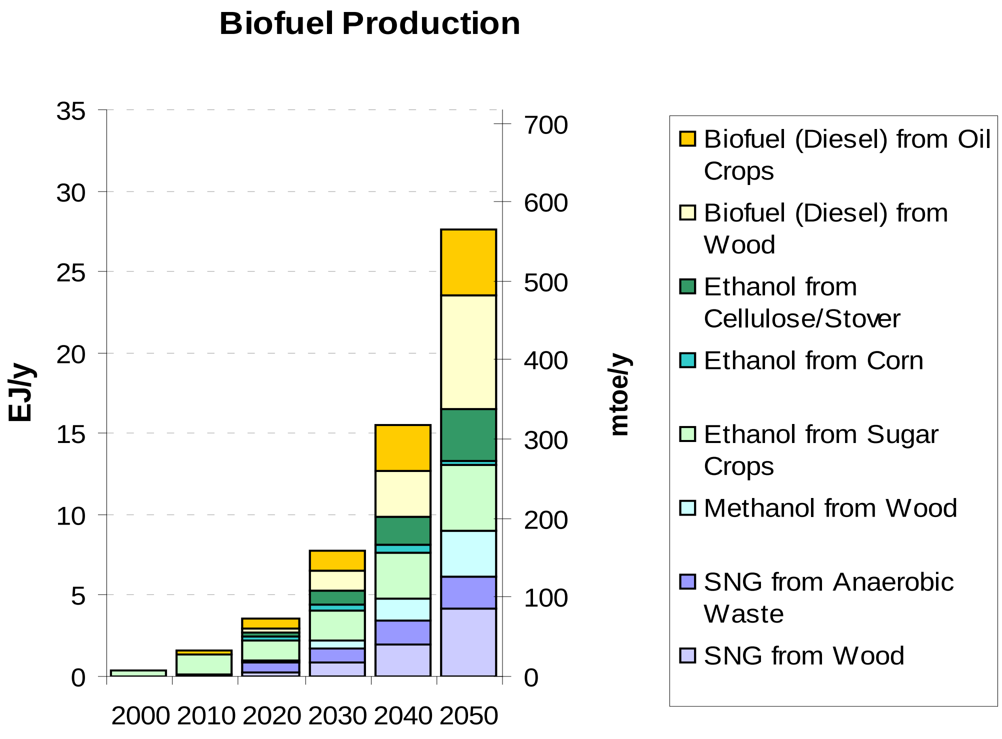


- Coal Gasification uses CCS
- Nuclear technologies: high-pressure / high-temperature electrolysis, and chemical heat cycles

- The major share of hydrogen is used in non-car surface transport

Alternative fuel production (all energy demand sectors)



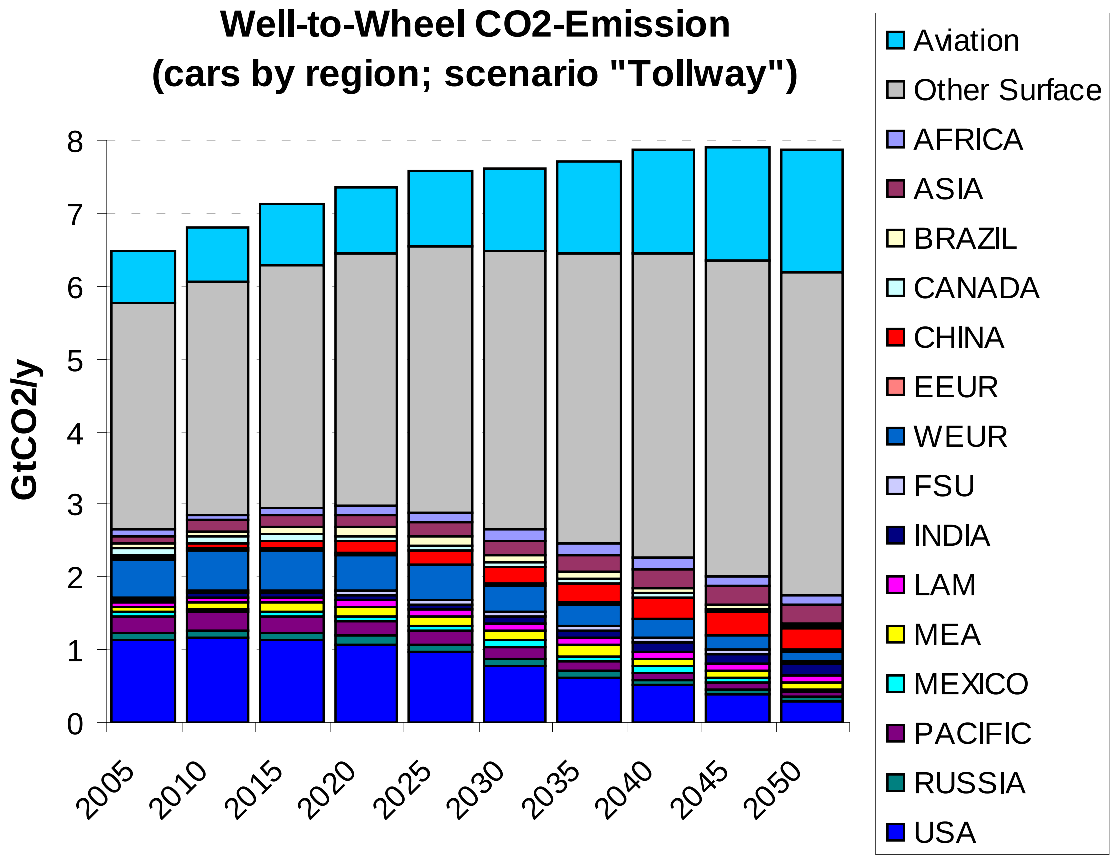


- Alternative fuels derived from coal play a transitory role and are phased out due to the climate policy.
- Biofuels become cost competitive especially due to the assumed carbon price, with second generation being cost-competitive.

Car Fuels

- **Petroleum/Synfuel:** gasoline (allowed to be blended with low percentage of bio- and non-bio-methanol); diesel; and Fischer-Tropsch-liquids (F-T-diesel). Note, the current representation of refineries in the model means that the shares of diesel and gasoline in ICEVs should not be relied upon.
- **CNG:** compressed natural gas
- **Methanol, Ethanol:** bio-methanol and bio-ethanol; may be used as a blend
- **Bio-SNG:** biogas, i.e., bio-synthetic gas from biomass, produced e.g. by fermentation of manure or waste, or by gasification of wood
- **Biofuel (Diesel):** biodiesel (FAME), produced e.g. from oil crops or by pyrolysis from wood; and bio-F-T-diesel, e.g. produced from Bio-SNG
- **Hydrogen:** hydrogen from fossil and from renewable sources
- **Electricity:** Electricity from the electricity grid. In GMM, an electricity demand from cars is spread equally over time, so night-time charging is supported (with simplification, see Open Issues).

Policy Scenario



WEC/PSI (2011): Global Transport Scenarios 2050

- Other surface & aviation: biofuels are not cost-effective, efficiency improvements limited → emissions increase in “Tollway”
- Developing world: increase in car-emissions (due to large increase in demand) is partially offset by mid- and long-term efficiency improvements