Life cycle based environmental impacts of energy system transformation strategies for Germany: Additional results from the InNOSys project

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Contents

1 Introduction

This report documents additional results from the study [4]. For each of the seventeen environmental indicators summarized in Table 1, the following results are shown in Section 2:

- Development of the indicator 2000-2050 on scenario level
- Environmental impacts for the year 2050 on the level of those sectors explicitly considered in the foreground model. A list of model sectors can be found below in Section 4.1.
- Environmental impacts for the year 2050 on the level of end-use applications. An overview of end-use applications considered here can be found in Section 4.2.
- Environmental impacts for the year 2050 on the level of individual technologies (impacts from construction and operation separated). In the figures, only technologies contributing more than 5% to the total impact on scenario level are shown individually. The impacts of all other technologies are shown in an aggregated manner.
- Environmental impacts for the year 2050, separated into direct impacts (from on-site emissions during operation of the technologies) and impacts from background processes (impacts from the construction of the technologies, impacts from the generation of fuels not explicitly considered in the foreground model, ...).
- Cumulated impacts (2020-2050) on the level of sectors explicitly considered in the foreground model (see Section 4.1).

In Section 3, the performance of all scenarios with respect to all indicators is compared, both on the level of entire scenarios, but also on the level of individual sectors (residential, service, industry, tranport, power generation, P2X and biofuel conversion).

Note that the scenarios I-V achieve a reduction of (direct) CO_2 emissions of ca. 80%. They are thus called the "80% scenarios". Scenarios VI-X achieve a reduction of (direct) CO_2 emissions of ca. 95% and are called the "95% scenarios".

A detailed description of the methods applied here as well as a principal discussion of the approach can be found in [2] and [3].

Category	Indicator	unit
Climate Change	Climate change	kg CO_2 eq
Ecosystem Quality	Freshwater and terrestrial acidification	mol H^+ eq
	Freshwater ecotoxicity	CTUe
	Freshwater eutrophiction	kg P eq
	Marine eutrophication	kg N eq
	Terrestrial eutrophication	mo N eq
Human Health	Carcinogenic effects	CTUh
	Non-carcinogenic effects	CTUh
	Ionizing radiation	kg U235 eq
	Ozone layer depletion	kg CFC-11 eq
	Photochemical ozone creation	kg NMVOC eq
	Respiratory effects, inorganics	disease incidence
Resources	Fossils	MJ
	Minerals and metals	kg Sb eq
	Land use	points
	Dissipated water	m^3 water eq
EU Environmental footprint	EU Environmental footprint	dimensionless

Table 1: Overview of life cycle based environmental impacts assessed here. All indicators are calculated with the methods summarized in [1], with the exception of Resources (minerals and metals), whcih uses the method from [5].

2 Additional results for individual indicators

2.1 Climate Change

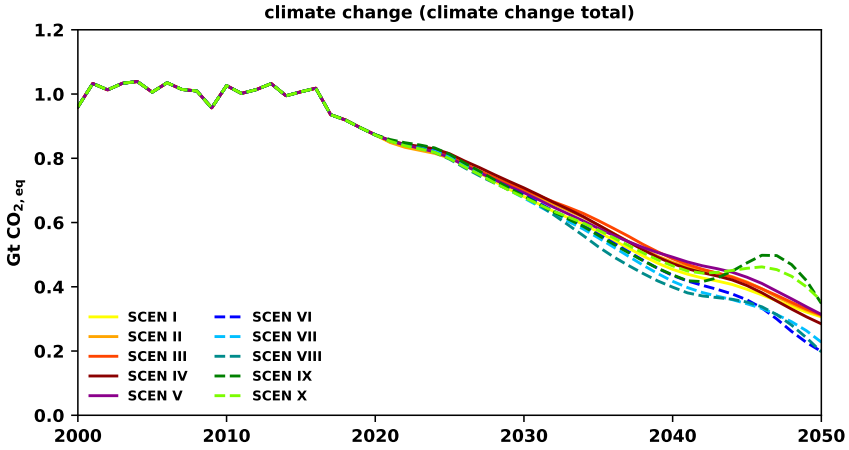

Figure 1: Climate Change: Development until 2050 in all scenarios

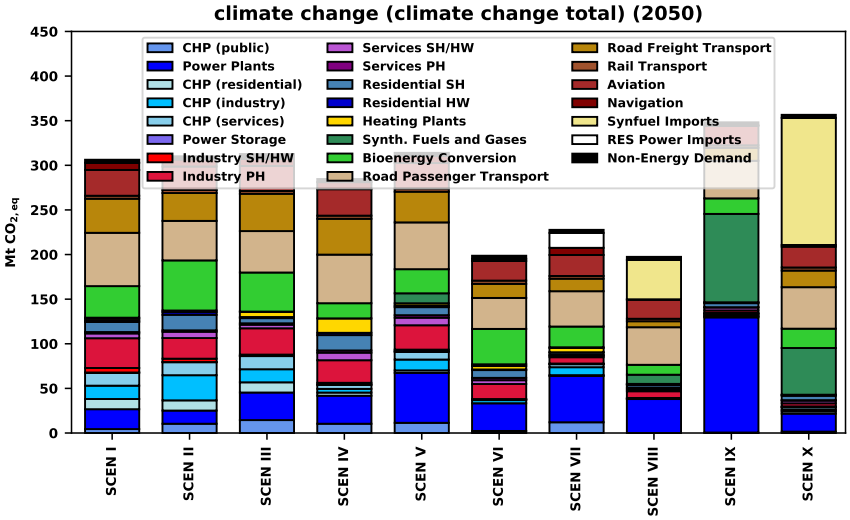

Figure 2: Climate Change: Impacts 2050 on sector level

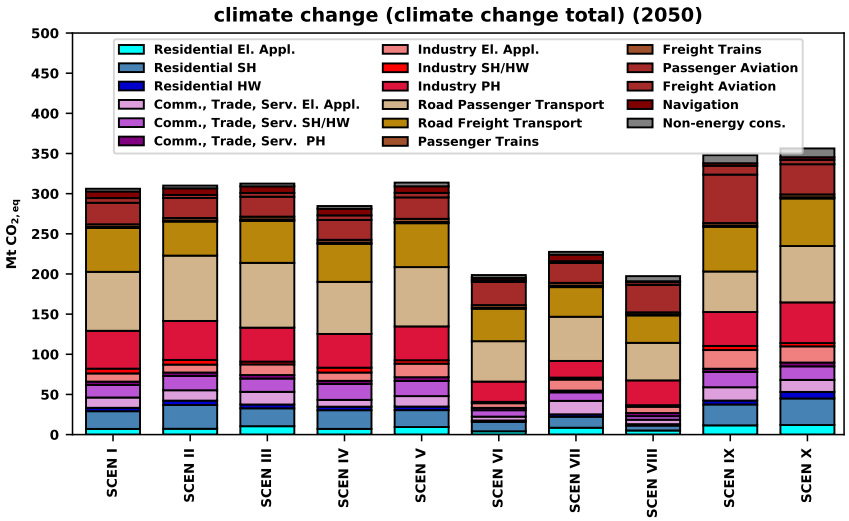

Figure 3: Climate Change: Impacts 2050 on enduse level

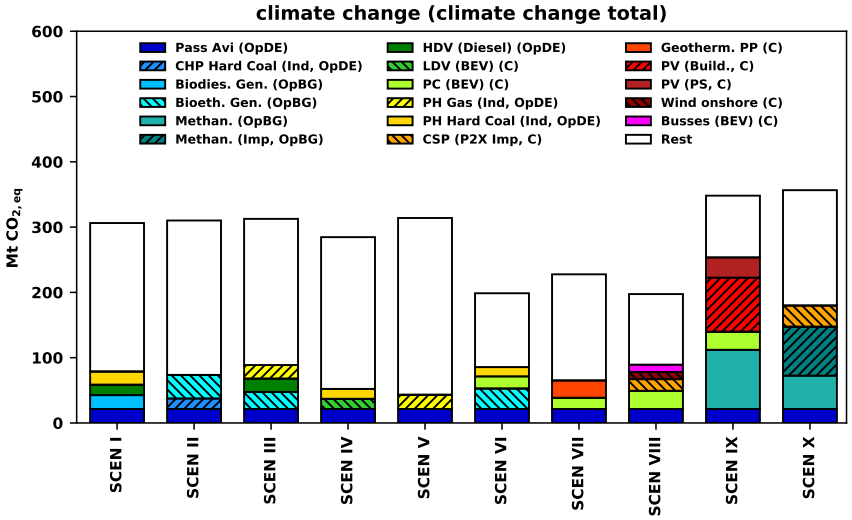

Figure 4: Climate Change: Impacts 2050 on technology level

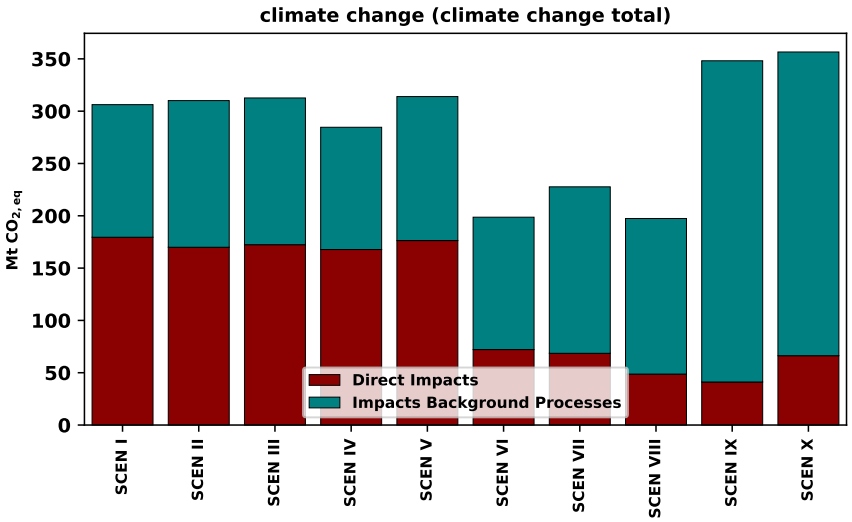

Figure 5: Climate Change: Direct impacts and impacts from background processes (2050)

