Optimising use of biomass in sustainable energy systems

Henrik Bindslev and Henrik Wenzel
SDU
Faculty of Engineering

CIGR AgEng 2016
Århus

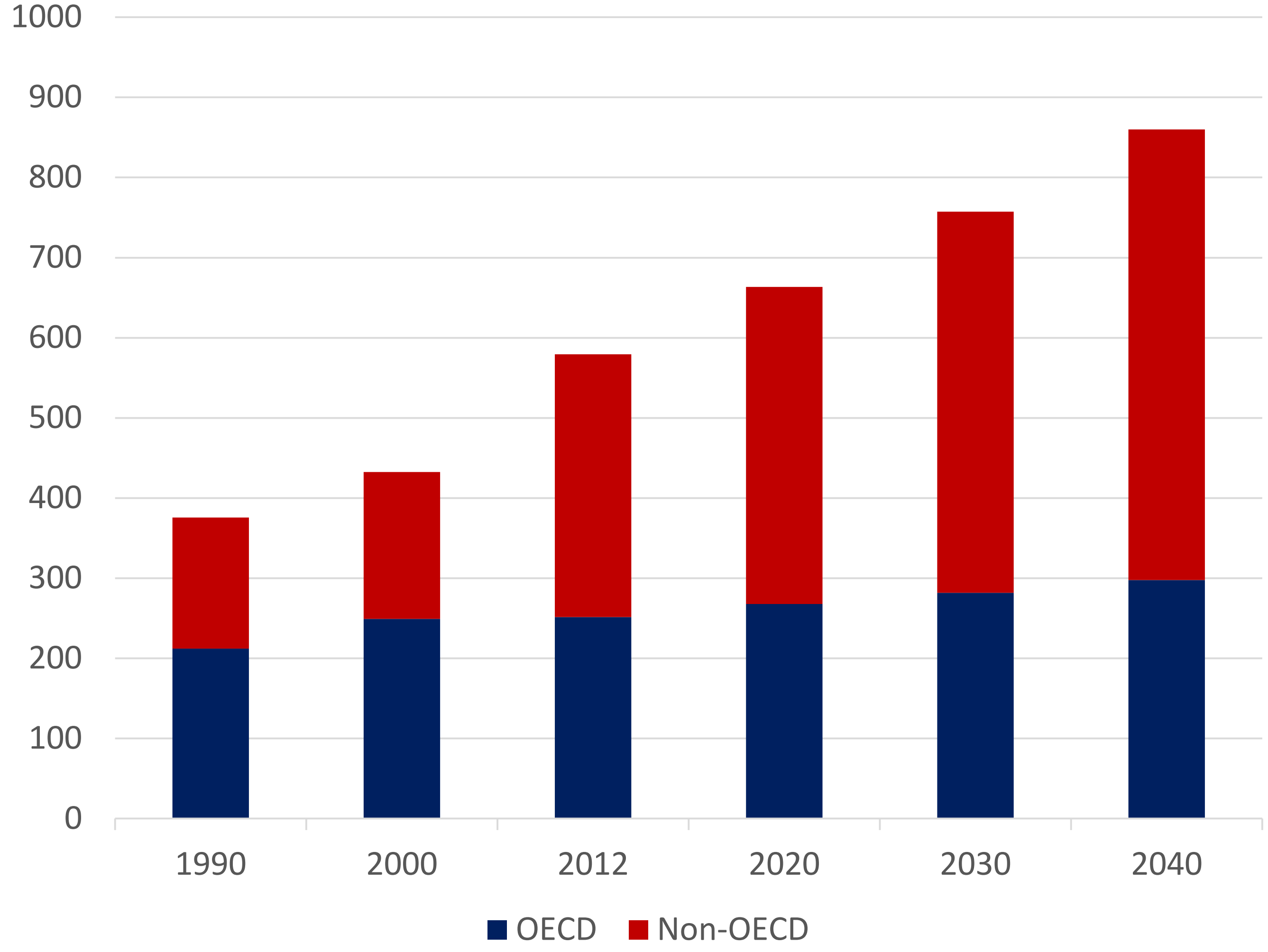
Demand for energy is rising

Particularly in the developing economies

Reflects growing population and growing living standards

US Energy Information Administration (eia), International Energy Outlook 2016

World energy consumption / [EJ/year]



Fossil fuels projected to dominate

Fossil fuels 2040

Oil: 260 EJ / year

Coal: 190 EJ / year

Nat. Gas: 220 EJ / year

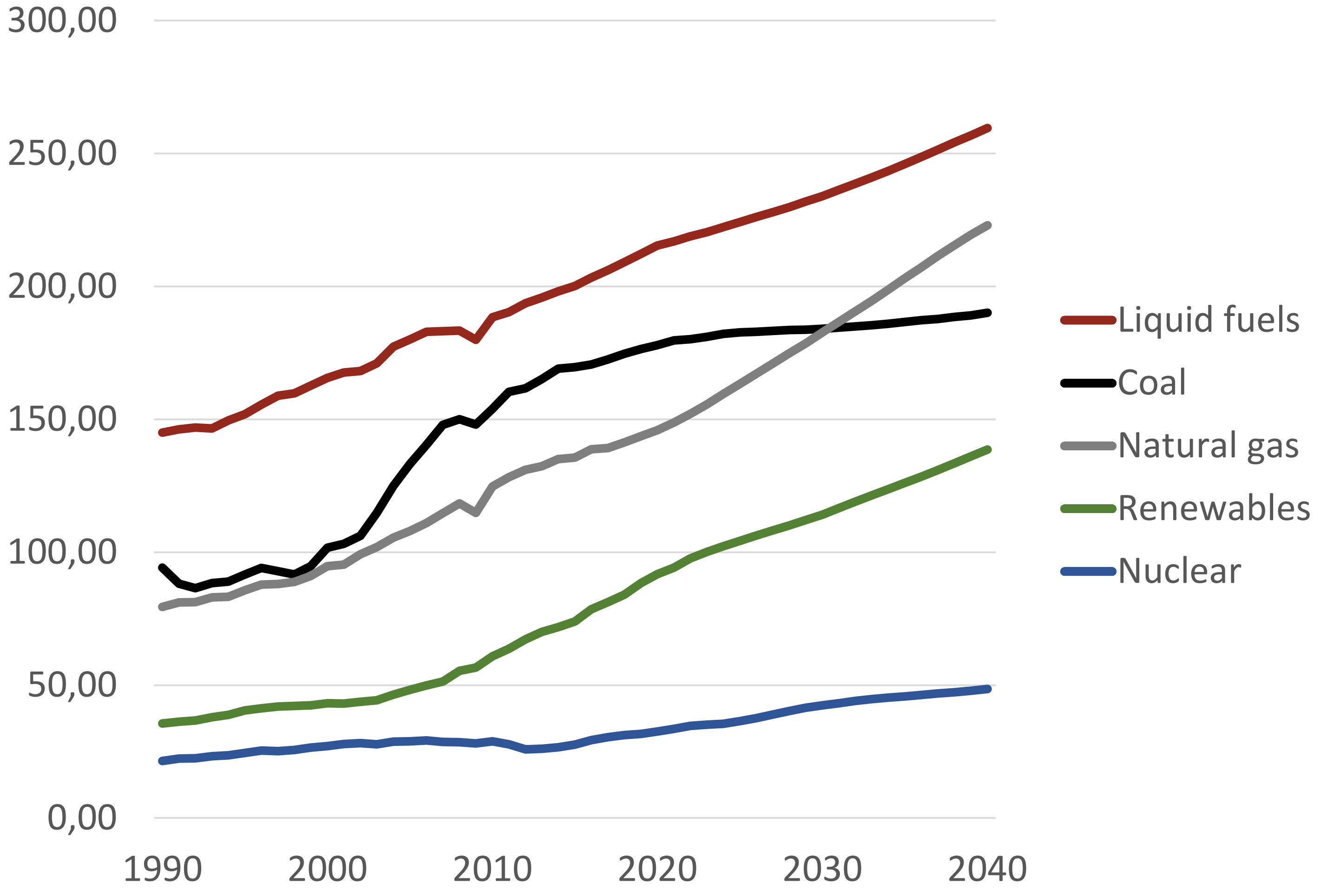
Total: 670 EJ / year

Renewables and Nuclear

Total 190 EJ / year

US Energy Information Administration (eia), International Energy Outlook 2016

World energy consumption / [EJ/year]



