Universität Stuttgart
IER Institut für Energiewirtschaft
und Rationelle Energieanwendung

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ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAM

Investigation of material efficiency and circular economy potentials for the chemical industry in order to achieve the net zero target

Follow ETSAP Workshop Stuttgart
05.06.2025

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Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

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Agenda

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Motivation

Understanding the need for comprehensive energy system modeling

Model overview

Gaining a broad understanding of the ETSAP TIAM Model's framework

Scenario definition

Defining specific scenarios for analysis within the model

Scenario analysis results

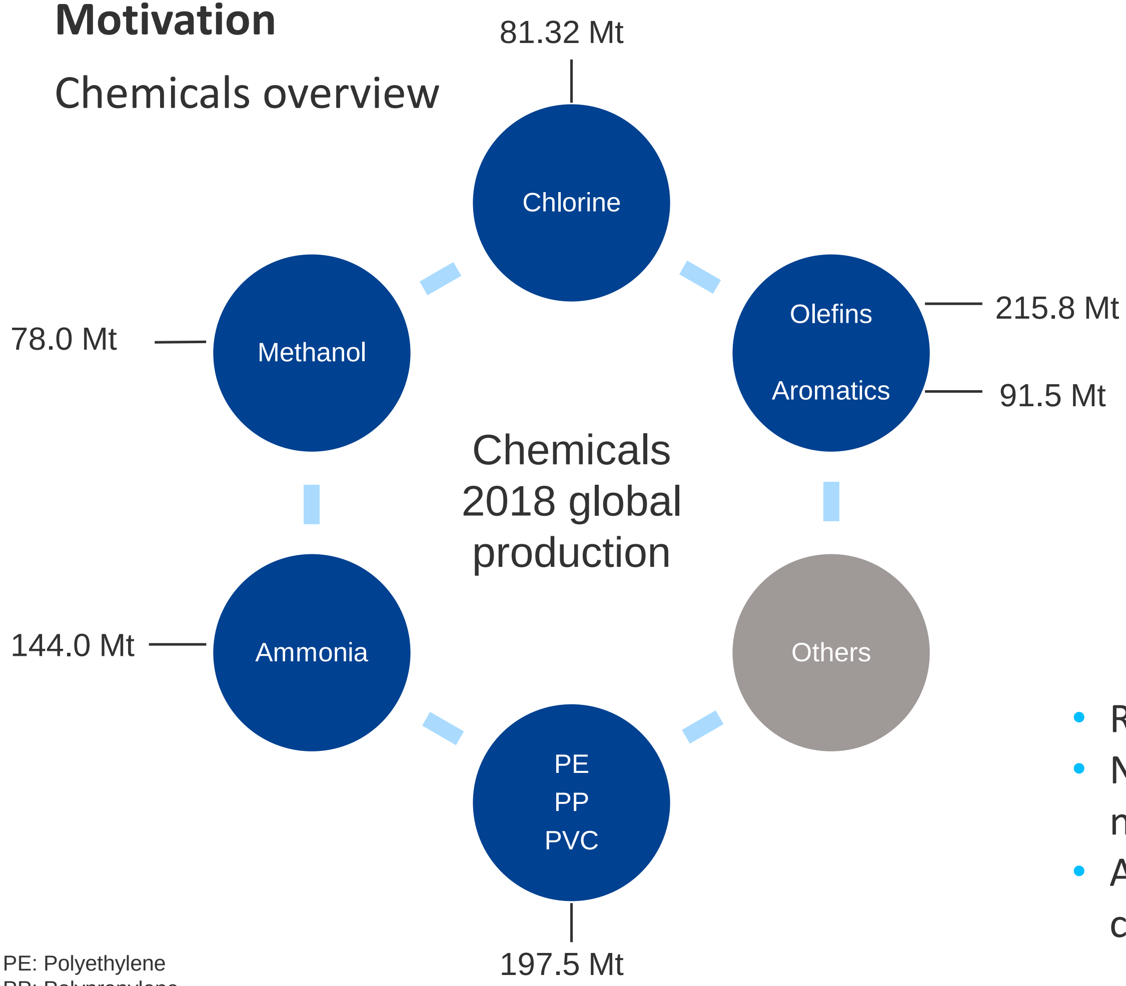
Analyzing and interpreting the results of the defined scenarios

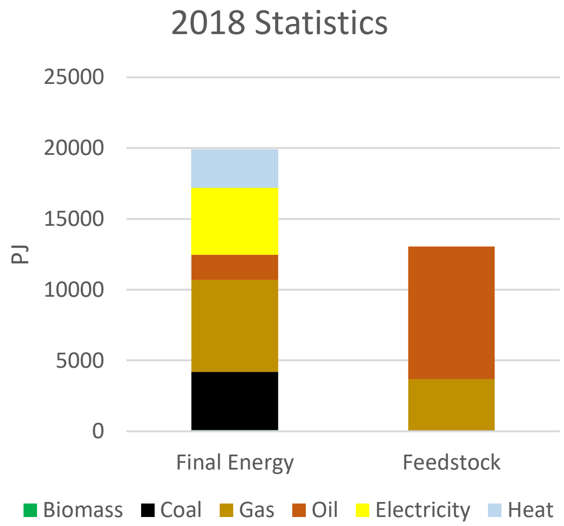
Conclusion & outlook

Summarizing findings and contemplating future implications

Motivation

Chemicals overview





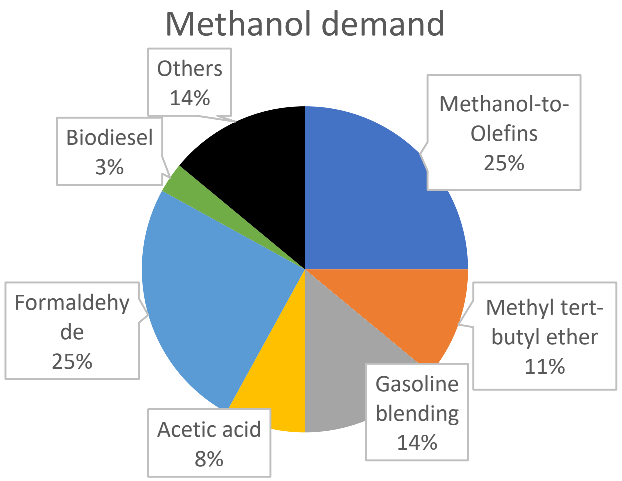
- Responsible for 18% of industrial CO_2 emissions.
- Not only decarbonization, but also defossilization is necessary.
- Alongside 20 EJ of final energy consumption, feedstock consumption is equally significant

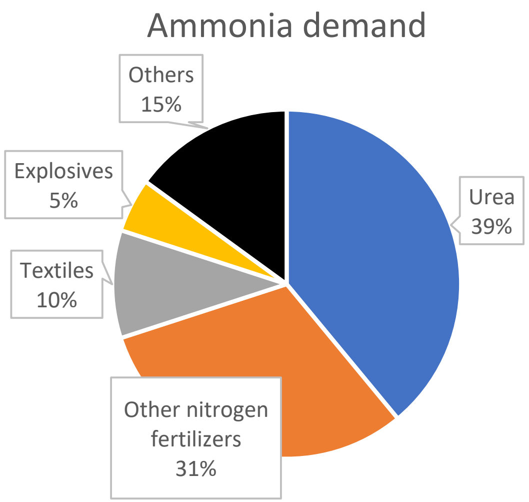
PE: Polyethylene
PP: Polypropylene
PVC: Polyvinyl chloride

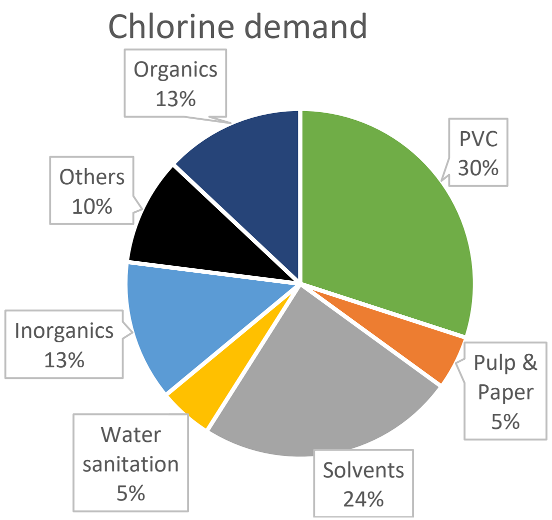
https://www.statista.com/statistics/1310477/chlorine-market-volume-worldwide/
https://www.statista.com/statistics/1266378/global-ammonia-production/
https://www.methanol.org/wp-content/uploads/2019/09/Methanol-as-a-vessel-fuel-and-energy-carrier.pdf
https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

Motivation

What are the chemicals needed for on global level in 2020?