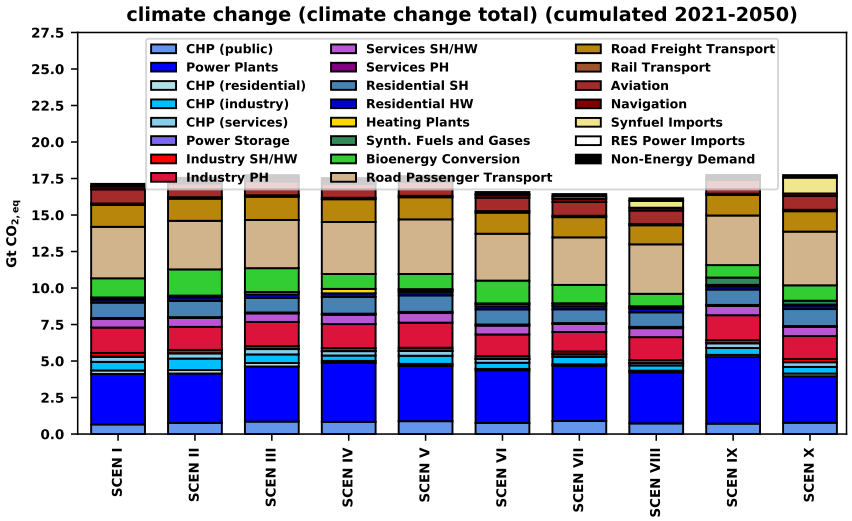

Figure 6: Climate Change: Cumulated Impacts (2020-2050) on sector level

2.2 Ecosystem Quality: Freshwater and Terrestrial Acidification

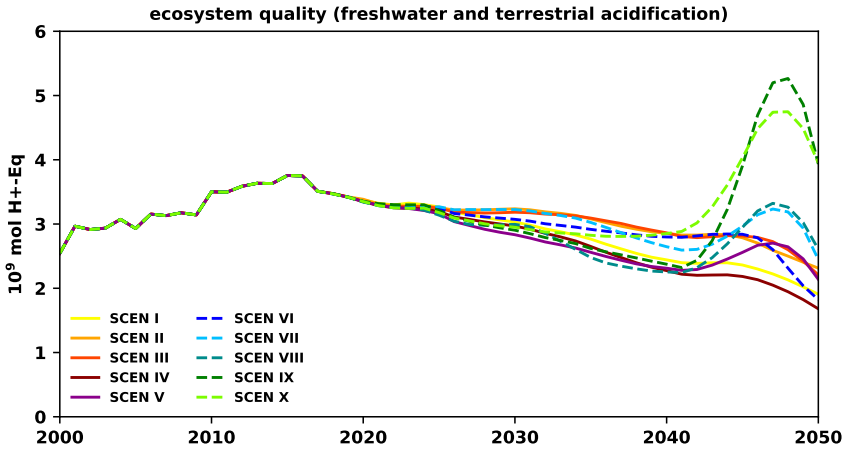

Figure 7: Ecosystem Quality (Freshwater & Terrestrial Acidification): Development until 2050 in all scenarios

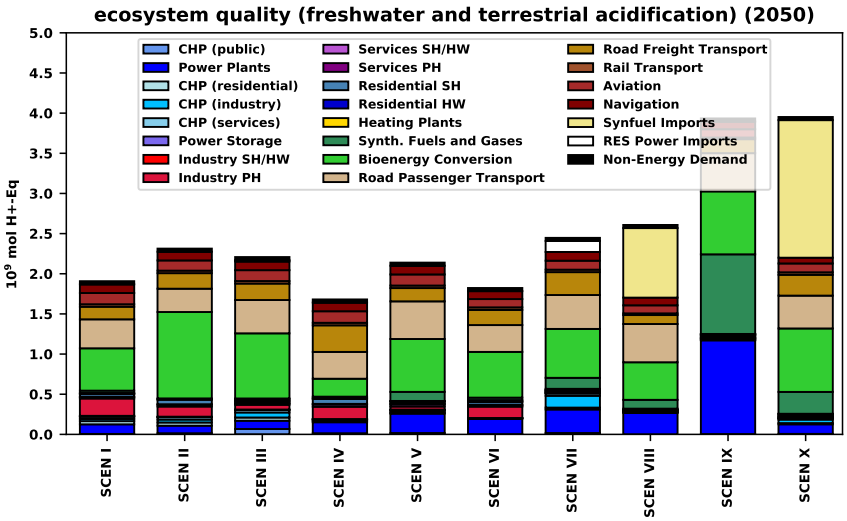

Figure 8: Ecosystem Quality (Freshwater & Terrestrial Acidification): Impacts 2050 on sector level

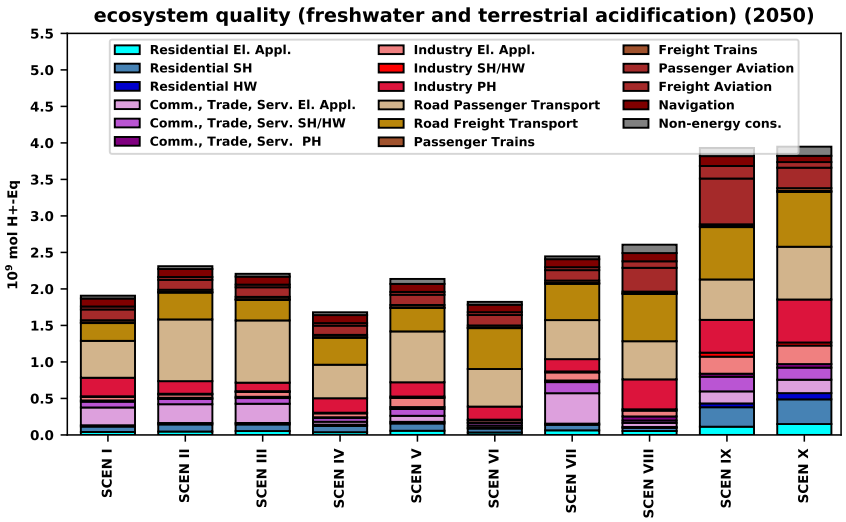

Figure 9: Ecosystem Quality (Freshwater & Terrestrial Acidification): Impacts 2050 on enduse level

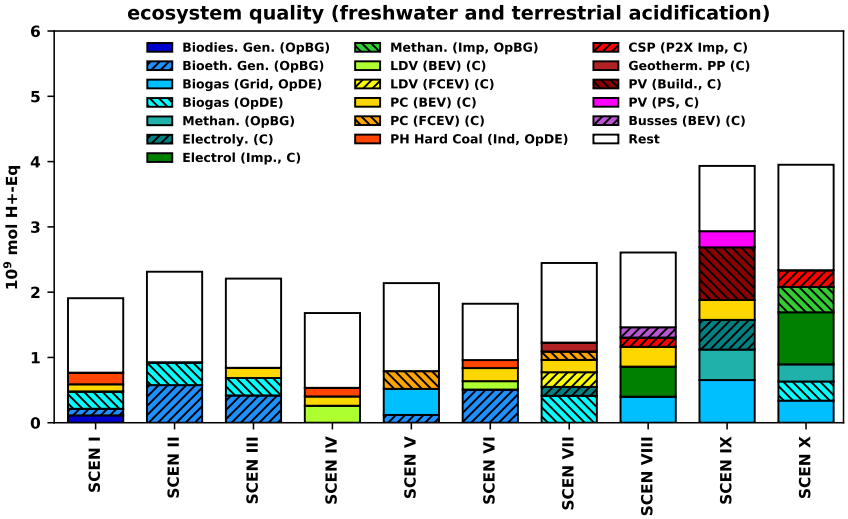

Figure 10: Ecosystem Quality (Freshwater & Terrestrial Acidification): Impacts 2050 on technology level

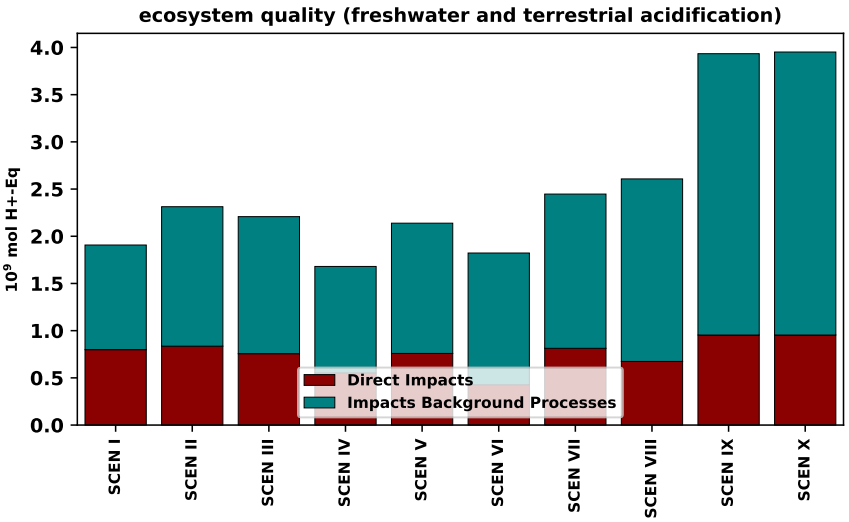

Figure 11: Ecosystem Quality (Freshwater & Terrestrial Acidification): Direct impacts and impacts from background processes (2050)

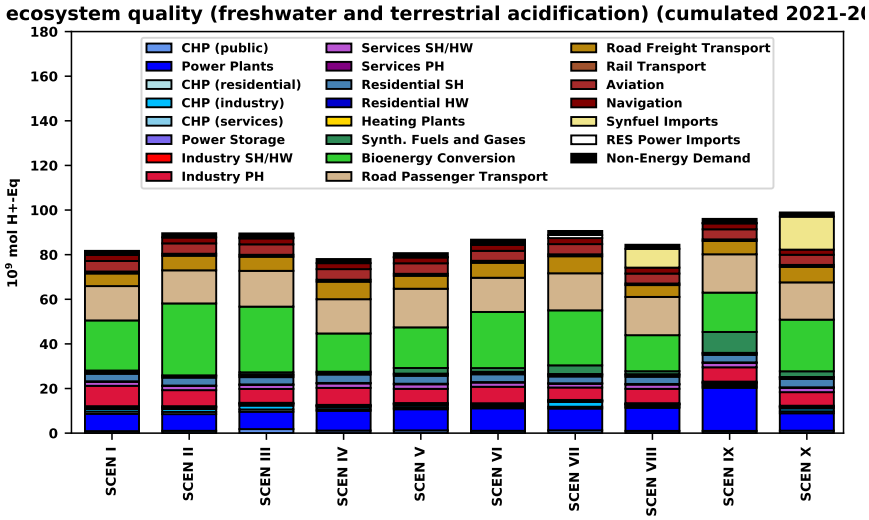

Figure 12: Ecosystem Quality (Freshwater & Terrestrial Acidification): Cumulated Impacts (2020-2050) on sector level