Global Energy consumption and CO2 emissions

Year	Primary Energy Consumption	Fossil fuel consumption	CO_2 total emissions	Electrical Energy Consumption	CO_2 from electric. IEA Blue
2012	580 EJ/year 18 TW 1)	486 EJ / Year	32 GT / year	22 PWh / year 2.5 TW 1)	10 GT/year
2040	860 EJ / year 27 TW 1)	670 EJ / year		4.2 TW 1)	
2050	970 EJ / year 31 TW 2)		Less than 14 GT / year 3)	5 TW 2)	Less than 1 GT/year
2100	600-1600 EJ / year 20-50 TW		0 GT/year	10 TW 2)	0 GT/year

1) eia International Energy Outlook 2016, realised and reference scenario
2) Extension of eia reference scenario
3) Copenhagen Accord (Max 2 degrees temperature rise)

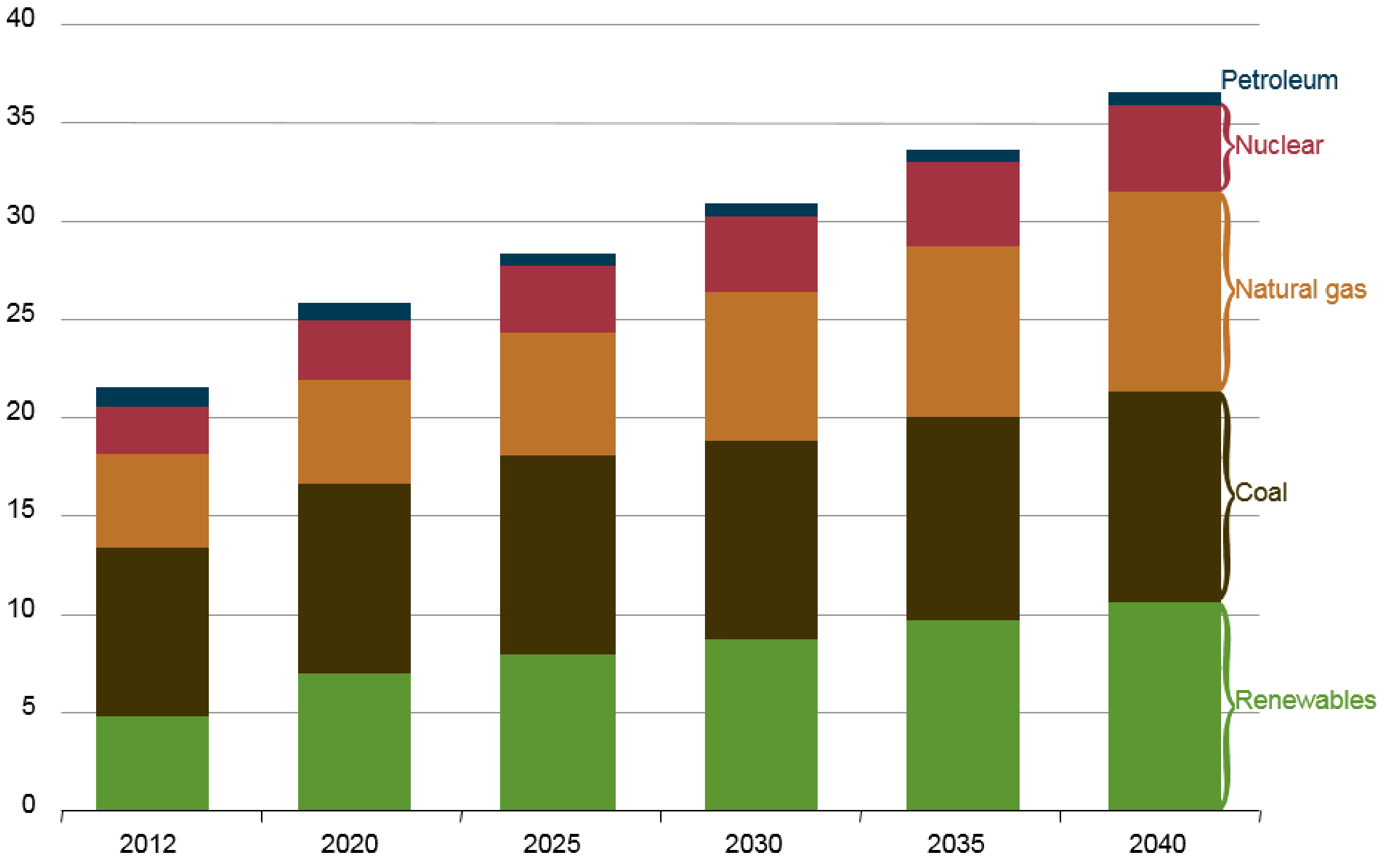
Electricity generation

Should be almost fully free of CO_2 emission by 2050.

Short of massive introduction of CCS we are not on track to meet the Copenhagen Accord

US Energy Information Administration (eia),
International Energy Outlook 2016, reference scenario

World electricity generation by fuel / [PWh/year]



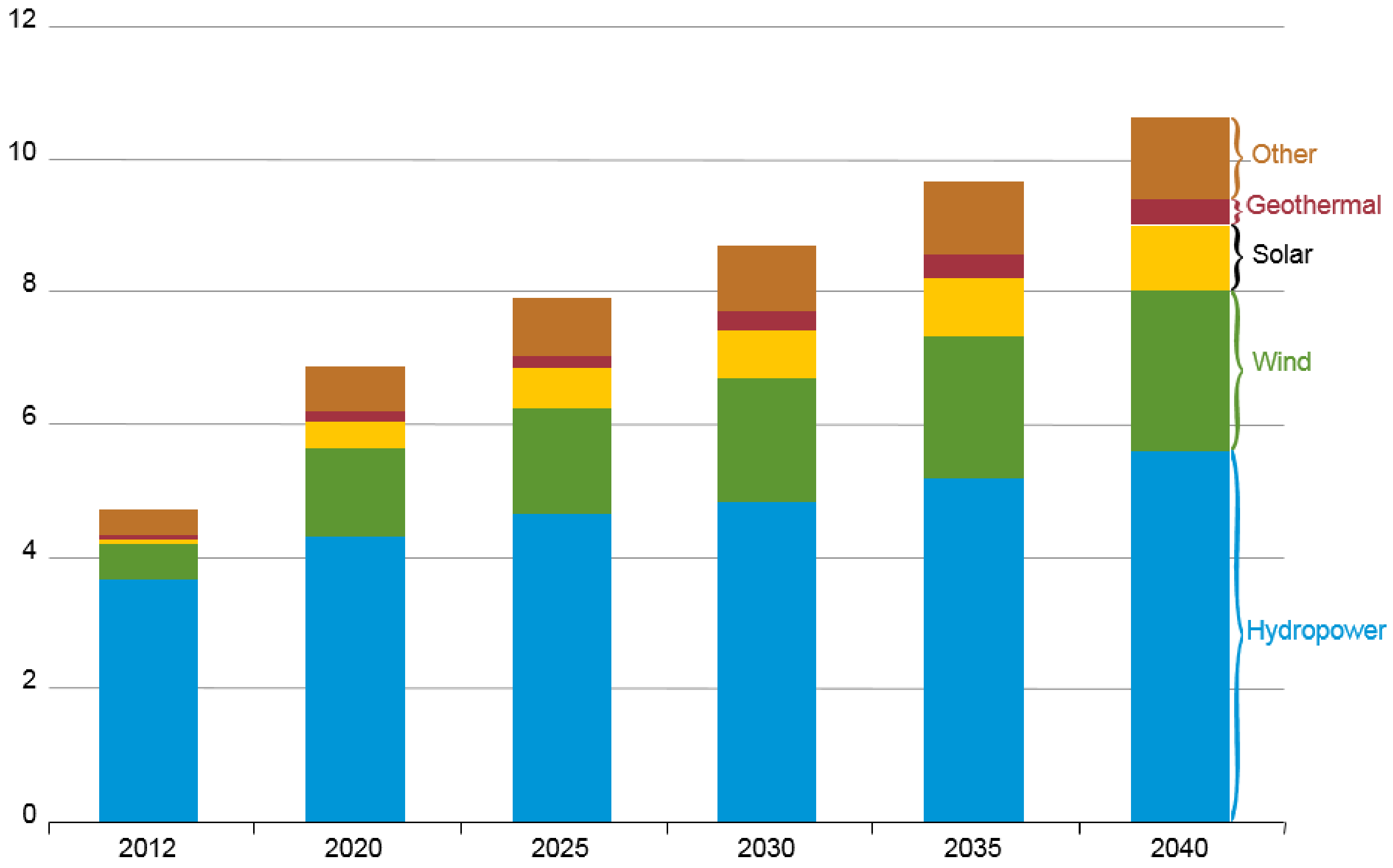
Electricity from renewables

Dominated by large hydro

Wind significant

Solar (PV) accelerating

US Energy Information Administration (eia),
International Energy Outlook 2016
World renewable electricity generation by source / [PWh/year]