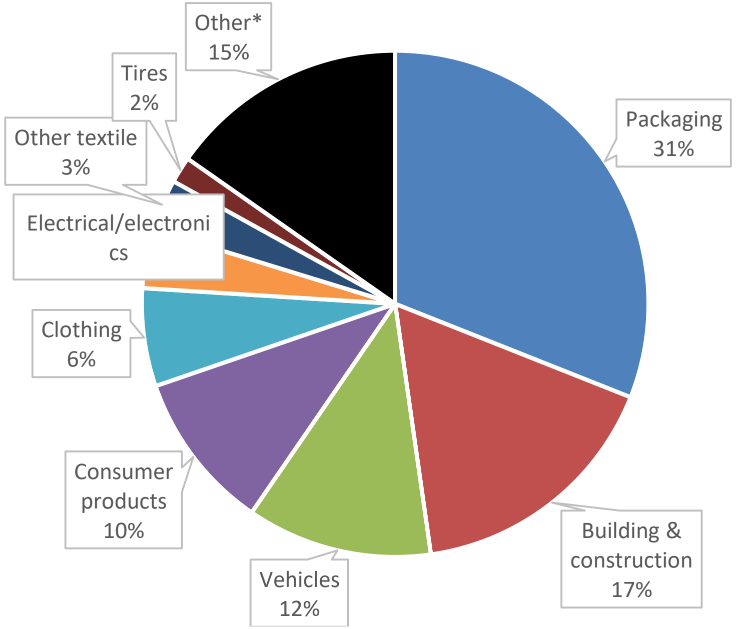
- The principal application of ammonia is in the synthesis of urea, predominantly for use as a nitrogen-based fertilizer.
- Chlorine demand is primarily driven by the production of PVC plastics
- Methanol demand is increasing as a feedstock for olefin production
- Olefins serve as key precursors for the manufacture of PP, PE, and PVC plastics
- Aromatics are essential building blocks for fibers, paints, coatings, and pharmaceuticals

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf
https://www.essentialchemicalindustry.org/chemicals/chlorine.html
https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf
https://www.techsciresearch.com/news/4860-aromatics-market-to-surpass-76-billion-by-2025-techsci-research.html?utm_source=chatgpt.com

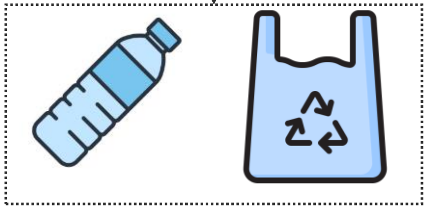
Motivation

Use of plastics in different sectors

- Highest use for packaging
- Buildings & Construction along with vehicles contribute to 29% of global plastics consumption as of 2018



PE & PP plastics

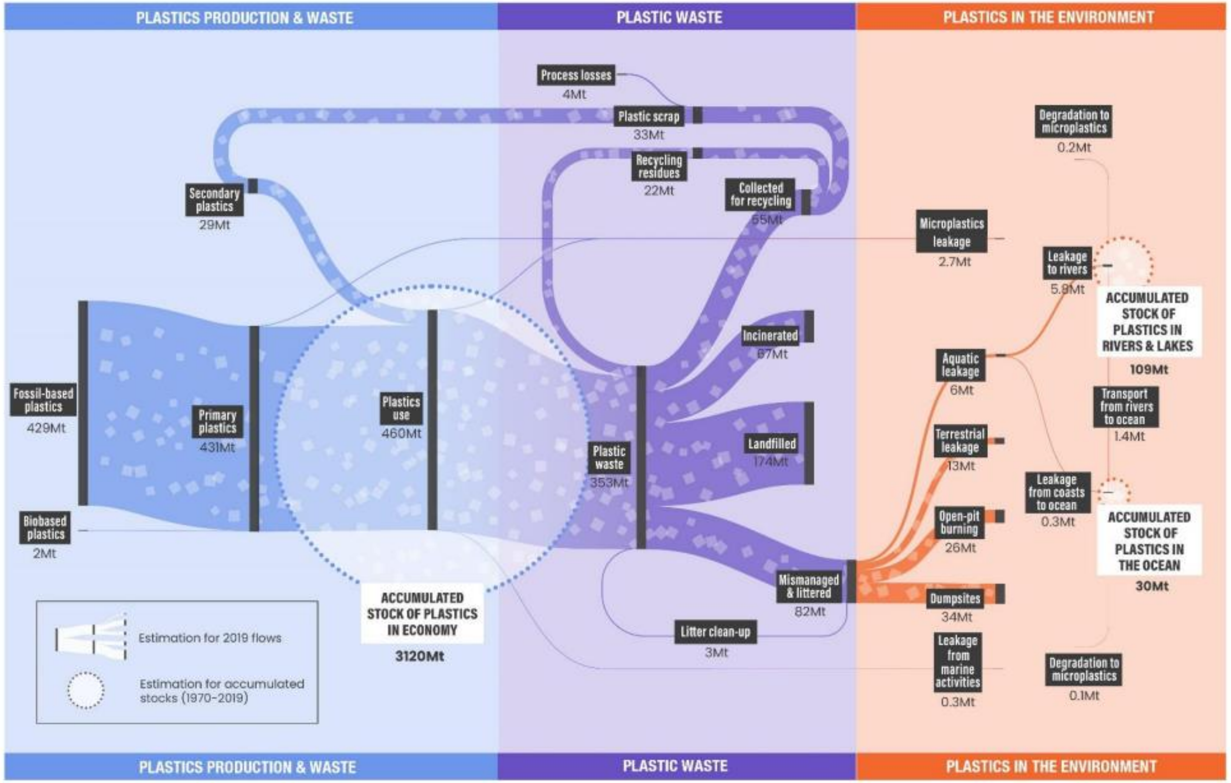


PVC plastic

https://www.vecteezy.com/vector-art/9317087-water-bottle-icon-logo-vector-illustration-plastic-bottle-symbol-template-for-graphic-and-web-design-collection
https://www.freepik.com/icon/plastic-bag_3506746
https://newtech-pipes.com/advantages-of-pvc-pipes/
https://www.statista.com/statistics/1002055/plastic-consumption-share-worldwide-by-application

Motivation

Global plastic waste flow in 2019



- Currently, only 9% of plastic waste is recycled
- Over 20% is mismanaged, contributing to accumulation in open dumps and aquatic environments
- A comparable proportion is incinerated, resulting in significant air pollutant emissions
- Higher rate of recycling can reduce energy consumption and emissions as well

Source: OECD Global Plastics Outlook Database, https://doi.org/10.1787/c0821f81-en

Motivation

Challange

- The global chemical sector is responsible for 1500 Mt of CO_2 in 2018
- The global feedstock demand is currently fossil dominated and needs to be switched as well
- Plastic mismanagement is the main environmental problem