2.3 Ecosystem Quality: Freshwater Ecotoxicity

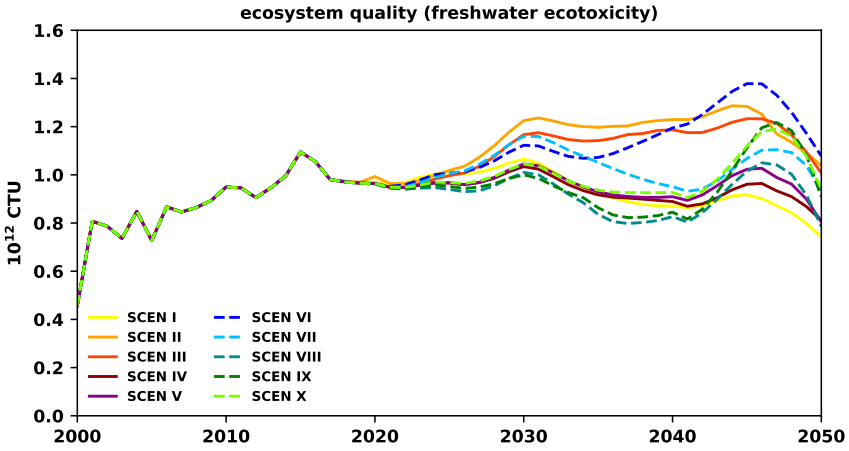

Figure 13: Ecosystem Quality (Freshwater Ecotoxicity): Development until 2050 in all scenarios

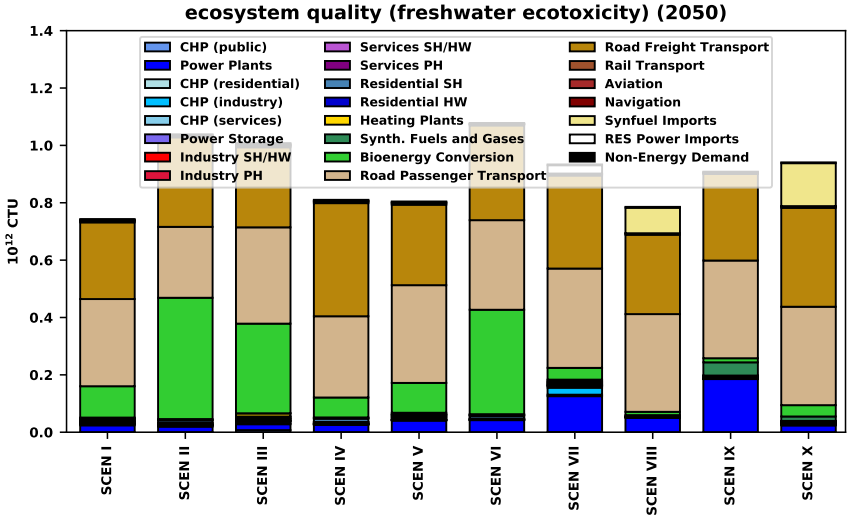

Figure 14: Ecosystem Quality (Freshwater Ecotoxicity): Impacts 2050 on sector level

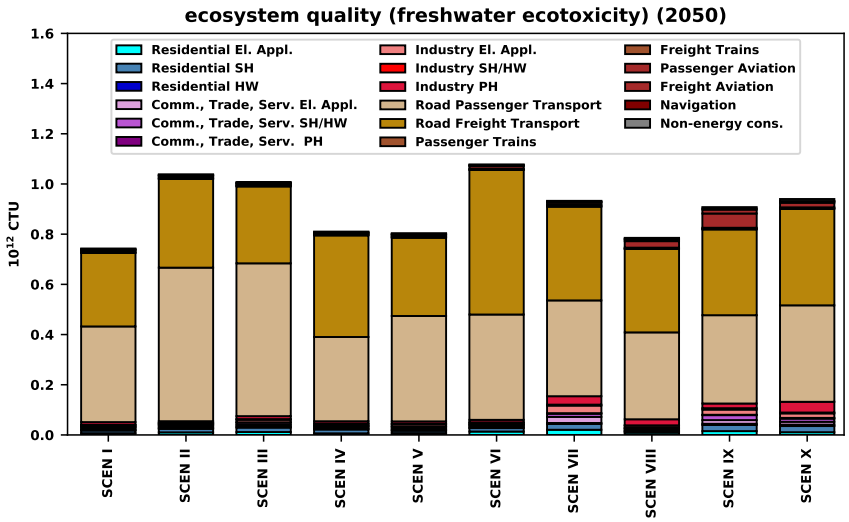

Figure 15: Ecosystem Quality (Freshwater Ecotoxicity): Impacts 2050 on end-use level

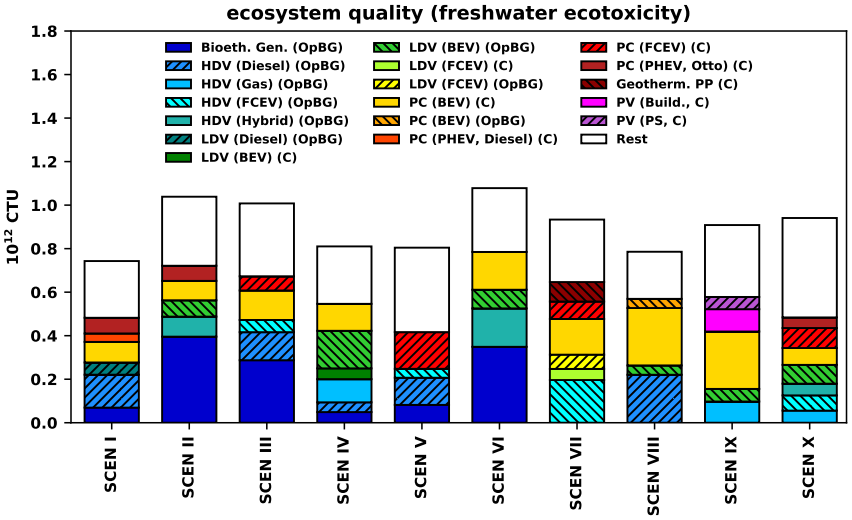

Figure 16: Ecosystem Quality (Freshwater Ecotoxicity): Impacts 2050 on technology level

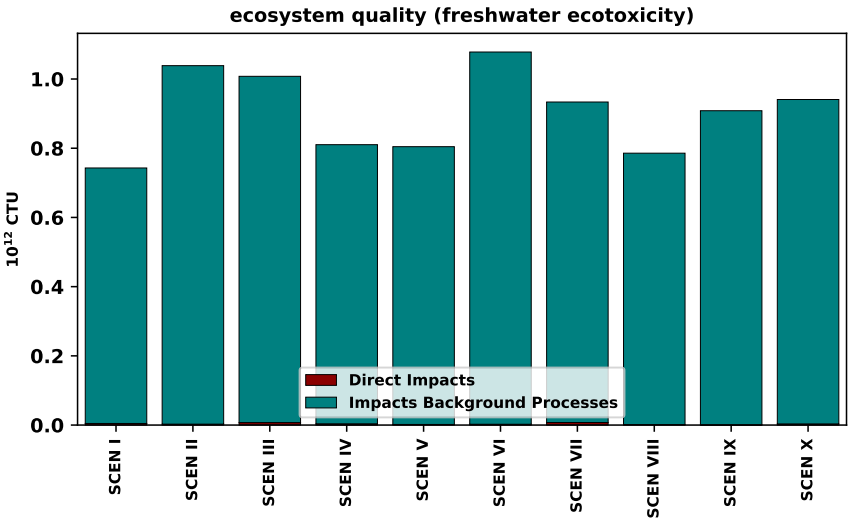

Figure 17: Ecosystem Quality (Freshwater Ecotoxicity): Direct impacts and impacts from background processes (2050)

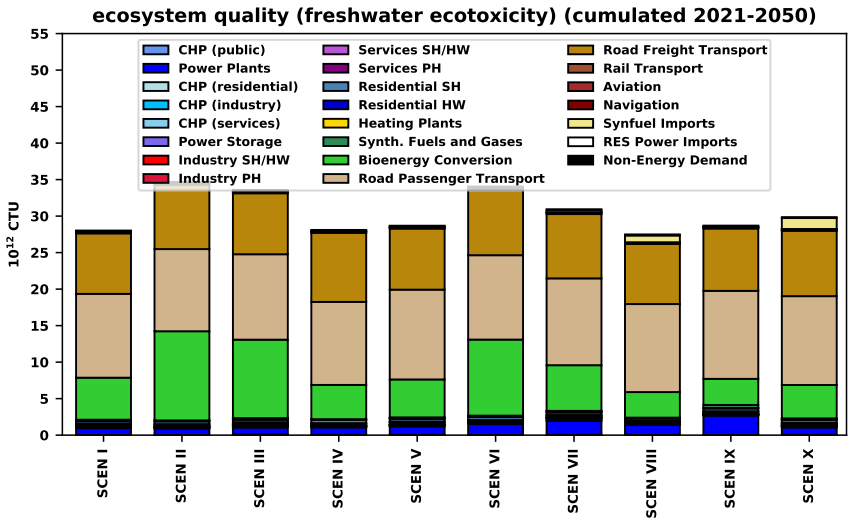

Figure 18: Ecosystem Quality (Freshwater Ecotoxicity): Cumulated Impacts (2020-2050) on sector level

2.4 Ecosystem Quality: Freshwater Eutrophication

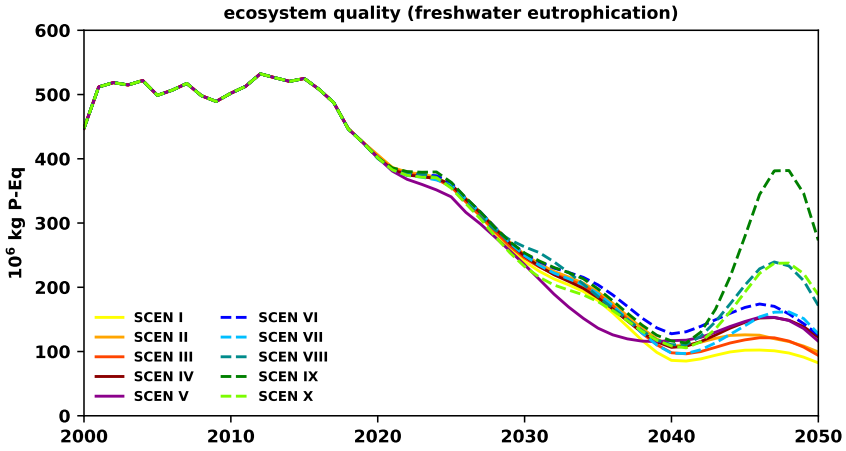

Figure 19: Ecosystem Quality (Freshwater Eutrophication): Development until 2050 in all scenarios

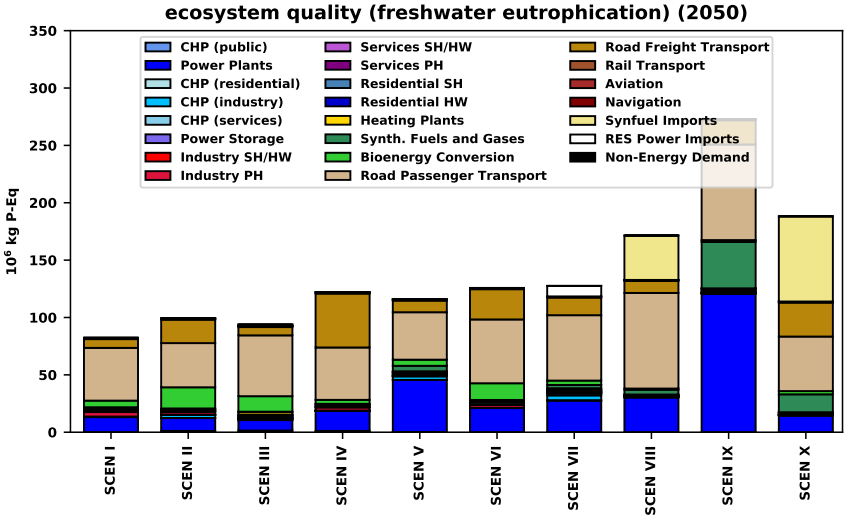

Figure 20: Ecosystem Quality (Freshwater Eutrophication): Impacts 2050 on sector level