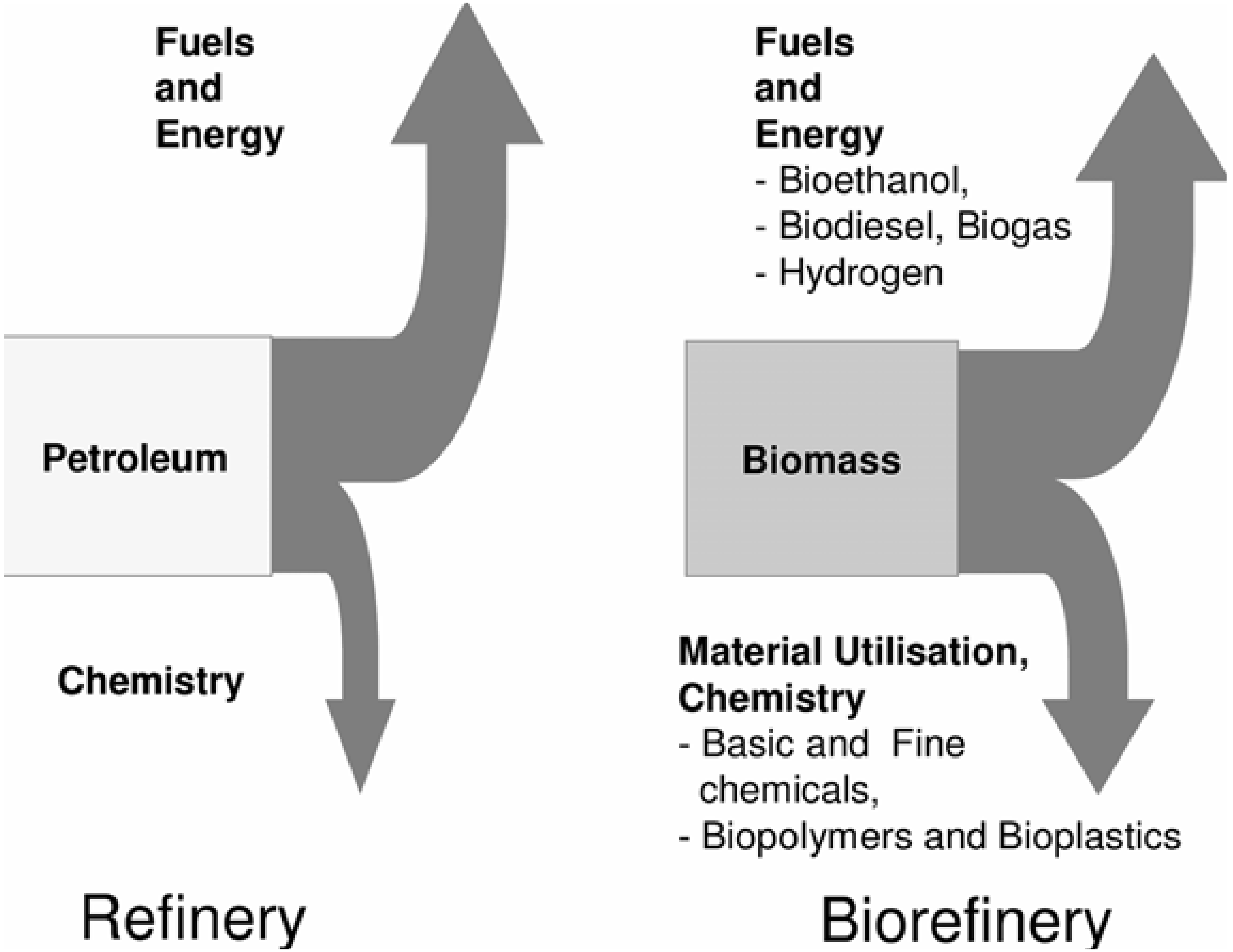
Can biomass replace fossil fuels?

Biomass can deliver all the types of services we get from fossil fuels.

But is there enough biomass?

- Straw and wood pellet replace coal in central power plants
- Bio-ethanol and bio-diesel replace fossil fuels for transport
- Bio-gas and gasification replace natural gas and more

Towards bio-refinery



SDU

Demands on biomass to substitute fossil fuels 2030

Highest priority customers for biomass are chemicals and aviation,

They can take all residue biomass

Demand type	Fuel consumption / [EJ/year]	Biomass demand / [EJ/year]
Chemicals and materials	30	60*
Jet fuels	25	50*
Long distance road (20% of road)	20	40*
Heat & electricity fuel buffer (20%)	90	90
Short distance road (80% of road)	80	160*
Heat & electricity bulk (80%) + other	350	350
	600	750