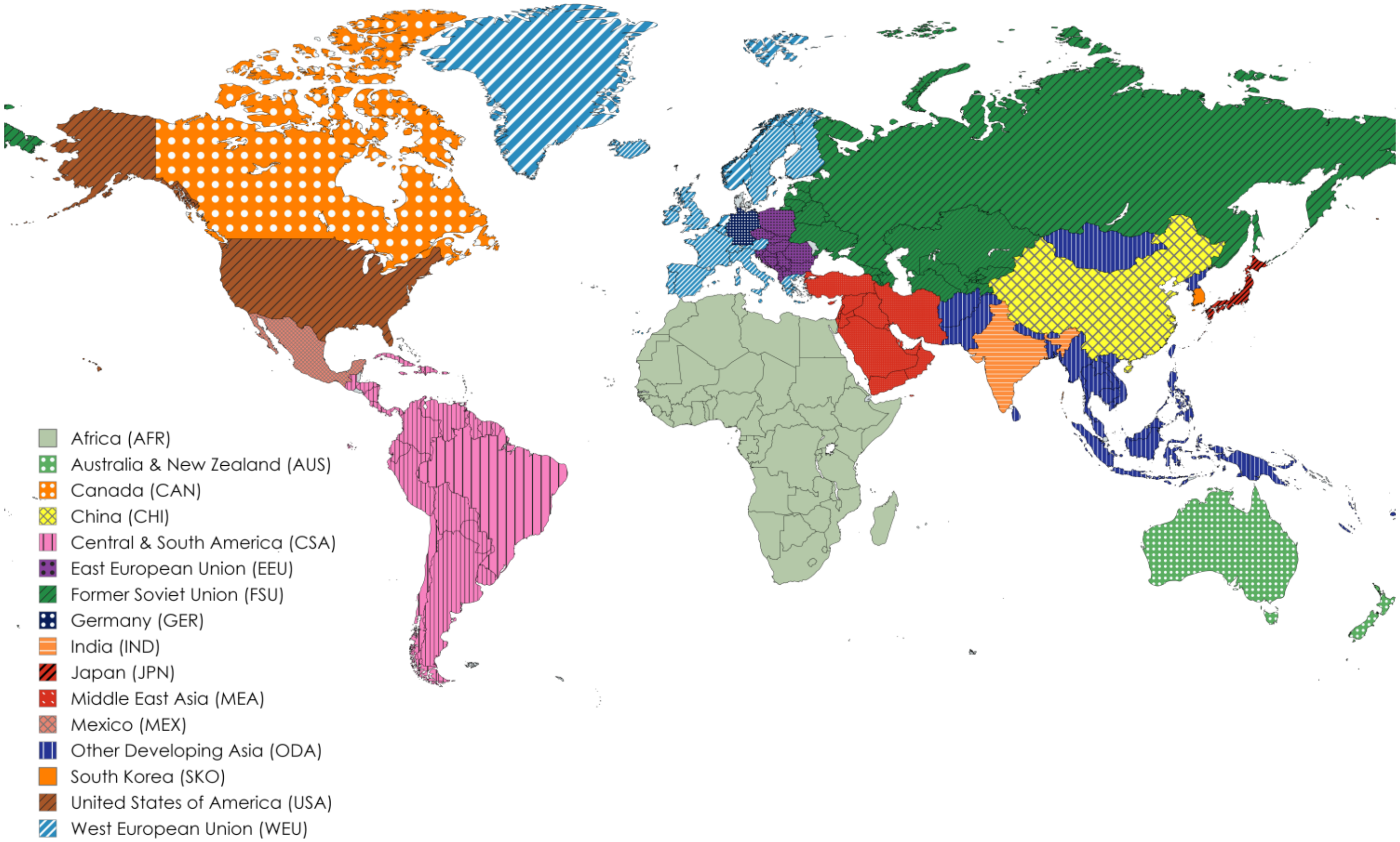
- Feedstock demand can be lowered by keeping materials in the loop -> circular economy
- Lowering the demand by material efficiency measures can help
- Chemical and mechanical plastics recycling can help to solve both, environmental and climate issues

ETSAP-TIAM model

ETSAP-TIAM model

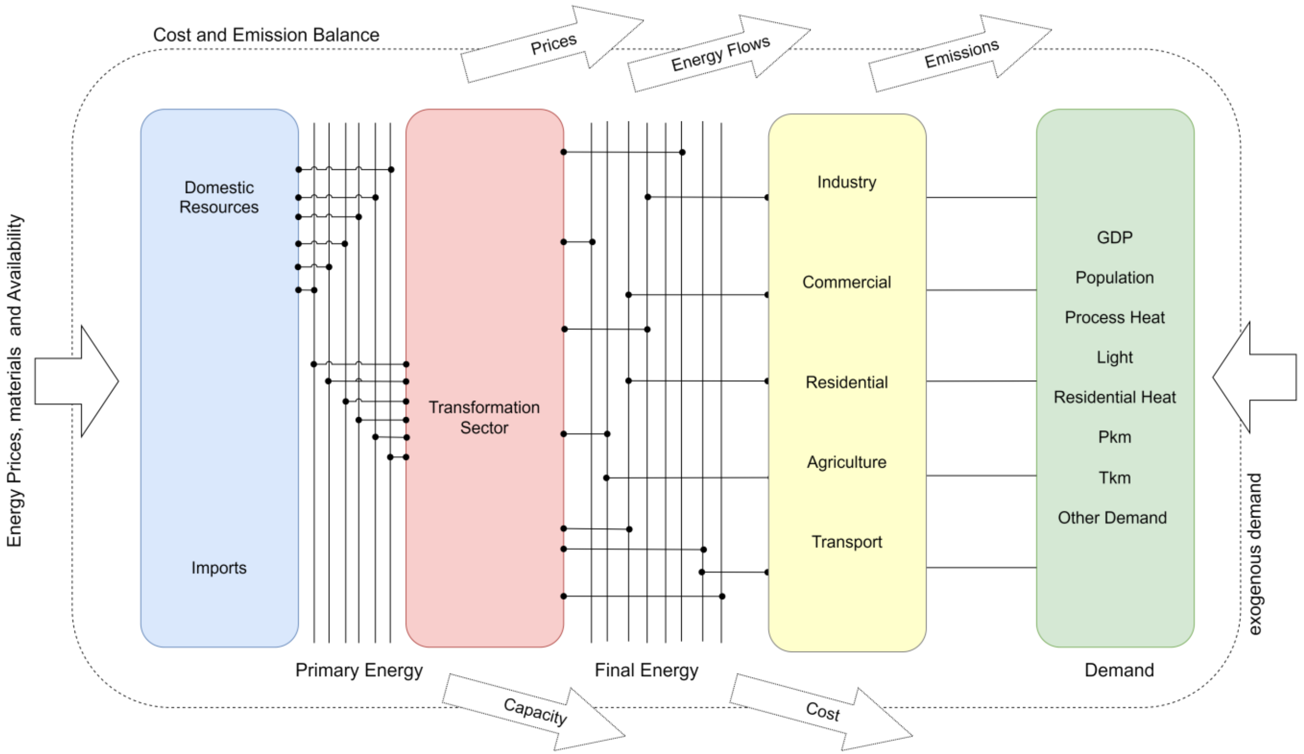
Overview

- Cost minimization
- Detailed process oriented bottom-up energy system model
- 16 world regions
- Time horizon: 2018-2100
- Base Year: 2018
- 12 time slices
- Perfect foresight



ETSAP-TIAM model

Reference energy system of TIAM



- Modelling primary energy to final energy
- 5 end use sectors covered: industry, commercial, residential, transport and agriculture
- Over 4000 technological processes to represent the global energy system
- Cost optimal solution for energy and energy services based on exogenous demands
- Investigation of climate policy on the energy system