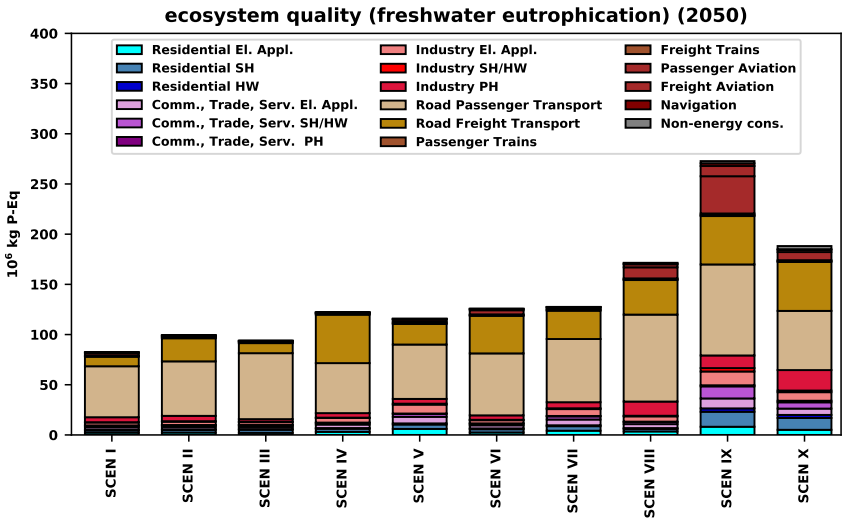

Figure 21: Ecosystem Quality (Freshwater Eutrophication): Impacts 2050 on enduse level

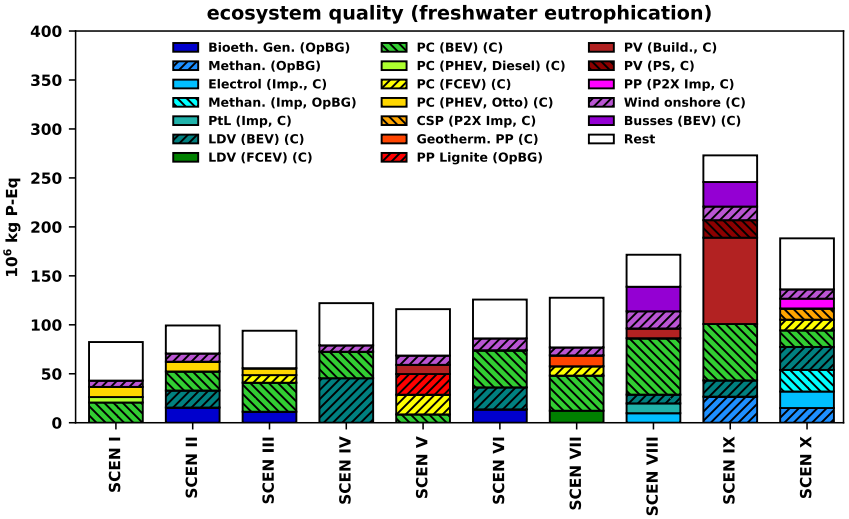

Figure 22: Ecosystem Quality (Freshwater Eutrophication): Impacts 2050 on technology level

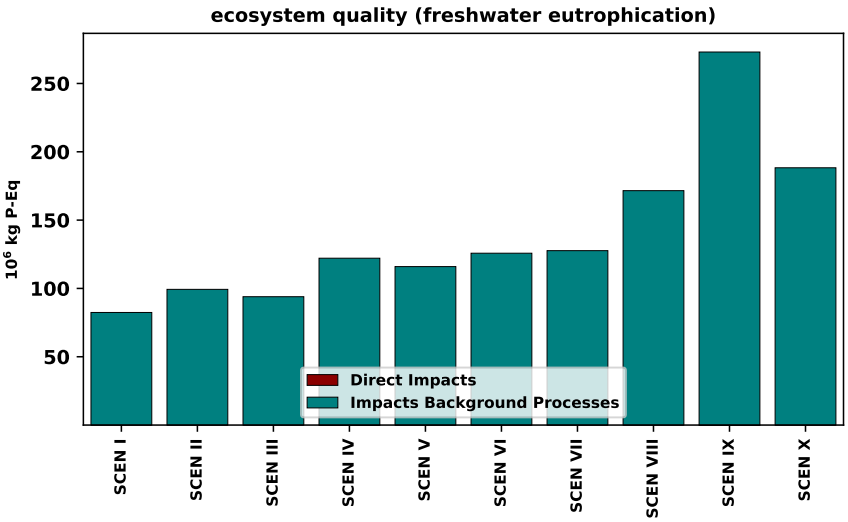

Figure 23: Ecosystem Quality (Freshwater Eutrophication): Direct impacts and impacts from background processes (2050)

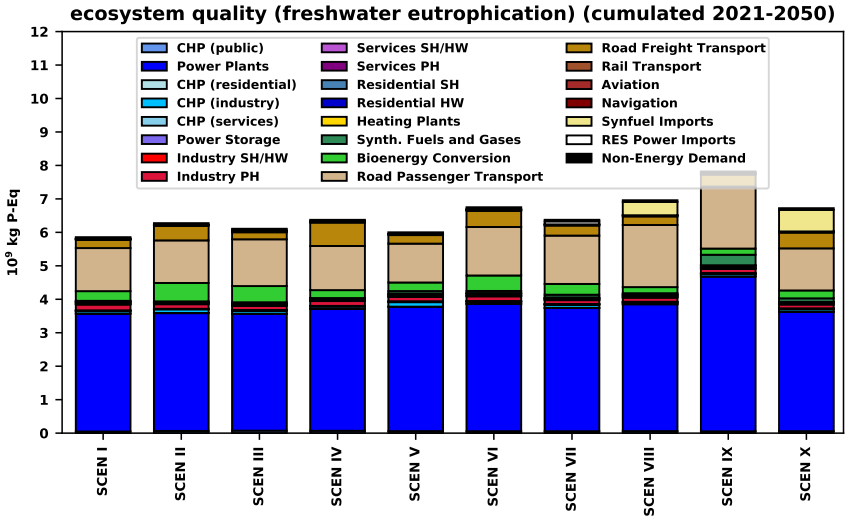

Figure 24: Ecosystem Quality (Freshwater Eutrophication): Cumulated Impacts (2020-2050) on sector level

2.5 Ecosystem Quality: Marine Eutrophication

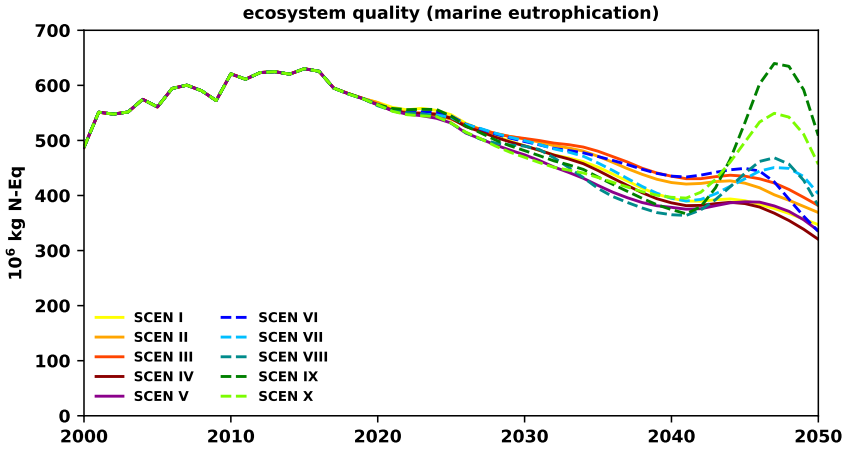

Figure 25: Ecosystem Quality (Marine Eutrophication): Development until 2050 in all scenarios

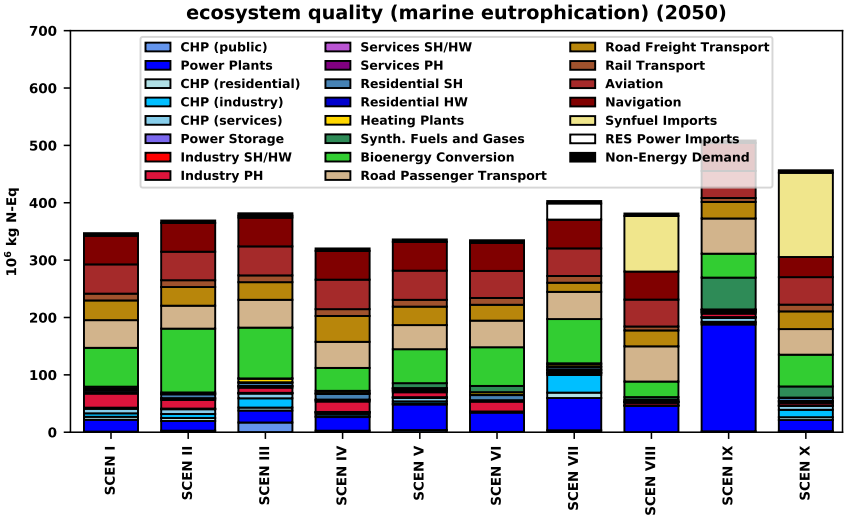

Figure 26: Ecosystem Quality (Marine Eutrophication): Impacts 2050 on sector level

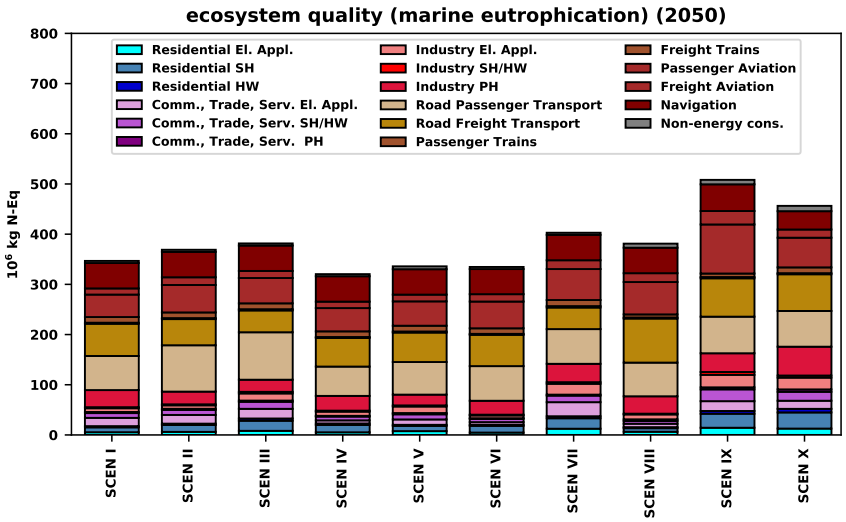

Figure 27: Ecosystem Quality (Marine Eutrophication): Impacts 2050 on end-use level