*conversion loss with current efficiencies

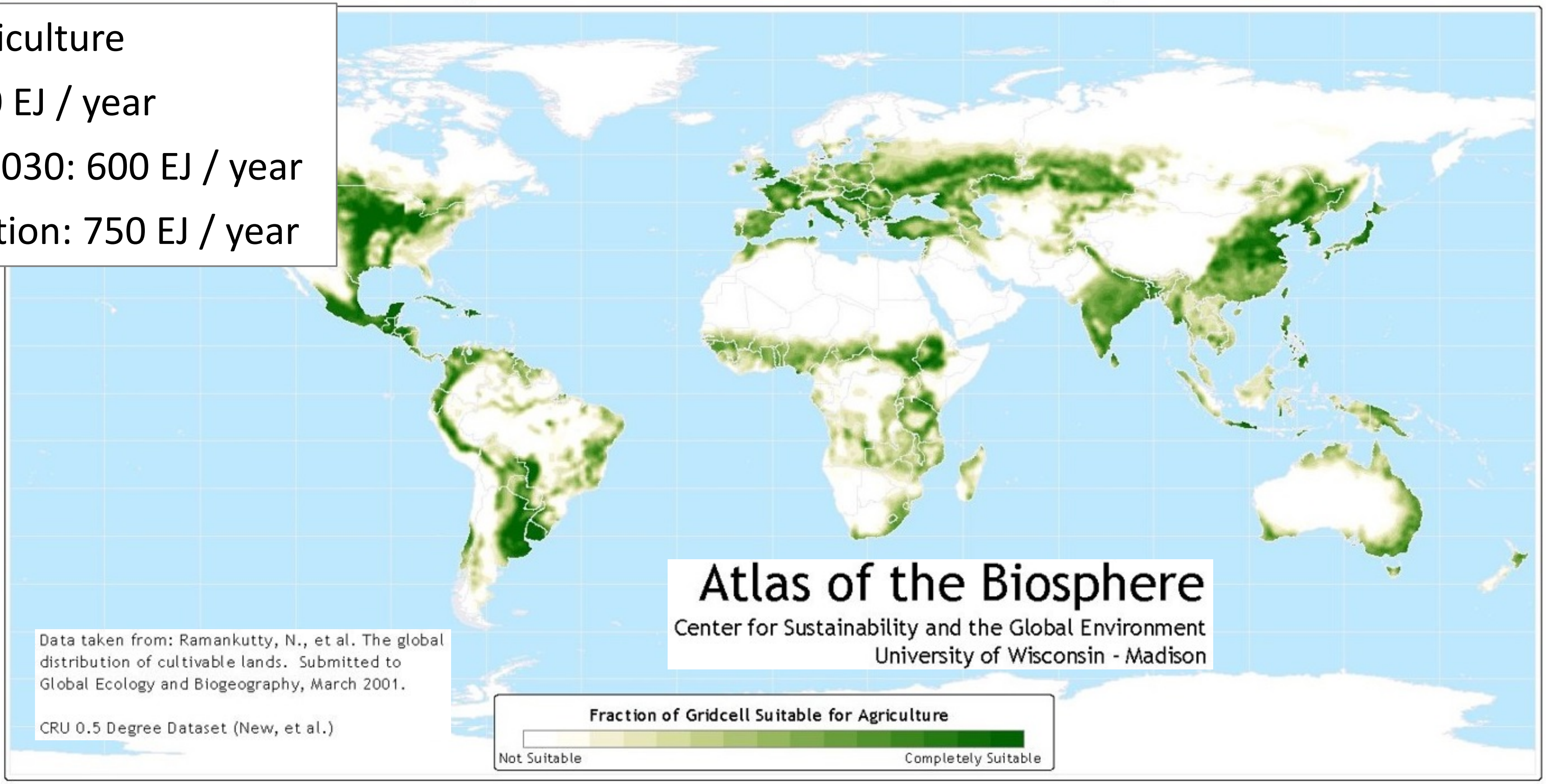
Biomass limitation

1/3 of land area used for agriculture

Biomass potential: 100 – 500 EJ / year

Consumption of fossil fuels 2030: 600 EJ / year

Biomass needed for substitution: 750 EJ / year



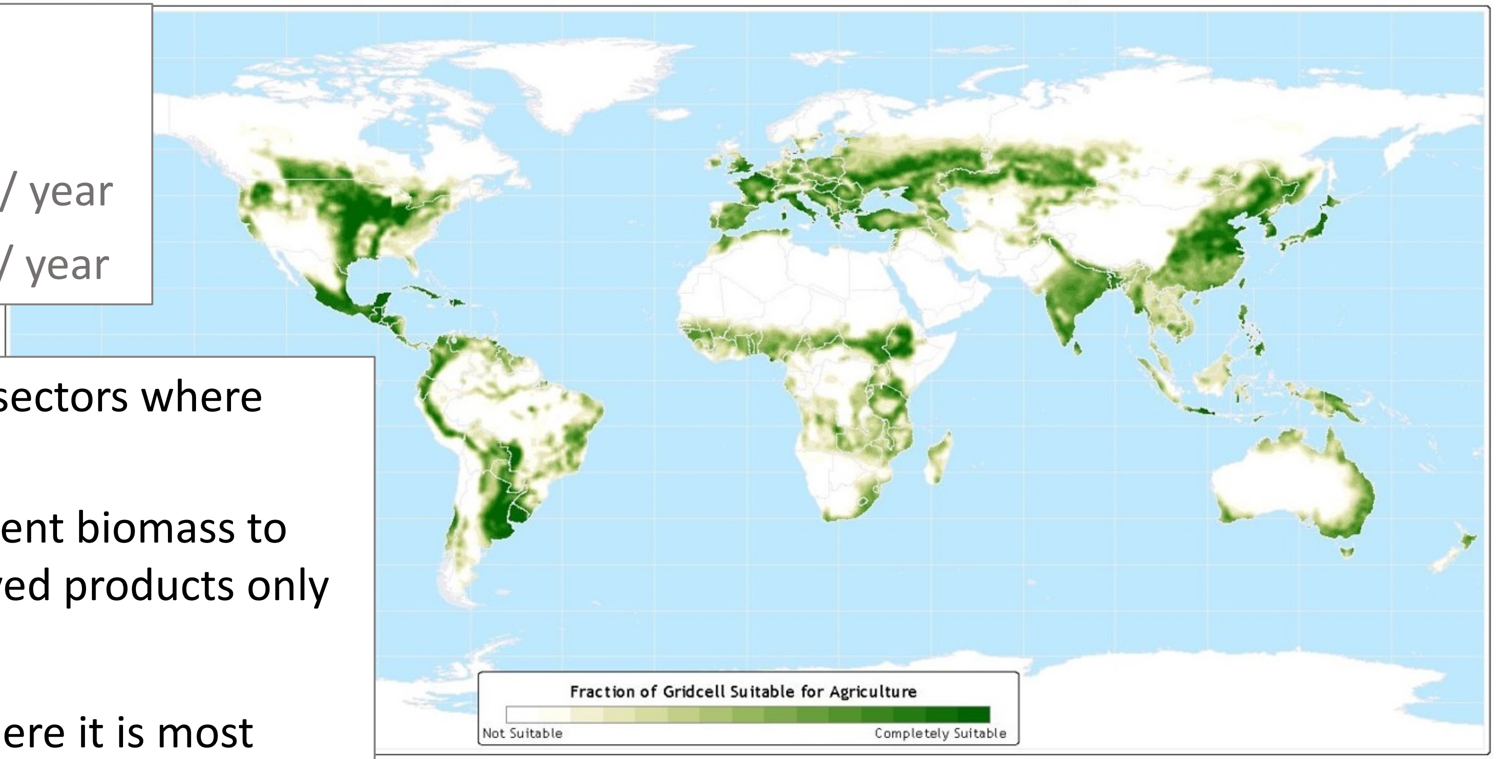
Biomass limitation

1/3 of land area used for agriculture

Biomass potential: 100 – 500 EJ / year

Consumption of fossil fuels 2030: 600 EJ / year

Biomass needed for substitution: 750 EJ / year



- Biomass is versatile and can enter all sectors where fossil fuels are in use today
- Difficult sustainably to produce sufficient biomass to replace fossil fuels with biomass derived products only
- Need other sources of energy
- Must prioritise the use of biomass where it is most acutely needed
- Must stretch the biomass derived products for instance by integrating electricity derived hydrogen

Biomass limitation

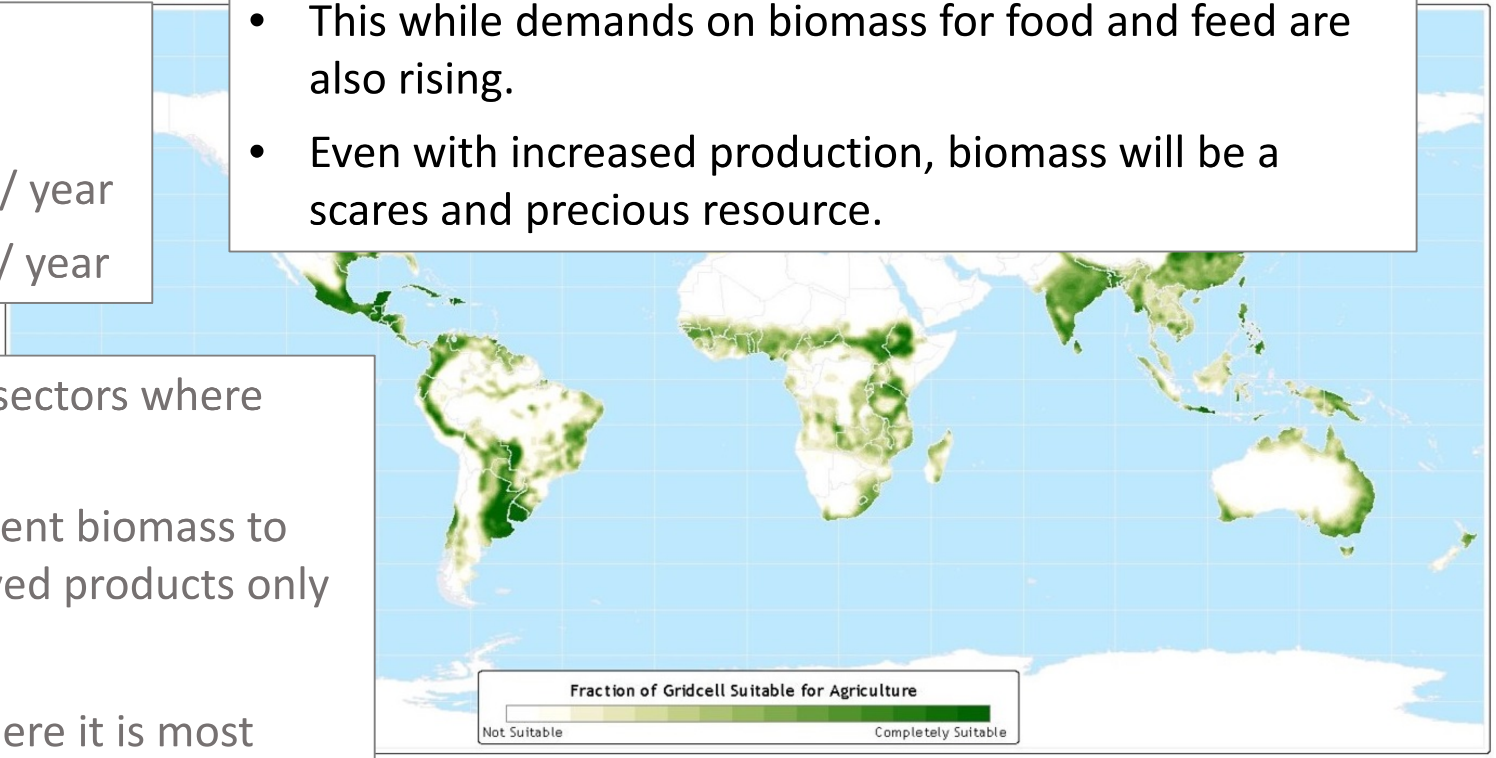
- Replacing the global fossil fuel consumption of today with bio-based products would require 4 times the gross biomass production of today.
- This while demands on biomass for food and feed are also rising.
- Even with increased production, biomass will be a scares and precious resource.