 Lippkau et. al, https://doi.org/10.1007/978-3-031-58897-6_11

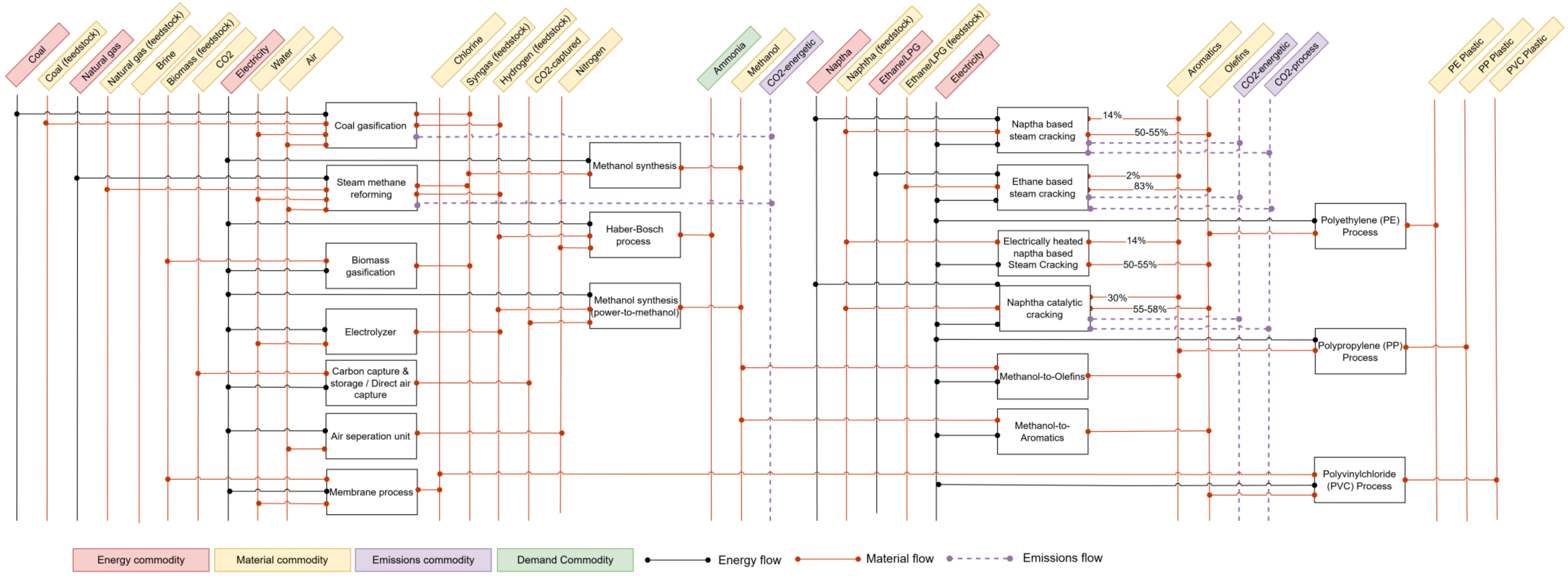
ETSAP-TIAM model

Modelling of circular economy and material efficiency in TIAM

- Detailed process oriented modelling of production pathways
- Consideration of energetic and non-energy related as well as process emissions
- Economically and ecologically evaluated materials and products
- Implementation of overall recycling strategies and recycling rates
- Barriers in circular economy are captured in the model as well

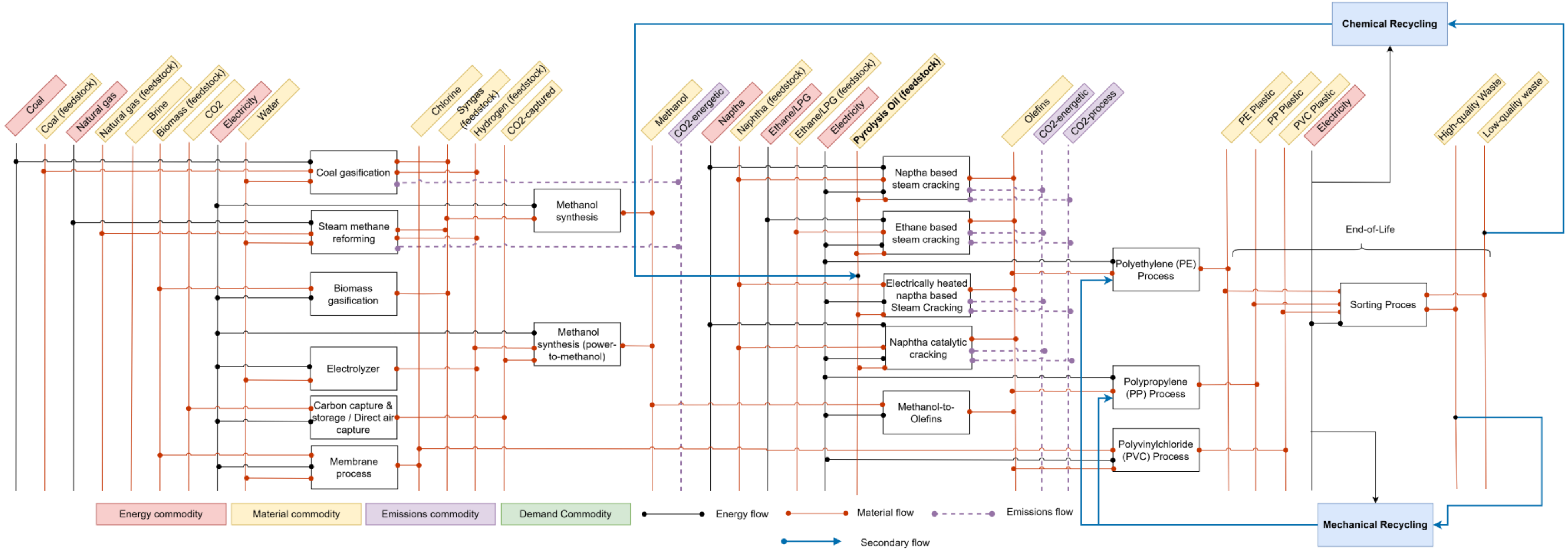
ETSAP-TIAM Model

Main chemical sector: Detailed overview for methanol, chlorine, olefins and plastics



ETSAP-TIAM Model

Extended main chemical sector with recycling pathways for plastics



ETSAP-TIAM Model

Scenario definition

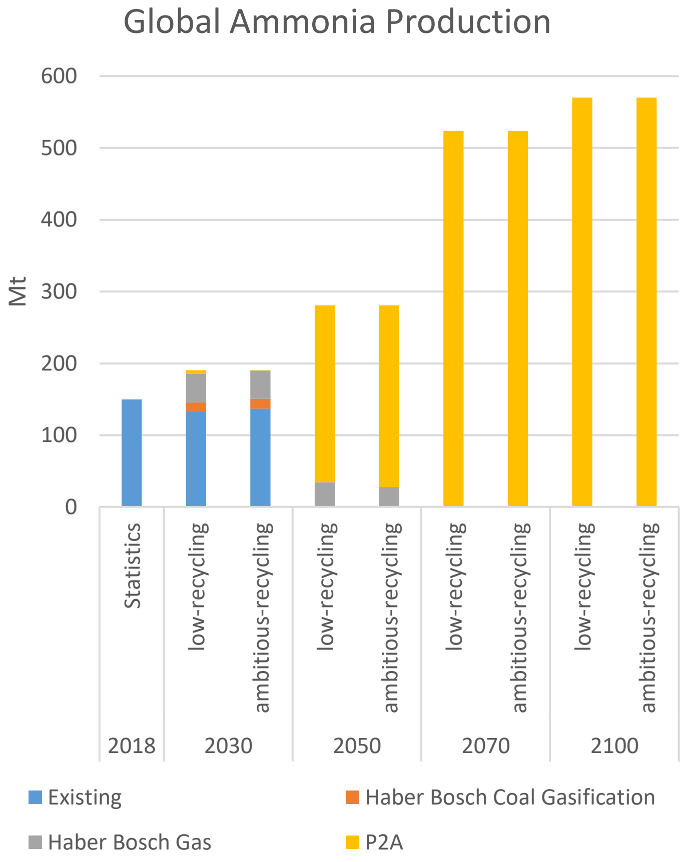
Scenario	Description	
	CO_2 budget in reaching Net-Zero	Plastic waste and recycling rates
Low-recycling	420 Gt until 2100	• Low recycling rates from 2019 until 2100 • High hydrogen needed for decarbonization
Ambitious recycling		• Ambitious recycling rates from 9% in 2018 to 60% until 2100. • Less plastic waste in the environment

[1] IPCC Climate Change 2021 The Physical Science Basis 2021
[2] https://www.oecd.org/en/publications/global-plastics-outlook_aa1edf33-en.html