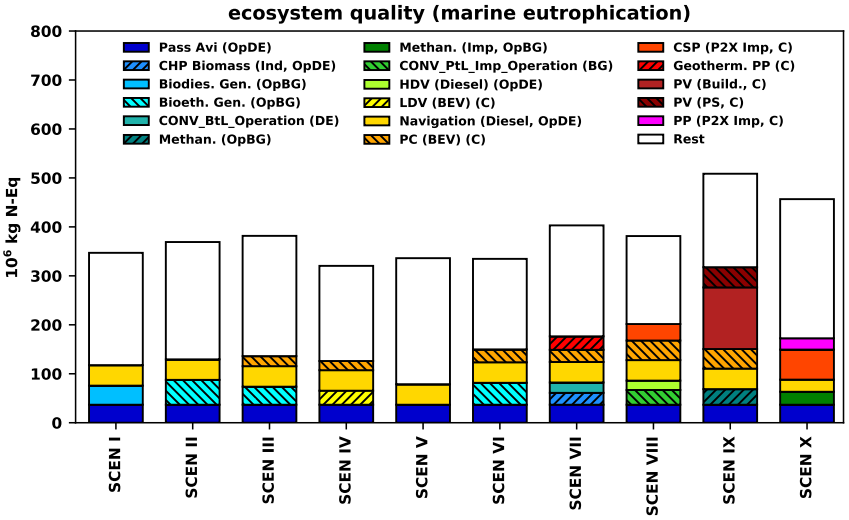

Figure 28: Ecosystem Quality (Marine Eutrophication): Impacts 2050 on technology level

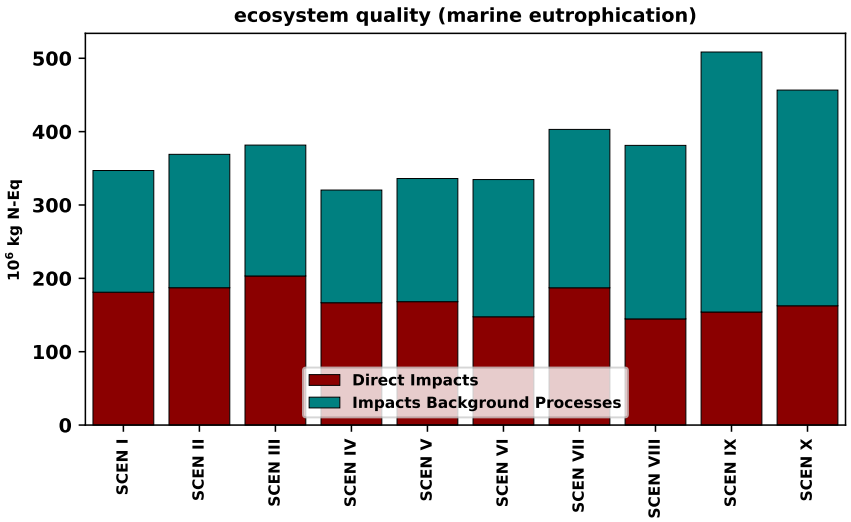

Figure 29: Ecosystem Quality (Marine Eutrophication): Direct impacts and impacts from background processes (2050)

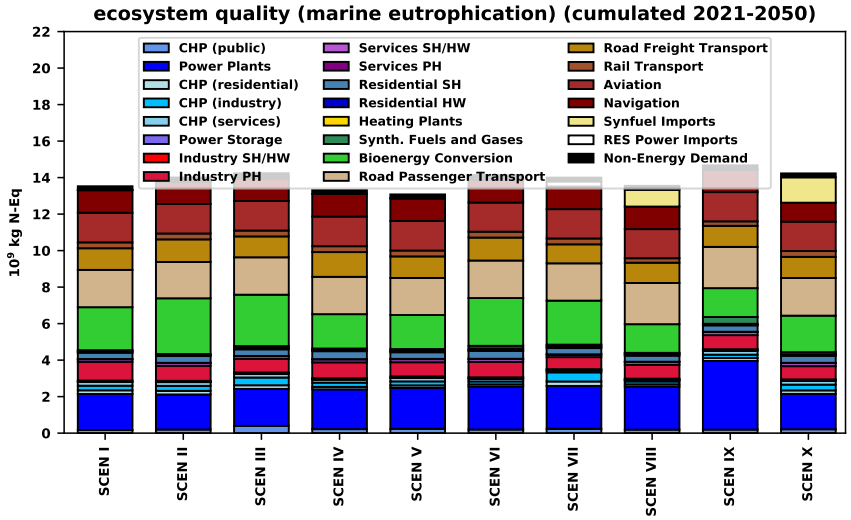

Figure 30: Ecosystem Quality (Marine Eutrophication): Cumulated Impacts (2020-2050) on sector level

2.6 Ecosystem Quality: Terrestrial Eutrophication

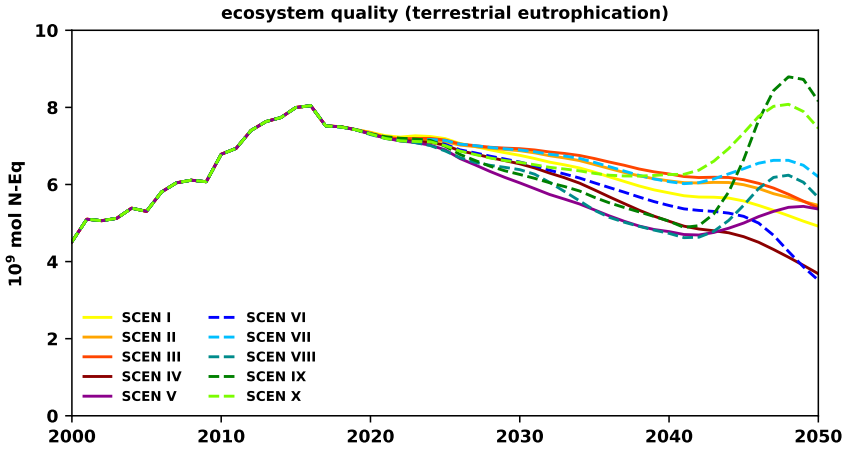

Figure 31: Ecosystem Quality (Terrestrial Eutrophication): Development until 2050 in all scenarios

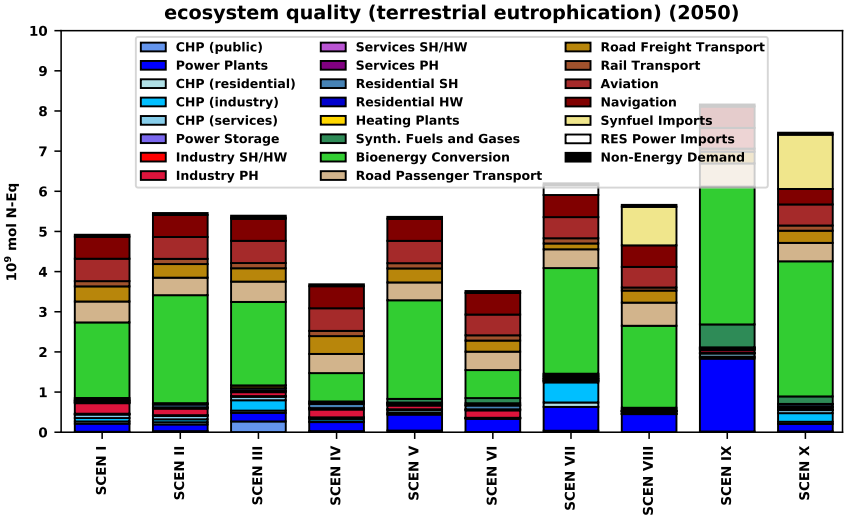

Figure 32: Ecosystem Quality (Terrestrial Eutrophication): Impacts 2050 on sector level

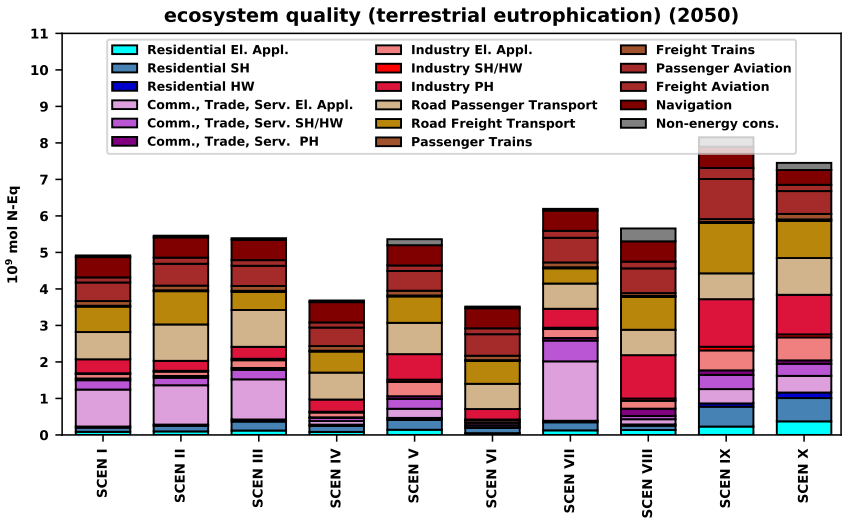

Figure 33: Ecosystem Quality (Terrestrial Eutrophication): Impacts 2050 on enduse level

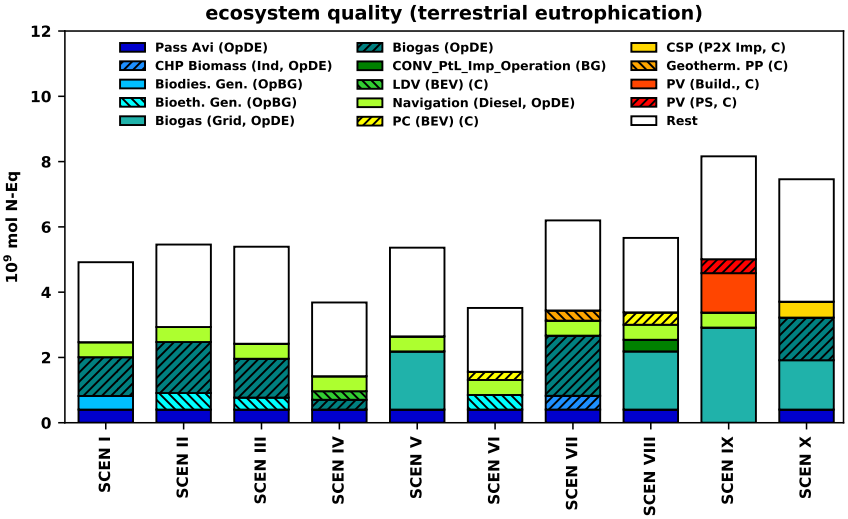

Figure 34: Ecosystem Quality (Terrestrial Eutrophication): Impacts 2050 on technology level