1/3 of land area used for agriculture

Biomass potential: 100 – 500 EJ / year

Consumption of fossil fuels 2030: 600 EJ / year

Biomass needed for substitution: 750 EJ / year



- Biomass is versatile and can enter all sectors where fossil fuels are in use today
- Difficult sustainably to produce sufficient biomass to replace fossil fuels with biomass derived products only
- Need other sources of energy
- Must prioritise the use of biomass where it is most acutely needed
- Must stretch the biomass derived products for instance by integrating electricity derived hydrogen

Solar Power
Photo Voltaic and Concentrated Solar Power

Solar farm area to cover World electricity and energy consumption

World electricity consumption, P_{We} = *2.5 TW*

Solar power generation density ≈ 50 GW/km^2

Area of solar farm to cover P_{We} = (250 km)^2

1 square for world electricity consumption.

4 squares for world energy consumption

Wind farm area to cover World electricity consumption 2008

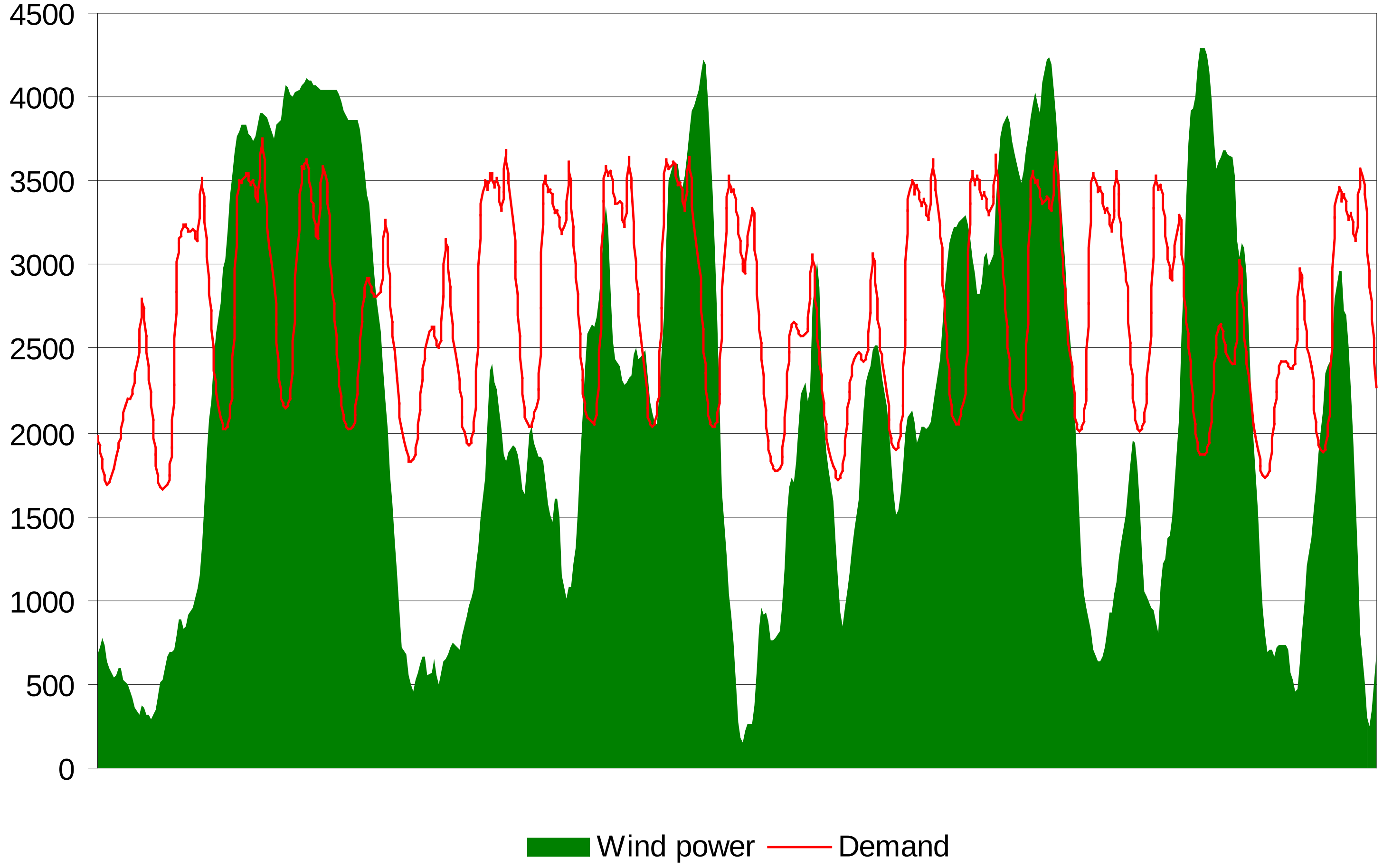
World electricity consumption, $P_{We} = 2\ TW$
Wind power density ≈ 2 GW/km^2
Area of wind farm to cover P_{We} = (1000 km)^2


Geothermal
4G Nuclear
Fusion
Wave
Tidal
CCS

Wind and solar can deliver the power but need balancing

Sustainable energy systems will rely in large measure on wind and solar power

- Fluctuations in produced power
- Limited ability to follow demand.
- Challenge in balancing loads and production
- The nature of the challenge and the optimal solutions evolve with extent of the transition to a sustainable system.