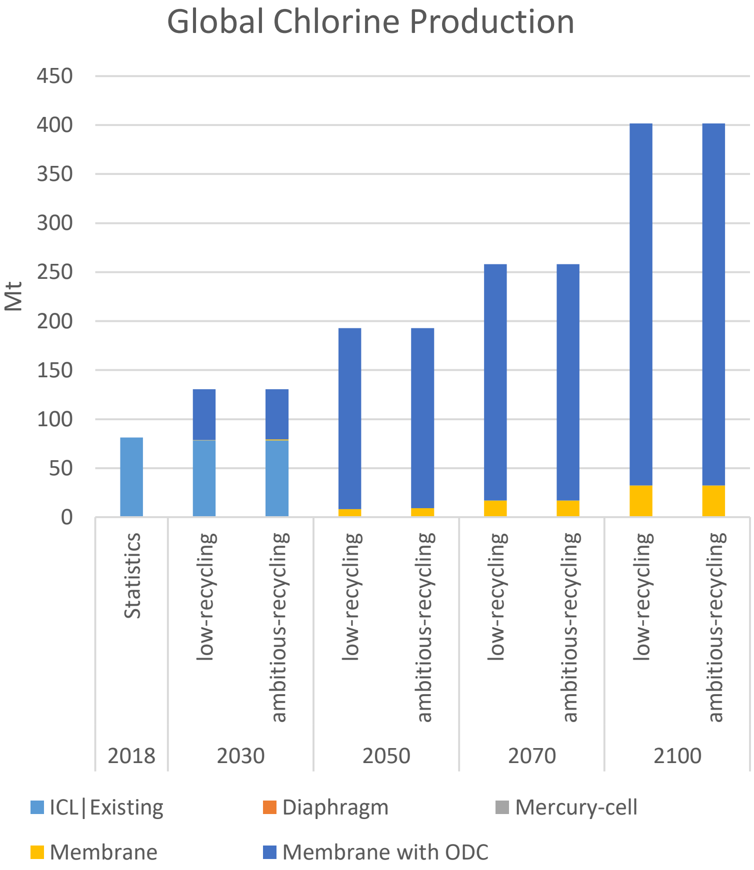
Scenario analysis results

Scenario analysis results

Global Ammonia and Chlorine Production

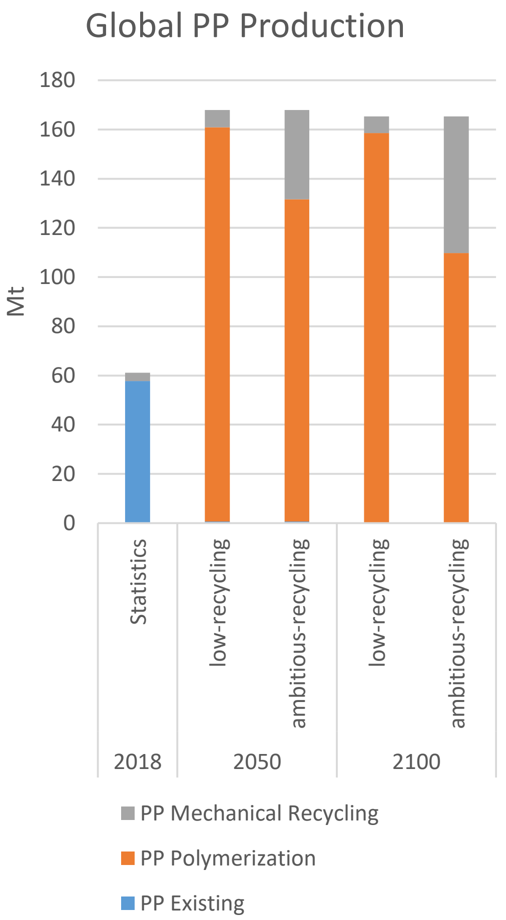


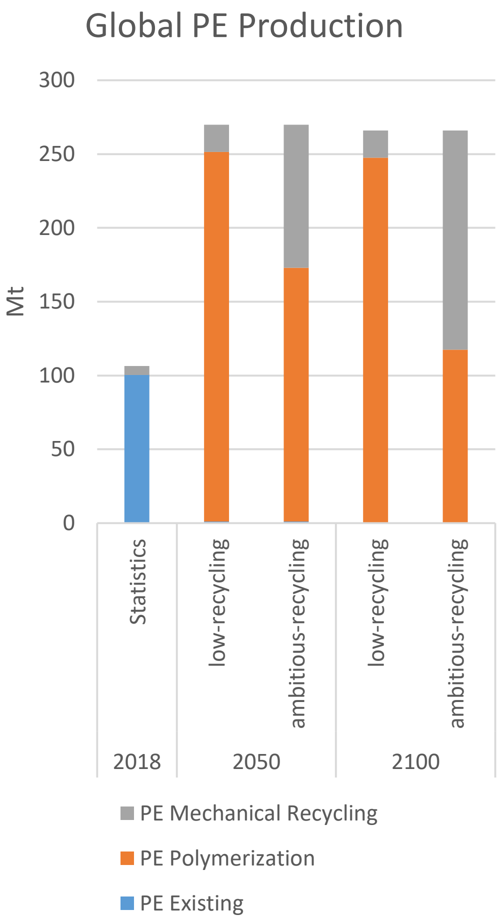
P2A Power to Ammonia



- Shifting from SMR and coal gasification to P2A in ammonia production
- Membrane with ODC for chlorine production has the highest efficiency but no hydrogen output
- For both materials electrification is the cost optimal way to decarbonize

Scenario analysis results

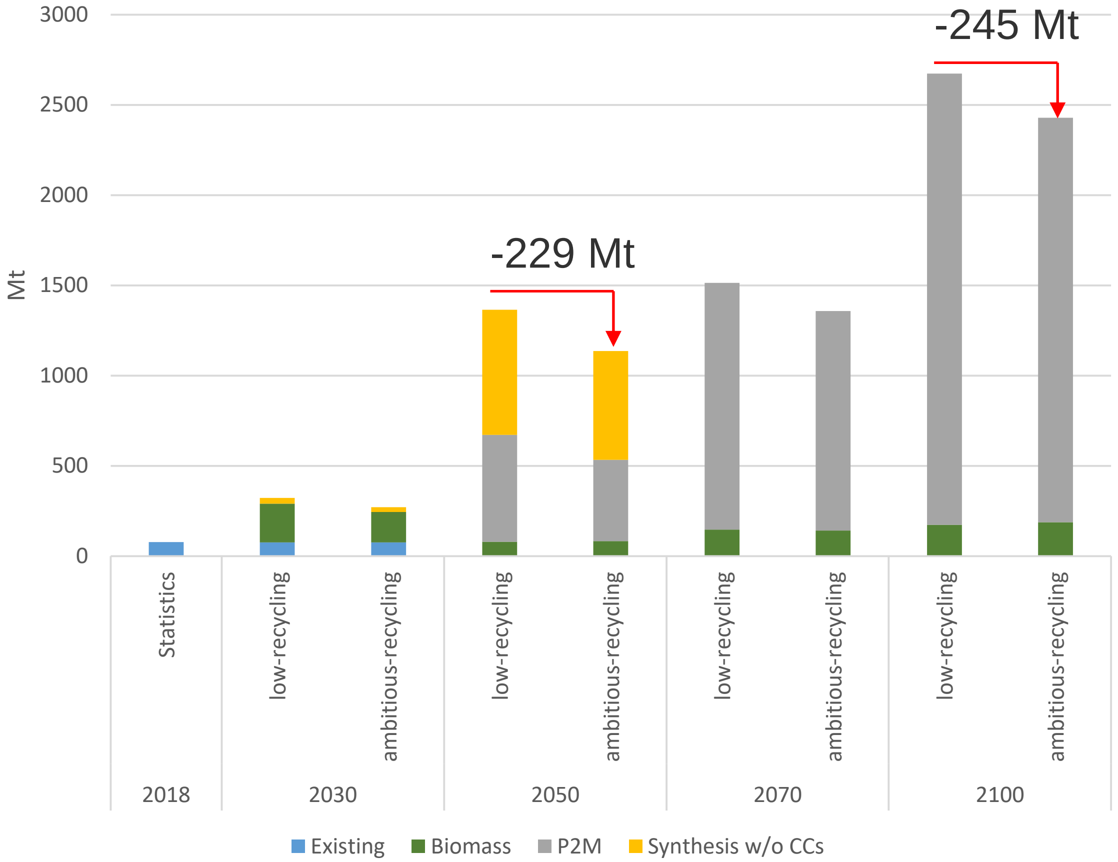




- Primary production remains the same technology with higher efficiency
- The higher availability of plastic scrap reduced the polymerization route by:
- 2050
  - 29 Mt for PP
  - 48 Mt for PE
- 2100
  - 48 Mt for PP
  - 130 Mt for PE