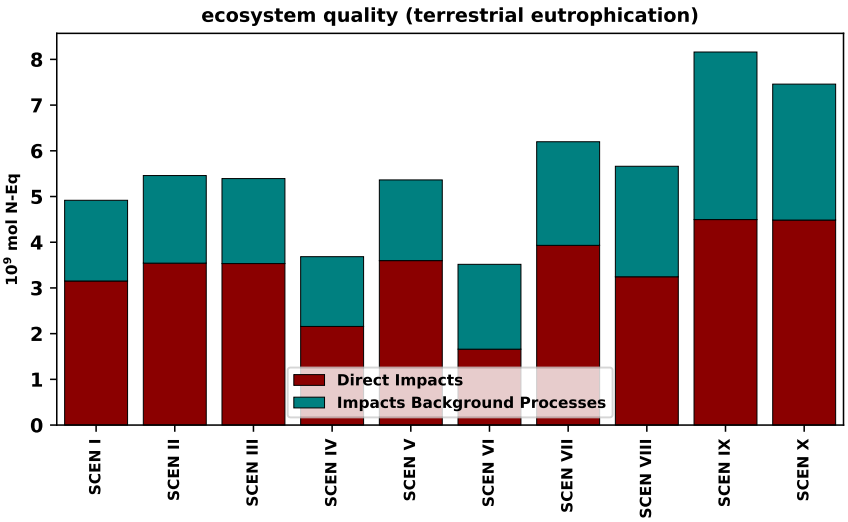

Figure 35: Ecosystem Quality (Terrestrial Eutrophication): Direct impacts and impacts from background processes (2050)

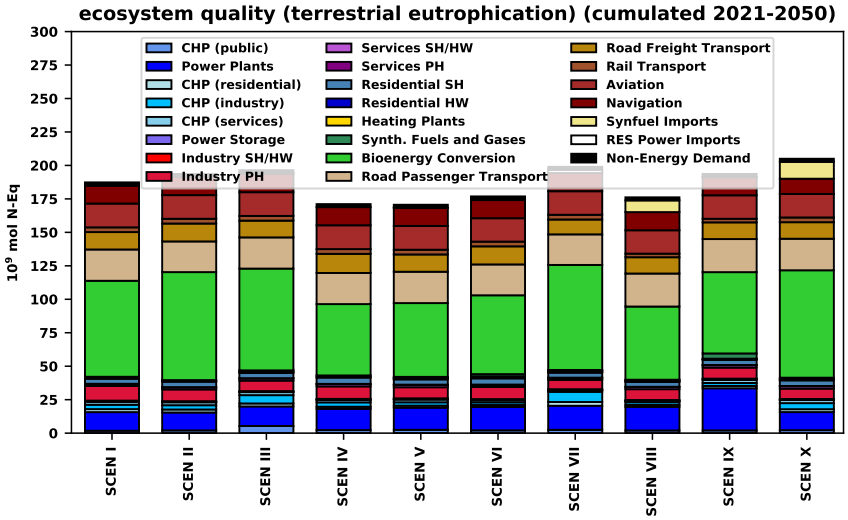

Figure 36: Ecosystem Quality (Terrestrial Eutrophication): Cumulated Impacts (2020-2050) on sector level

2.7 Human Health: Carcinogenic Effects

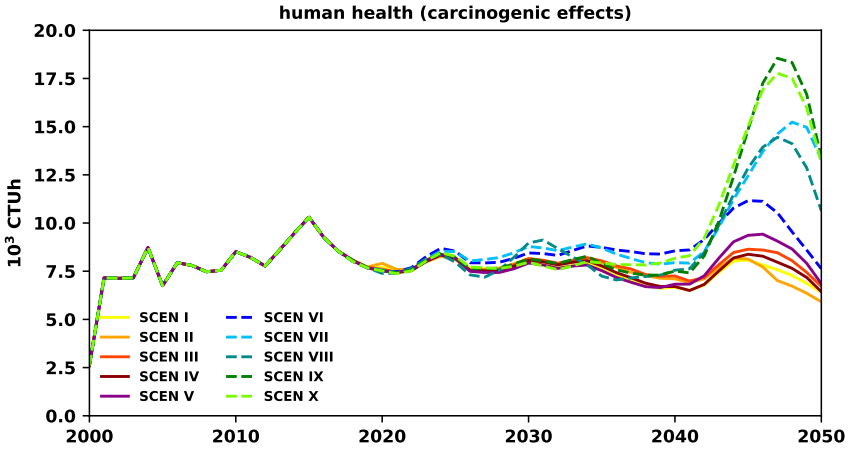

Figure 37: Human Health (carcinogenic effects): Development until 2050 in all scenarios

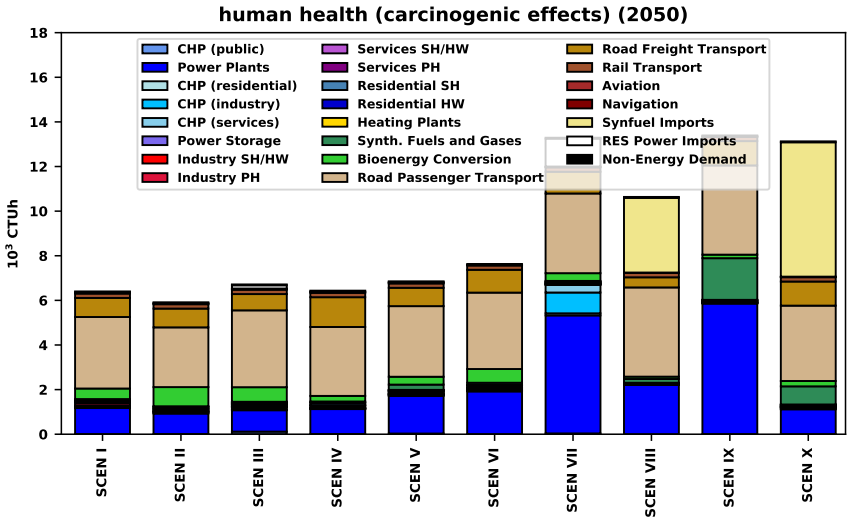

Figure 38: Human Health (carcinogenic effects): Impacts 2050 on sector level

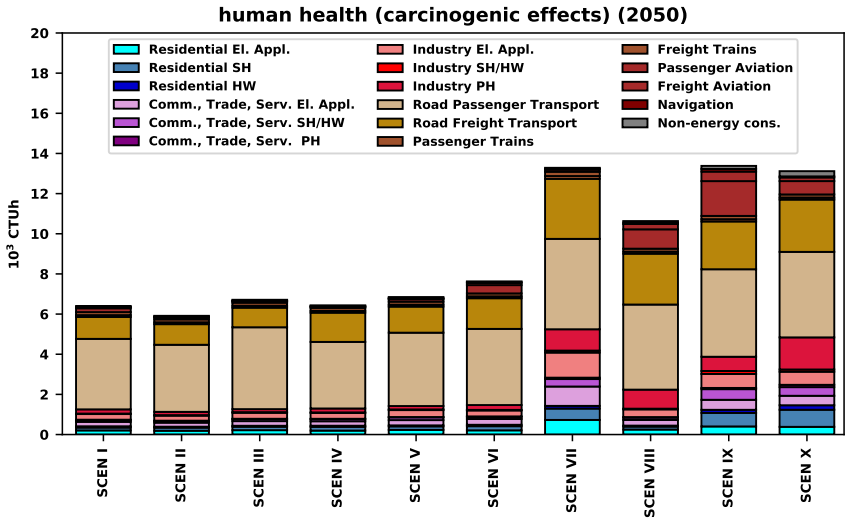

Figure 39: Human Health (carcinogenic effects): Impacts 2050 on enduse level

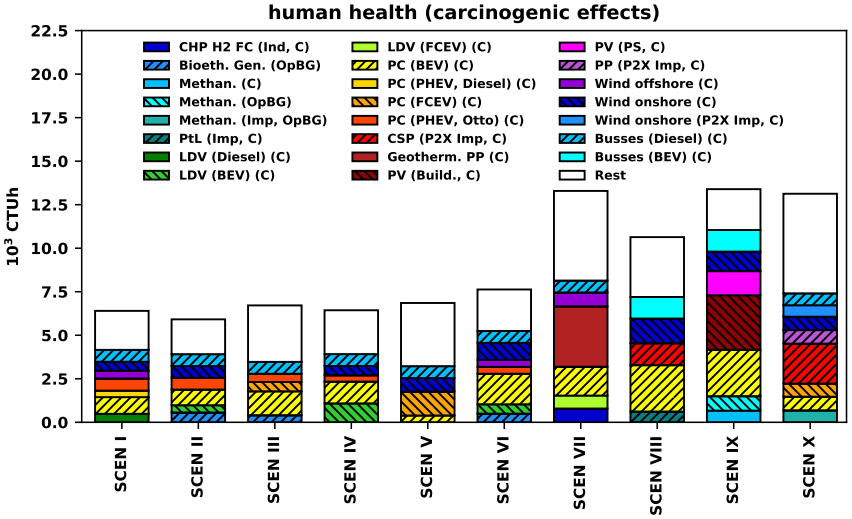

Figure 40: Human Health (carcinogenic effects): Impacts 2050 on technology level

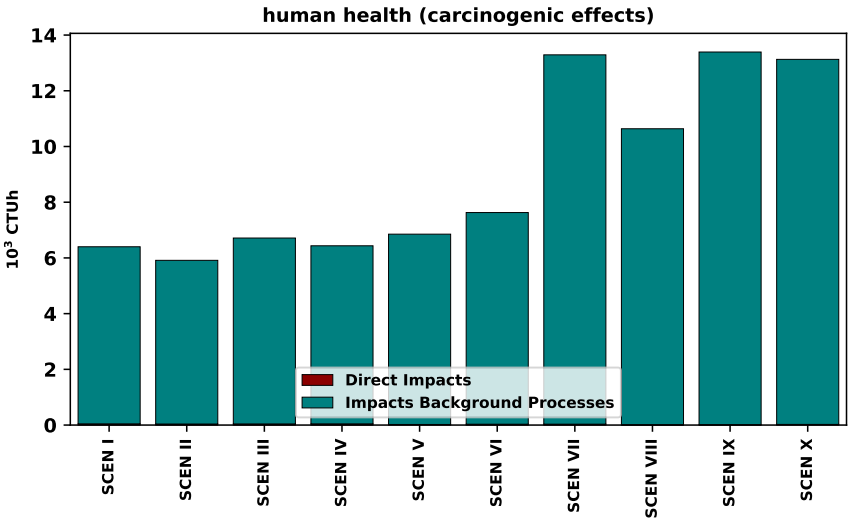

Figure 41: Human Health (Carcinogenic effects): Direct impacts and impacts from background processes (2050)