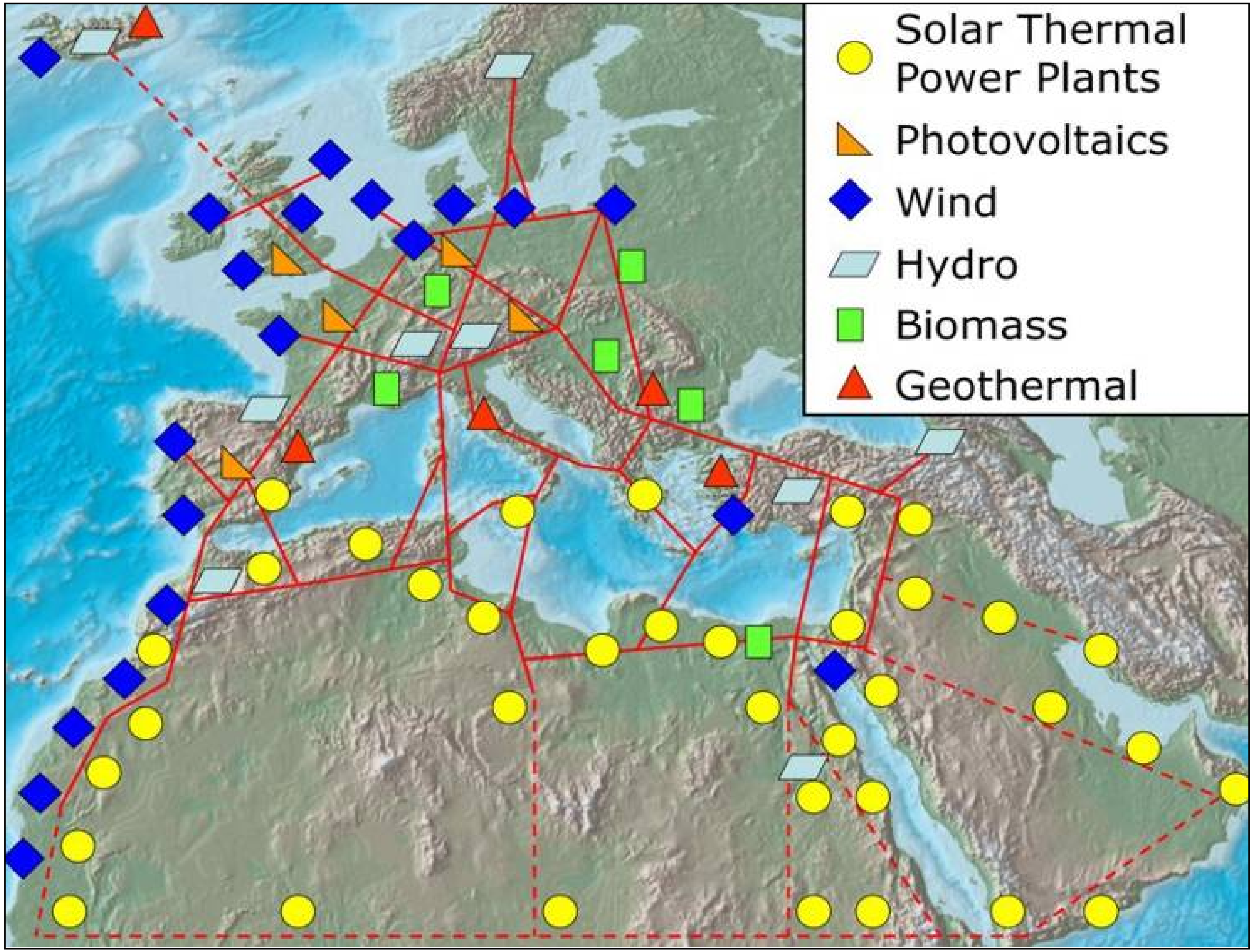
Integration and balancing

Long timescales

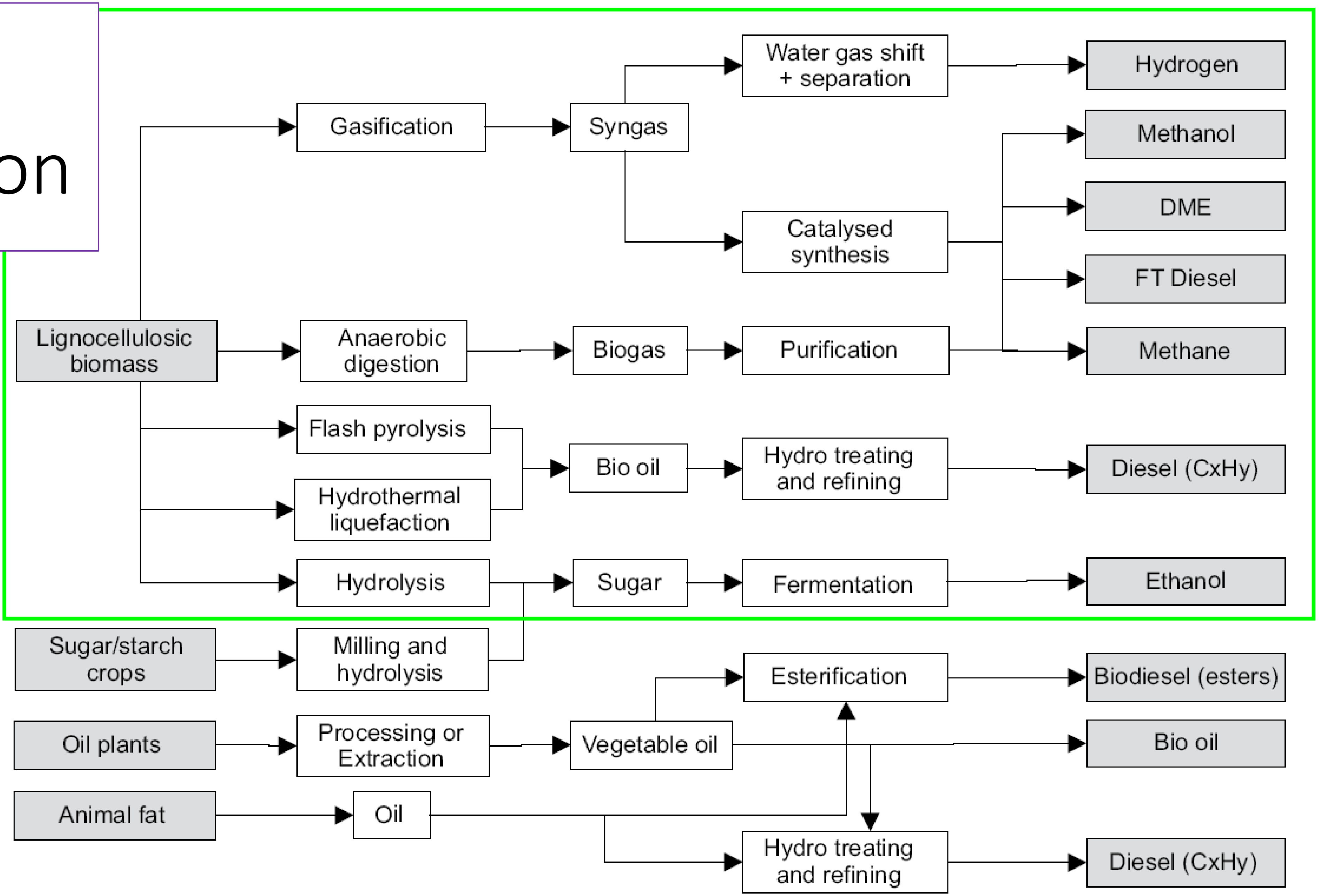
- **Super grids**
- Pump storage
- Bio-energy
- Synthetic gas & fuels

Short timescales

- Batteries
- Demand response
- Heat pumps
- Compressed air

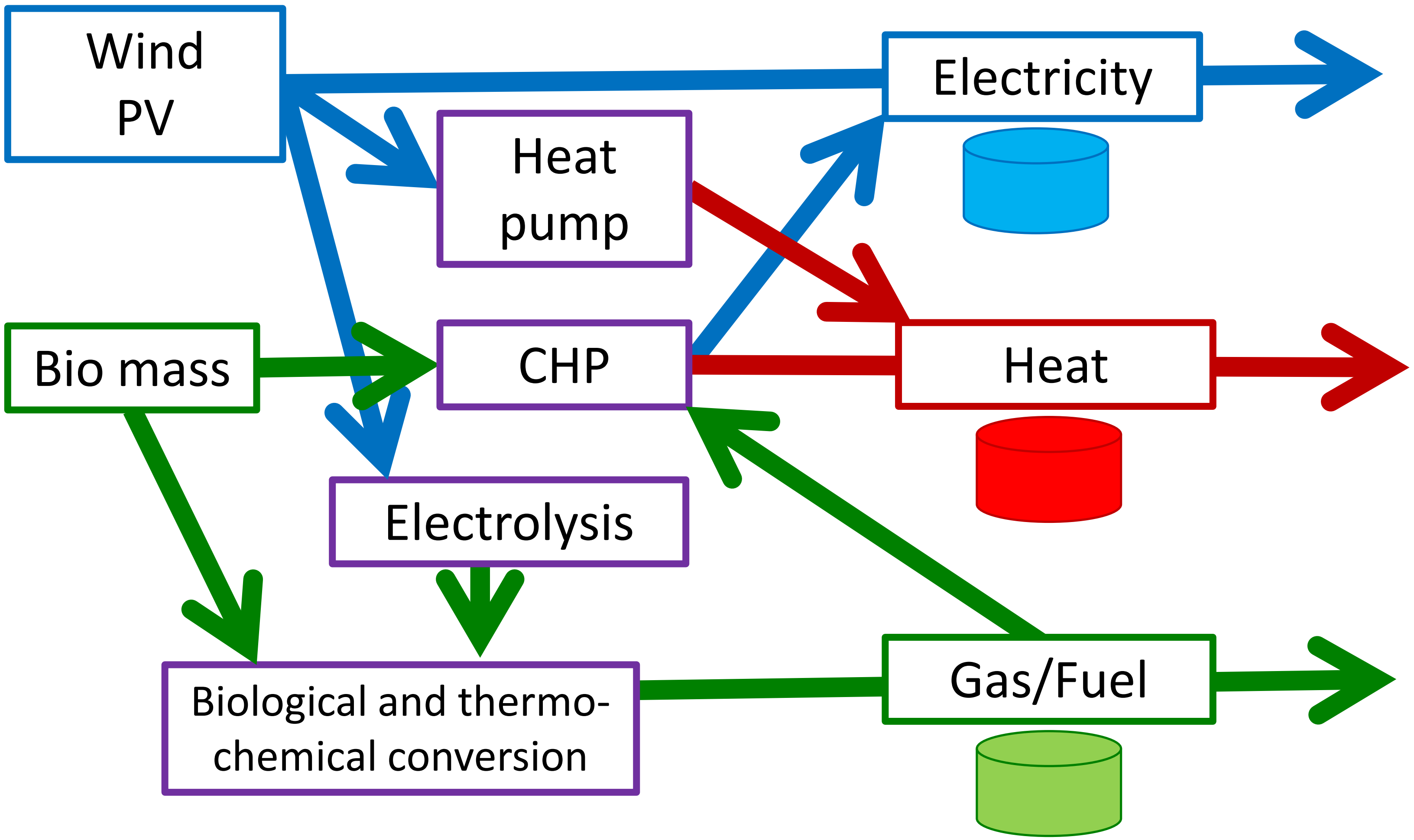


Biomass conversion



SDU

Flexibility and storage



Hydrogenation

Hydrogenation to methane:

$C_6(H_2O)_5$	+	$12\ H_2$	$\longrightarrow$	$6\ CH_4$	+	$5\ H_2O$
biomass		hydrogen		methane		water
2,8 MJ		2,9 MJ		4,8 MJ		

Hydrogenation to diesel:

$C_6(H_2O)_5$	+	$5{,}75\ H_2$	$\longrightarrow$	$\frac{1}{2}\ C_{12}H_{23}$	+	$5\ H_2O$
biomass		hydrogen		diesel		water
2,8 MJ		1,4 MJ		3,8 MJ		

Recycling CO_2

Carbon Capture and Recycling (CCR)

Methanol synthesis by CCR:

$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O$$

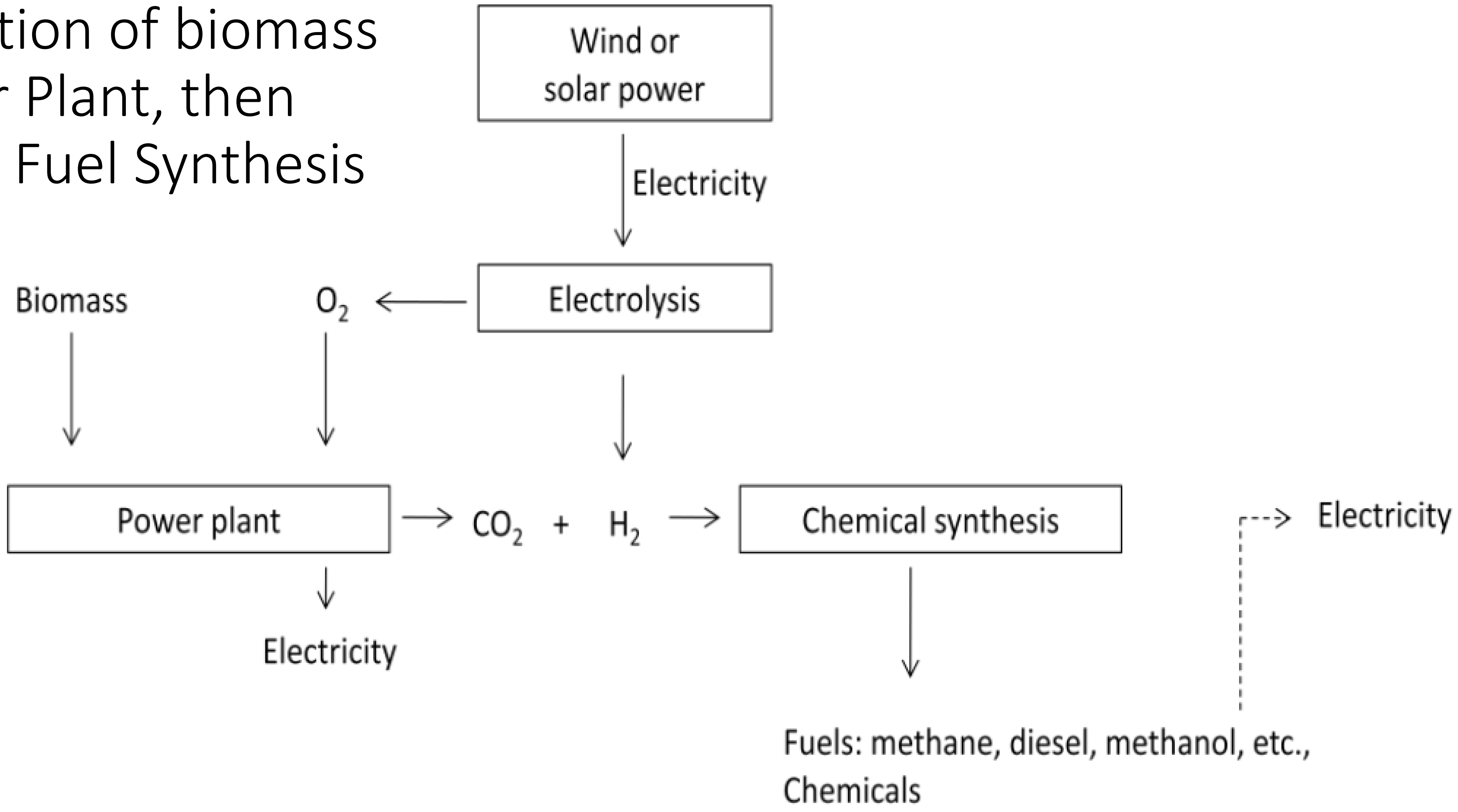
CCR to methane:

6 CO_2	+	24 H_2	$\longrightarrow$	6 CH_4	+	12 H_2O
carbon dioxide		hydrogen		methane		water
0 MJ		5,8 MJ		4,8 MJ		

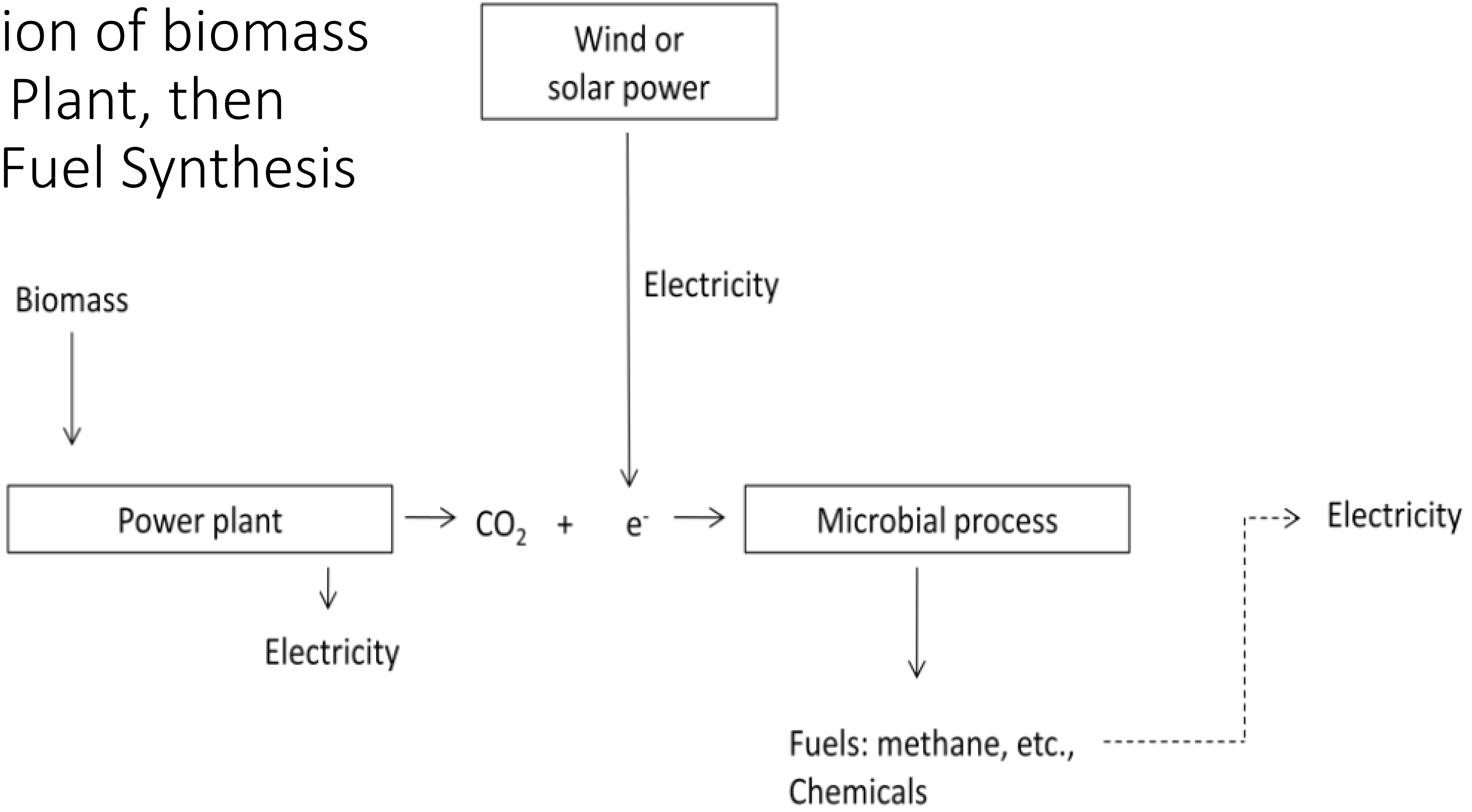
CCR to diesel:

6 CO_2	+	17,75 H_2	$\longrightarrow$	½ $C_{12}H_{23}$	+	5 H_2O
carbon dioxide		hydrogen		diesel		water
0 MJ		4,3 MJ		3,8 MJ		

Combustion of biomass in Power Plant, then CCR and Fuel Synthesis



Combustion of biomass in Power Plant, then CCR and Fuel Synthesis



Boosting energy content of bio-products

Conventional fermentation to liquid fuels

100 PJ biomass → **50 PJ liquid fuels**

→ **20 PJ solid fuel or animal feed**

Hydrogenation

To methane:

100 PJ biomass → **170 PJ methane**

hydrogen 100 PJ

To diesel:

100 PJ biomass → **130 PJ diesel**

hydrogen 50 PJ

Boosting energy content of bio-products

Carbon Capture and Recycling, CCR

To methane:

100 PJ biomass → **100 PJ solid fuel** → Heat & power + CO_2 → **170 PJ methane**

hydrogen (200 PJ) → CO_2

To diesel:

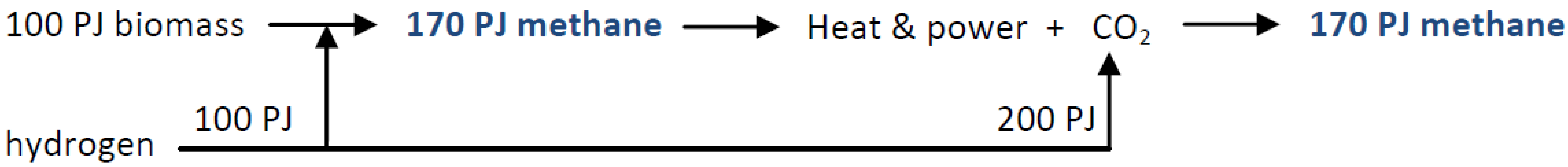
100 PJ biomass → **100 PJ solid fuel** → Heat & power + CO_2 → **130 PJ diesel**

hydrogen (150 PJ) → CO_2

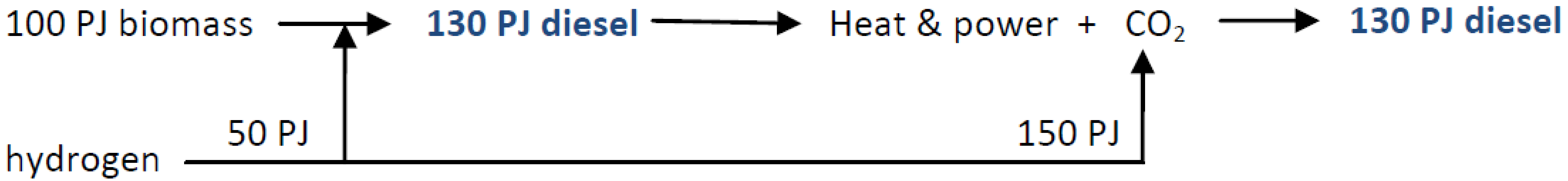
Boosting energy content of bio-products

Hydrogenation together with CCR

To methane:



To diesel:



Boosting energy content of bio-products

Conversion process	Inputs (PJ)		Outputs (PJ)			
	biomass	hydrogen	solid fuel	liquid fuel road	liquid fuel road and air	methane
Fermentation	100		20	50		
Hydrogenation to methane	100	100				170
Hydrogenation to diesel	100	50			130	
CCR to methane	100	200	100			170
CCR to diesel	100	150	100		130	
Hydrogenation & CCR to methane	100	300				340
Hydrogenation & CCR to diesel	100	200			260	

Siemens vision

Storing energy
Energy density

Energy carrier	kJ/ml	kJ/g
Gasoline (Octane)	33	48
Liquid Methane	20	55
Methane 250 bar	9	55
Liquid Hydrogen	10	141
Hydrogen at 700 bar	6	141
Advanced Battery	1.2	0.7
Methanol	18	22
Liquid Ammonia	17	25

Optimal use of Biomass in **transition** to sustainable system

while fossil fuels are still used extensively

- Efficient displacement of fossil fuels
- Use fossil fuels where conversion of biomass is expensive (transport fuels)
- Biomass primarily used in power and heat production in larger central power plants
- … and to lesser extent in fuels for transport
- Avoid lock-in
- … and loss of valuable assets

- Displace Coal
- Free up oil and gas for transportation
    - Central thermal biomass combustion plants are efficient in displacing fossil fuels
    - New such plants will be obsolete before they are written off (lock-in or stranded asset)

Optimal use of Biomass in **transition** to sustainable system

while fossil fuels are still used extensively

- Efficient displacement of fossil fuels
- Use fossil fuels where conversion of biomass is expensive (transport fuels)
- Biomass primarily used in power and heat production in larger central power plants
- … and to lesser extent in fuels for transport
- Avoid lock-in
- … and loss of valuable assets

- Natural gas distribution and storage system:
  - Challenged financially in short term by loss of domestic heating sector
  - Potentially essential asset in fully sustainable energy system
  - Provides needed energy storage
  - Efficient distribution of transport fuel

Optimal use of Biomass in **transition** to sustainable system

while fossil fuels are still used extensively

- Avoid lock-in
- … and loss of valuable assets
- Timely development and introduction of technologies for sustainable system

- Need to upgrade biomass while absorbing excess electricity production from fluctuating renewables

Optimal use of Biomass in **sustainable** energy system

Scarcity of biomass relative to the needed services will be acute.

Boosting energy content of the biomass products will be the path of choice.

In a future sustainable energy system:

- Sufficient but fluctuating power production
- Need to store energy
- Need to provide energy for mobility
- … could be batteries
- … and fuels from biomass and electricity

- Biomass is not just a source of energy but a sustainable source of carbon
- … which through hydrogenation can be upgraded both in energy content and versatility of use
- Surplus electricity from fluctuating renewables is readily converted to hydrogen through electrolysis of water
- For some purposes hydrogen can and should be used directly.
- But hydrogen is more difficult to transport and store than hydrocarbons.

Optimal use of Biomass in sustainable energy system

Scarcity of biomass relative to the needed services will be acute.

Boosting energy content of the biomass products will be the path of choice.

In a future sustainable energy system:

- Sufficient but fluctuating power production
- Need to store energy
- Need to provide energy for mobility
- … could be batteries
- … and fuels from biomass and electricity

- But hydrogen is more difficult to transport and store than hydrocarbons.
- Binding the hydrogen to carbon makes it easier to handle
- … and allows us to use existing infrastructures such as the natural gas and liquid fuel systems.
- Both include extensive storage and distribution systems.

Optimal use of Biomass in sustainable energy system

Scarcity of biomass relative to the needed services will be acute.

Boosting energy content of the biomass products will be the path of choice.

In a future sustainable energy system:

- Sufficient but fluctuating power production
- Need to store energy
- Need to provide energy for mobility:
- … could be batteries
- … and fuels from biomass and electricity

- Both include extensive storage and distribution systems.
- Capturing the CO2 emissions at central facilities
- … and, with use of hydrogen, converting it to fuels,
- … would allow multiple cycles of use of the biomass derived carbon,
- … before it is released to the atmosphere in decentral applications such as transport.

Needed developments
for sustainable system with optimal use of biomass

Storage and distribution of bio-fuels, can use existing infrastructures

… which are highly developed, abundant and relatively inexpensive,

Conversion processes are adding significant costs

… and should be the target of further development.

- Biogas
- Hydro-thermal Liquifaction
- Gasification
- Synthesis from syngas
- Hydrogenation
- Electrolysis (H_2O and CO_2)
- Catalysts






Bio-economy

Multiple valuable streams from biomass

Separation and conversion processes are adding significant costs

… and should be the target of further development.

- Food and feed
- Recycle valuable substances to soil
- Fuels and energy storage
- Building blocks of chemical industry
- Pharmaceuticals