Scenario analysis results

Global Methanol Production

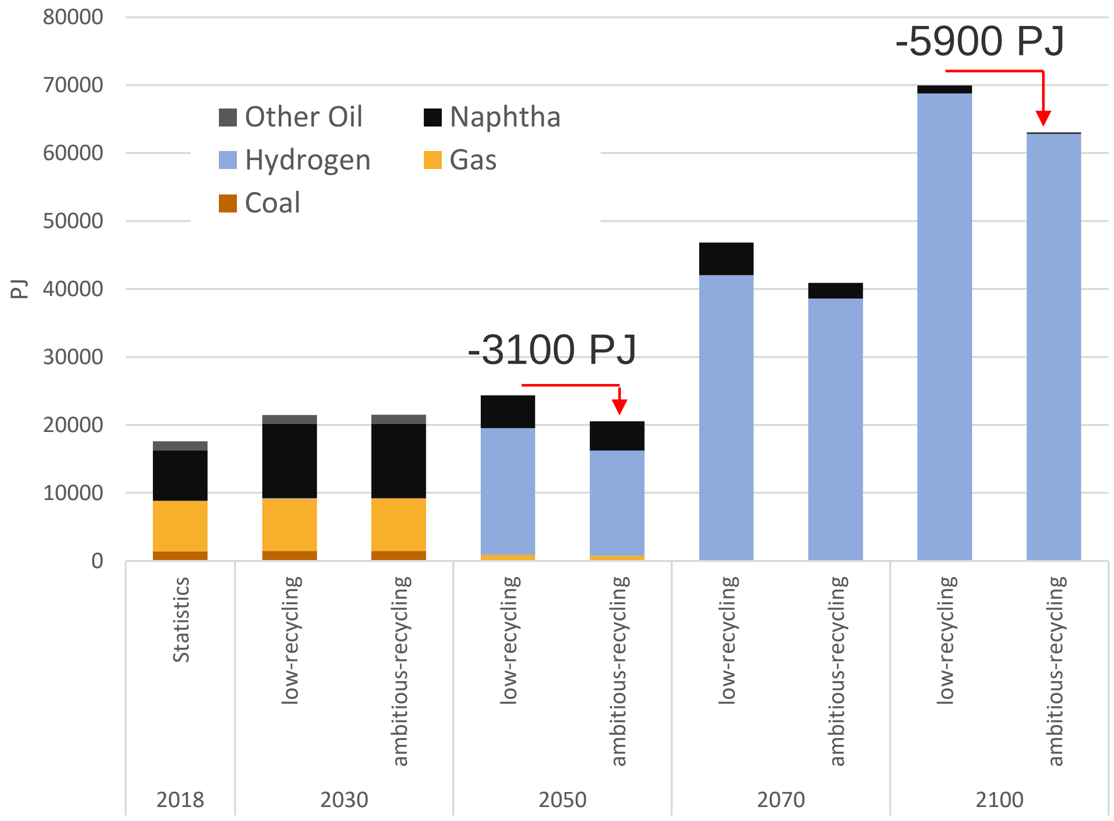


- Methanol demand is rising caused by endogenous demand for olefines and exogenous demand as well
- Fossil dominated in 2018
- Promoting ambitious recycling could significantly lower the growth in methanol demand, particularly from technologies such as P2M and methanol synthesis

P2M Power to Methanol

Scenario analysis results

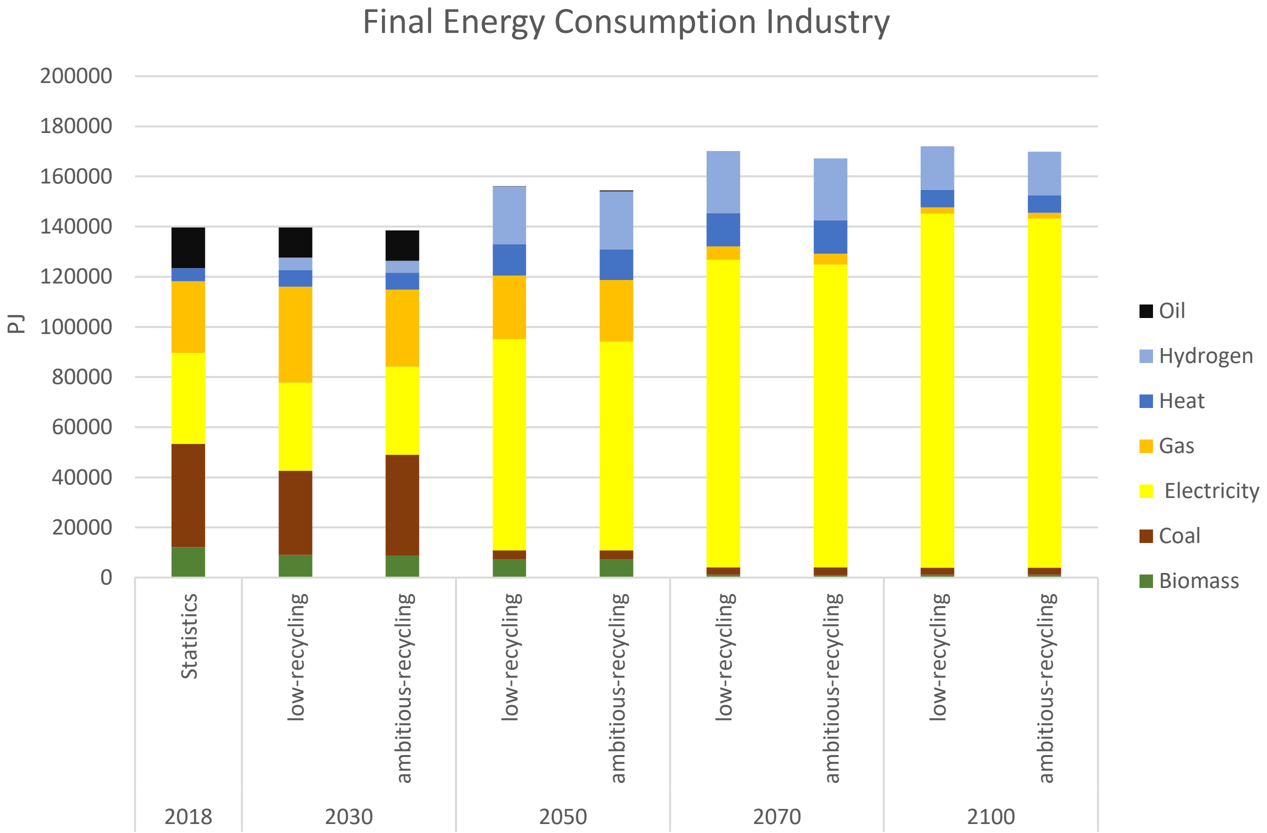
Feedstock Chemicals



- The feedstock demand is mainly driven by ammonia and methanol
- Tremendous transition to fossil-free feedstock carriers in 2050
- Lowering the demand in methanol because of recycling lowers the demand in overall feedstock by 5900 PJ in 2100
- Long lifetimes of steam crackers result in long usage of fossil feedstock

Scenario analysis results

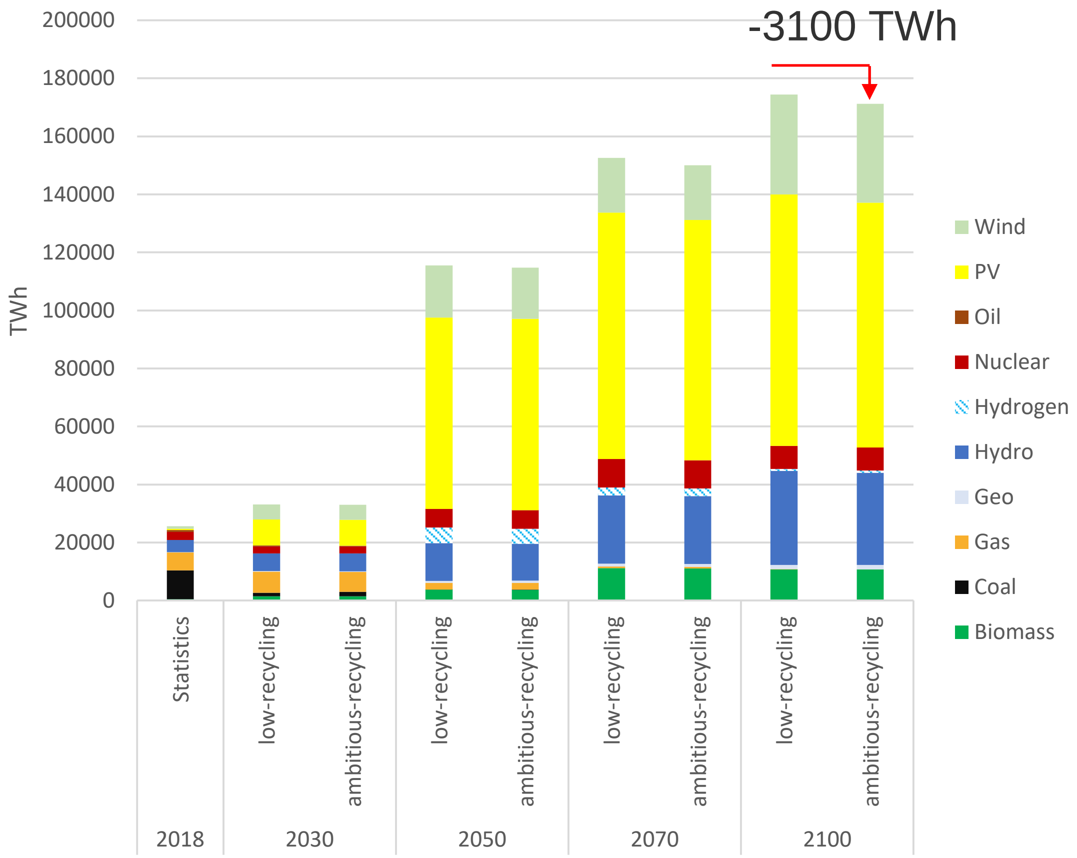
Global Final Energy Consumption (FEC)