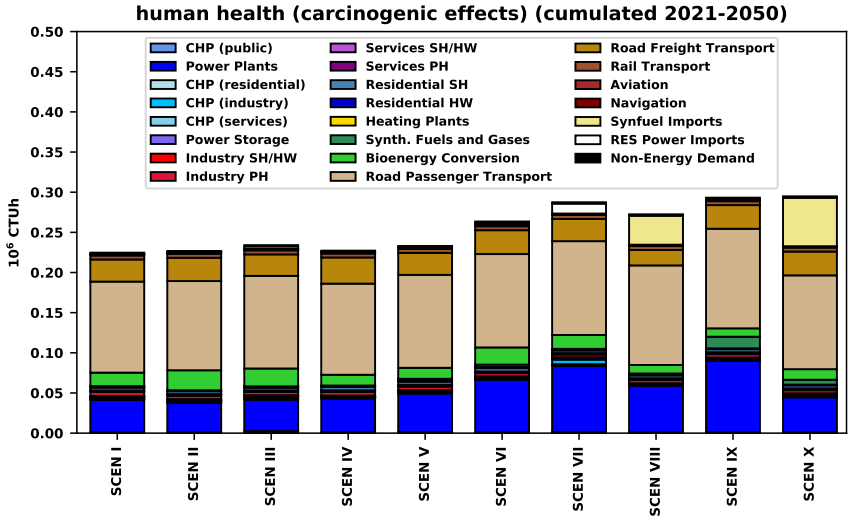

Figure 42: Human Health (Carcinogenic effects): Cumulated Impacts (2020-2050) on sector level

2.8 Human Health: Non-carcinogenic Effects

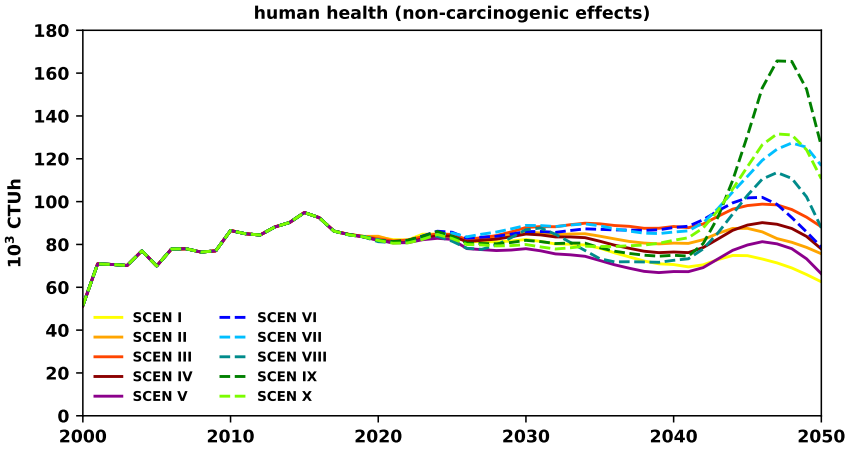

Figure 43: Human Health (non-carcinogenic effects): Development until 2050 in all scenarios

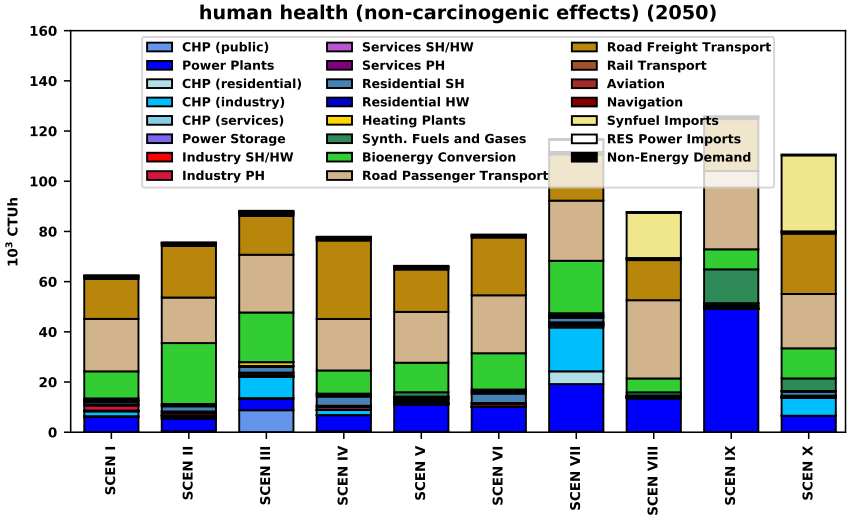

Figure 44: Human Health (non-carcinogenic effects): Impacts 2050 on sector level

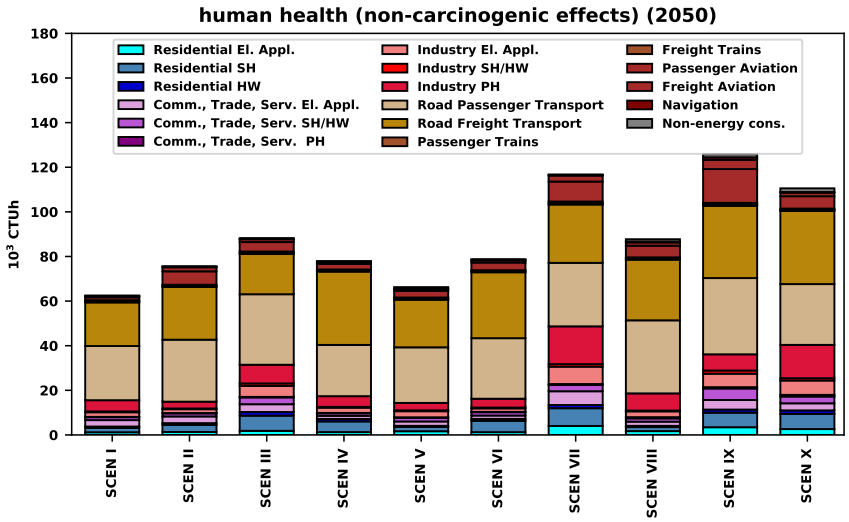

Figure 45: Human Health (non-carcinogenic effects): Impacts 2050 on enduse level

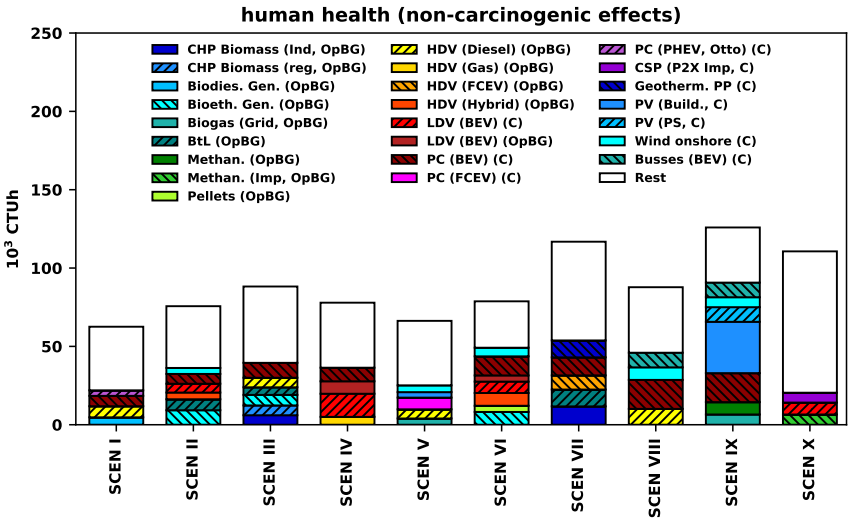

Figure 46: Human Health (non-carcinogenic effects): Impacts 2050 on technology level

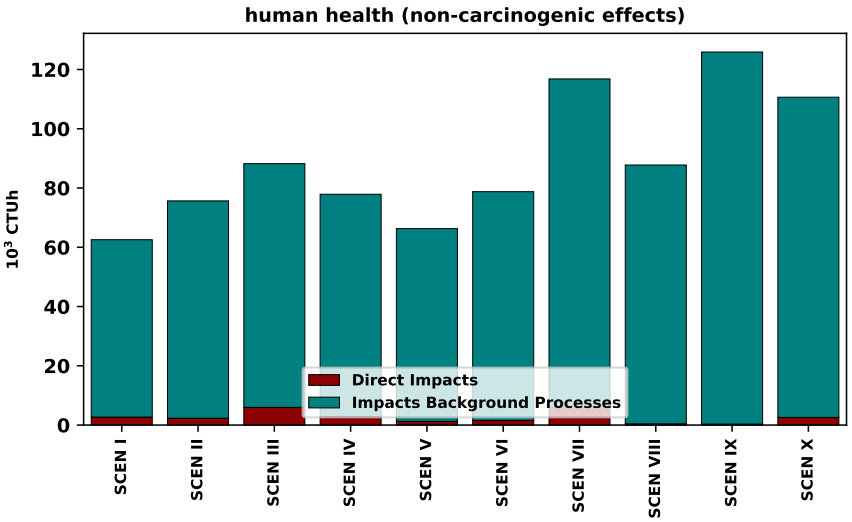

Figure 47: Human Health (non-carcinogenic effects): Direct impacts and impacts from background processes (2050)

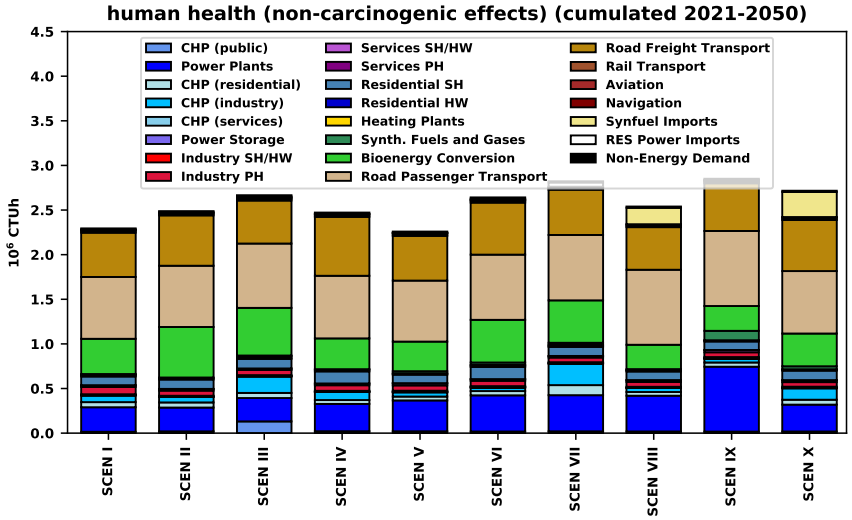

Figure 48: Human Health (non-carcinogenic effects): Cumulated Impacts (2020-2050) on sector level