- Starting with high shares of fossil energy mainly for heat supply
- Electricity becomes the dominant energy carrier for the global Industry
- Hydrogen needed for high temperature processes
- Recycling causes a slight decrease in final energy consumption

Scenario analysis results

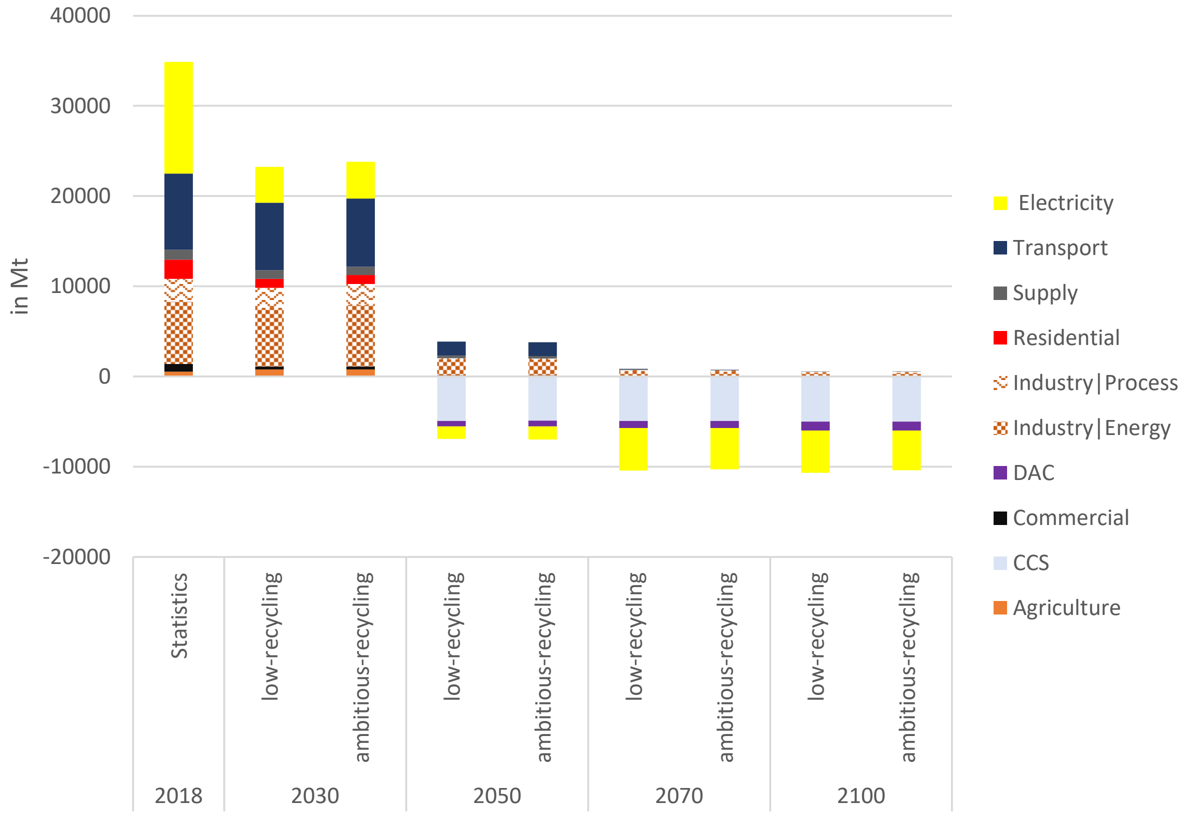
Global net electricity generation



- Electricity mix is fossil dominated in 2018
- The electricity sector does not only need to get fossil free, but also produce final energy for other sectors which leads to a demand rise
- Wind and solar PV becomes the dominant production routes
- Biomass becomes important for negative emissions

Scenario analysis results

Global CO2 Emissions



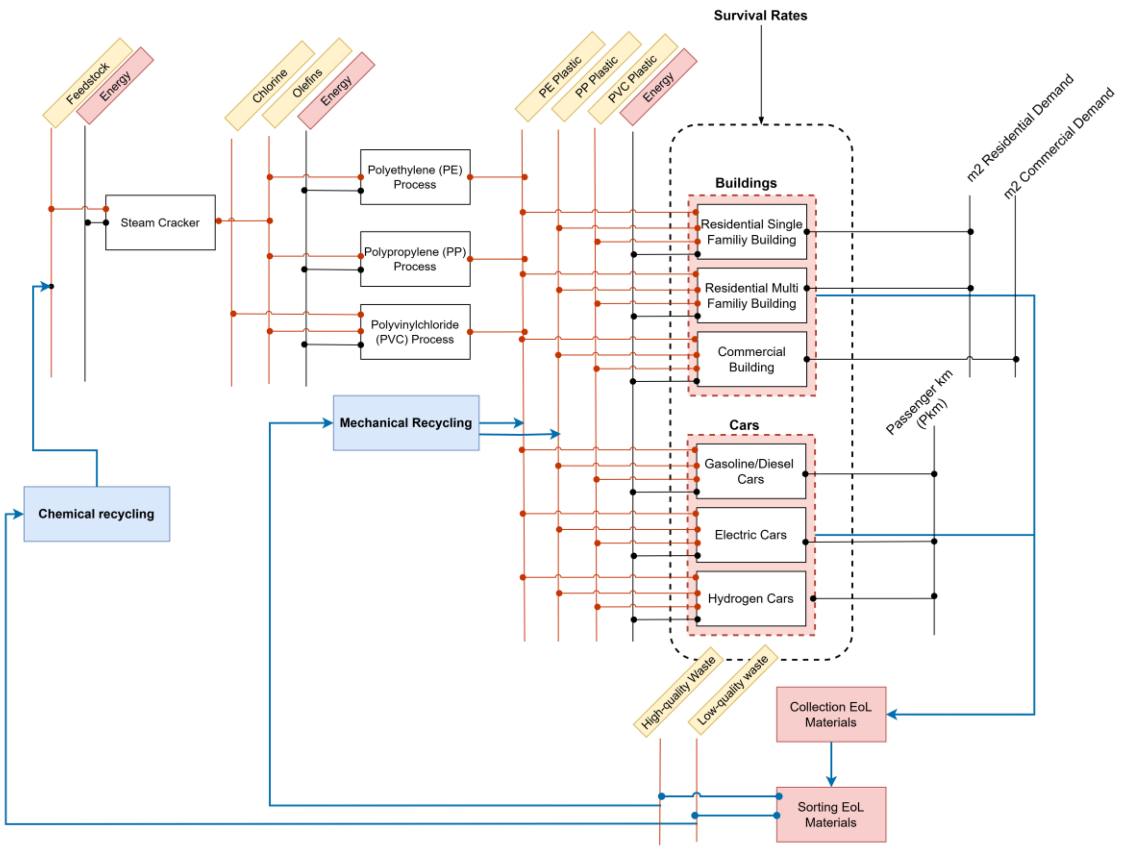
- Starting 2018 the electricity sector has the highest emissions due to high shares of coal and gas
- Biomass becomes an important energy carrier for both electricity and BECCS
- Transport and industry can drastically reduce the emissions by using technologies relying on electricity
- Negative emissions are needed to meet the CO2 budget

Conclusion

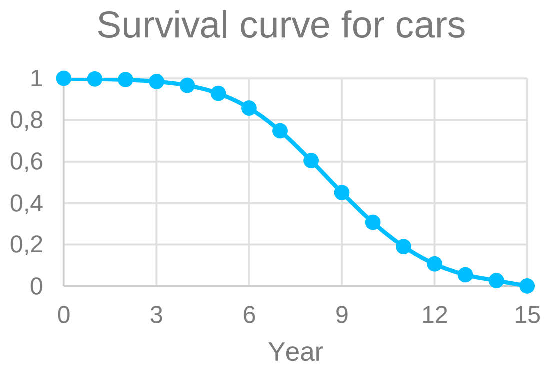
- 1% more recycling leads up to 115 PJ of less demand in hydrogen for feedstock
- As steam crackers have a enormous lifetime the transition to hydrogen in 2030-2050 is very important to achieve net zero in the long run
  - Trade links need to be established in order to be able to switch to fossil free feedstock
  - Chemical recycling is a promising technology but given the current data too expensive in comparison to MTO and MTA
  - If chemical recycling becomes cost competitive, the remaining stock of steam crackers can be used with pyrolysis oil
- Ambitious recycling can reduce the cumulative (2018-2100):
  - hydrogen feedstock demand by 225 EJ
  - Electricity demand by 43000 TWh

Outlook

Next steps: implementing endogenous material efficiency



- Passenger cars and buildings will be considered as examples for material inputs for plastics.
- Defining survival rates in the model will determine when plastics become available for recycling
- Material efficiency strategies like higher lifetimes and higher recycling rates will be modelled to investigate the complete effect on energy consumption.



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Thank you!

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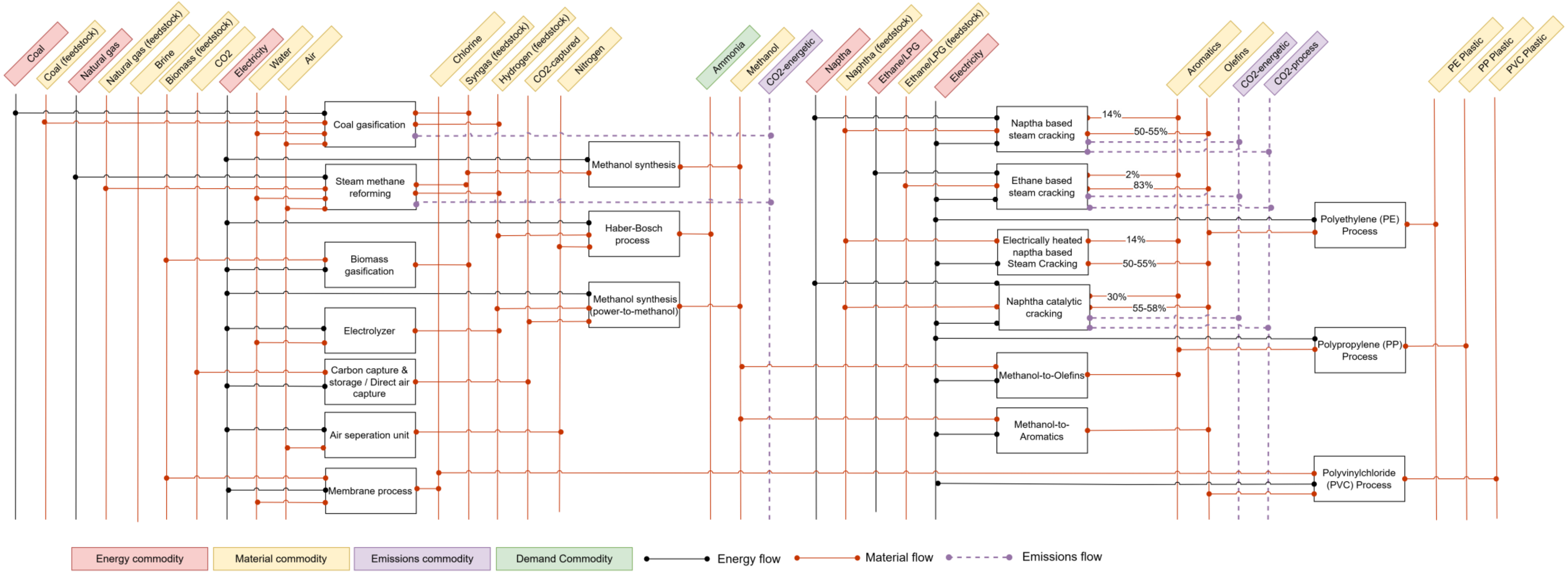
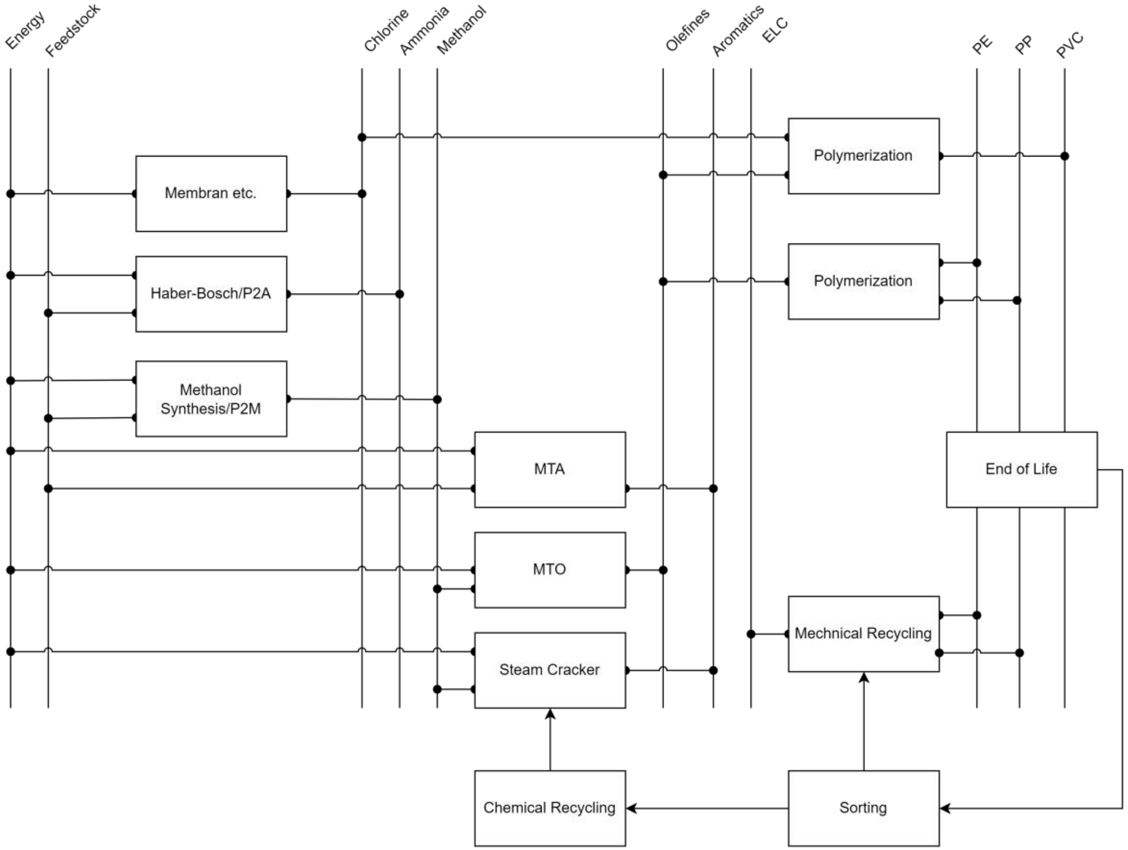
Appendix

ETSAP-TIAM Model



ETSAP-TIAM Model

Chemical sector in the model: Brief overview



MTA: Methanol to Aromatics
MTO: Methanol to Olefines
P2A: Power to Ammonia