2.9 Human Health: Ionizing Radiation

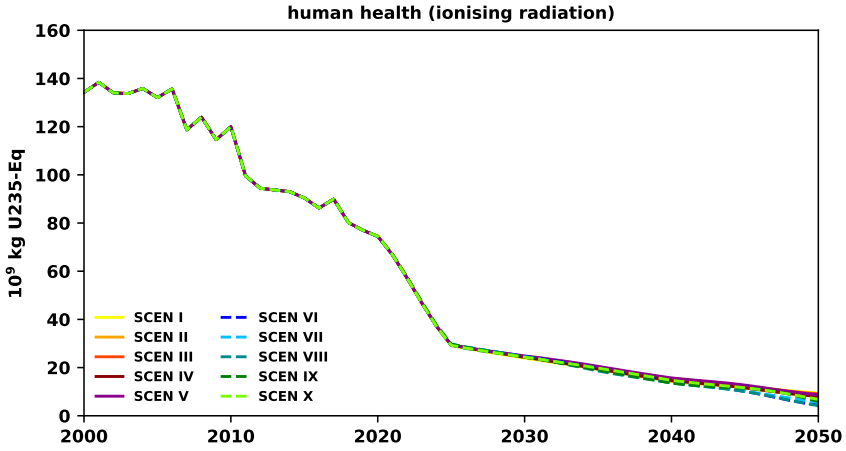

Figure 49: Human Health (ionizing radiation): Development until 2050 in all scenarios

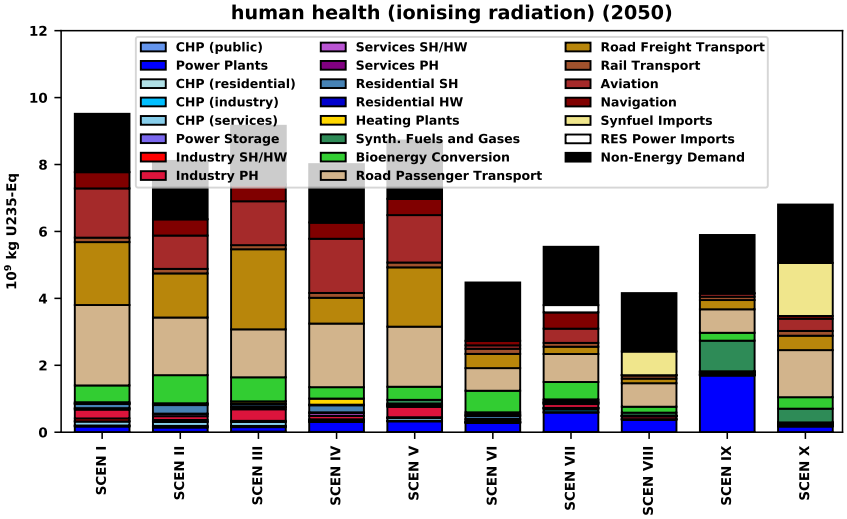

Figure 50: Human Health (ionizing radiation): Impacts 2050 on sector level

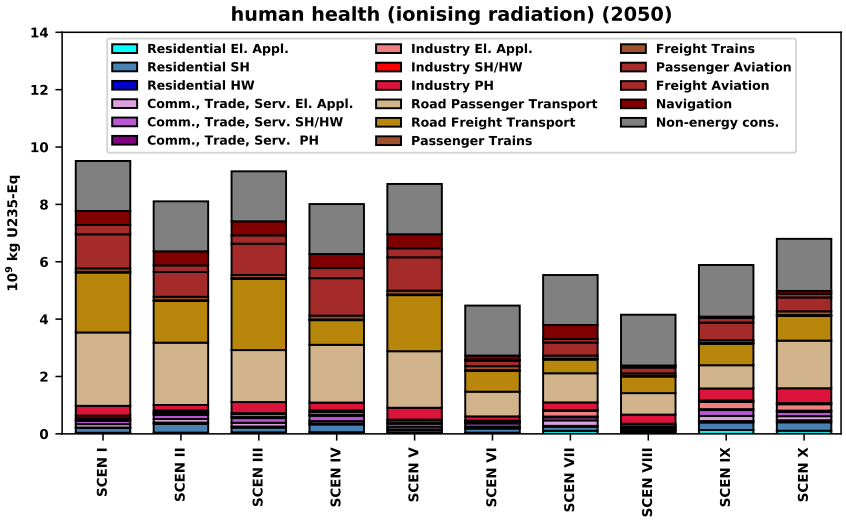

Figure 51: Human Health (ionizing radiation): Impacts 2050 on enduse level

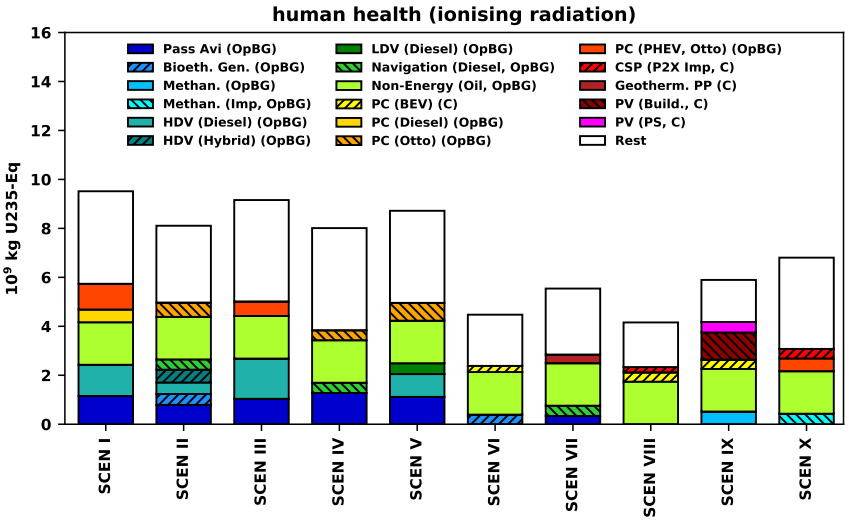

Figure 52: Human Health (ionizing radiation): Impacts 2050 on technology level

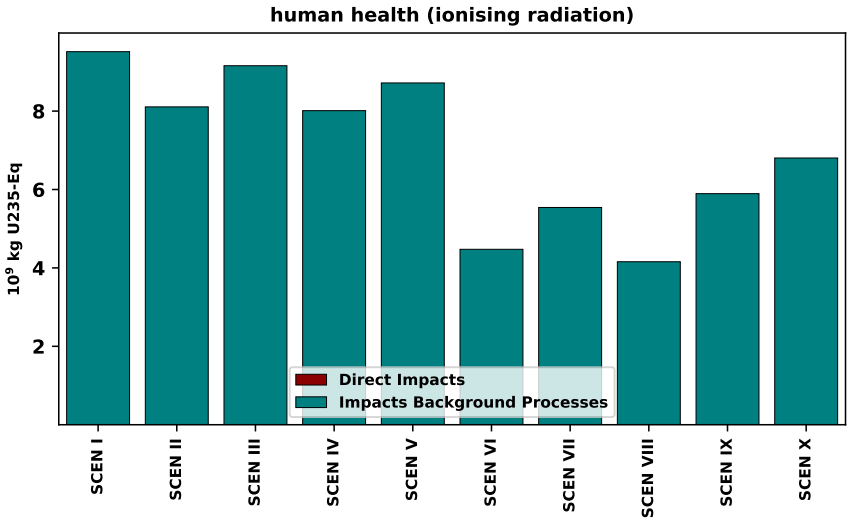

Figure 53: Human Health (ionizing radiation): Direct impacts and impacts from background processes (2050)

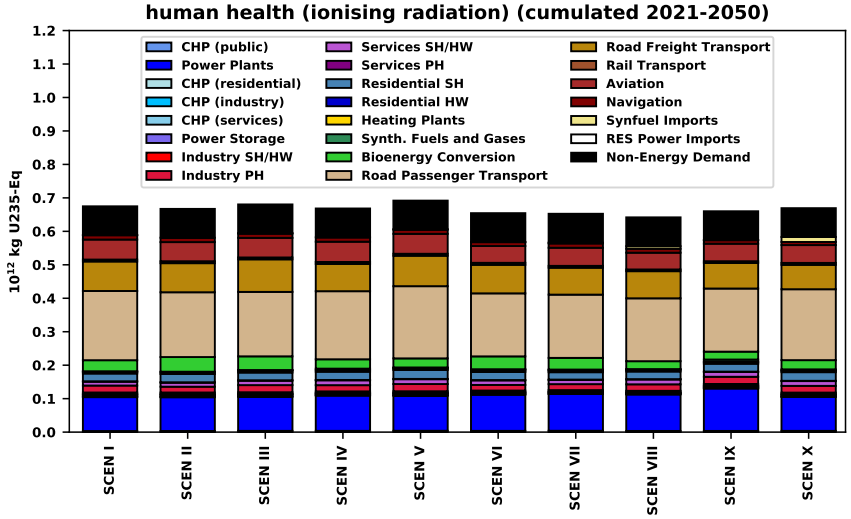

Figure 54: Human Health (ionizing radiation): Cumulated Impacts (2020-2050) on sector level

2.10 Human Health: Ozone Layer Depletion

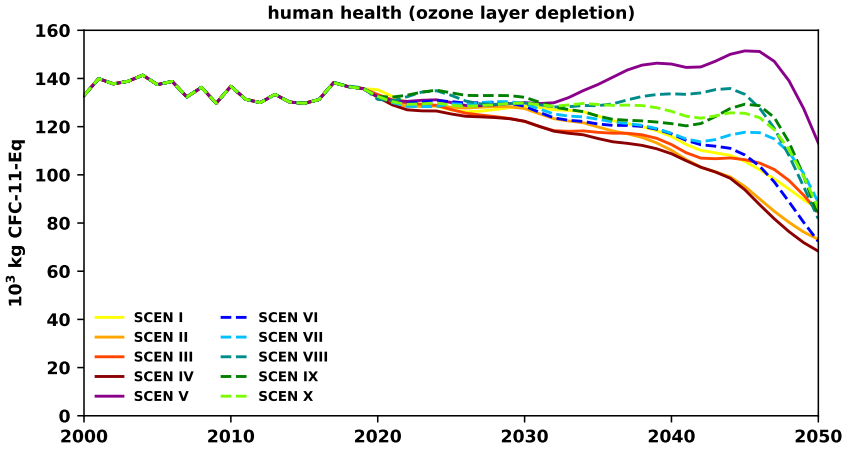

Figure 55: Human Health (Ozone layer depletion): Development until 2050 in all scenarios

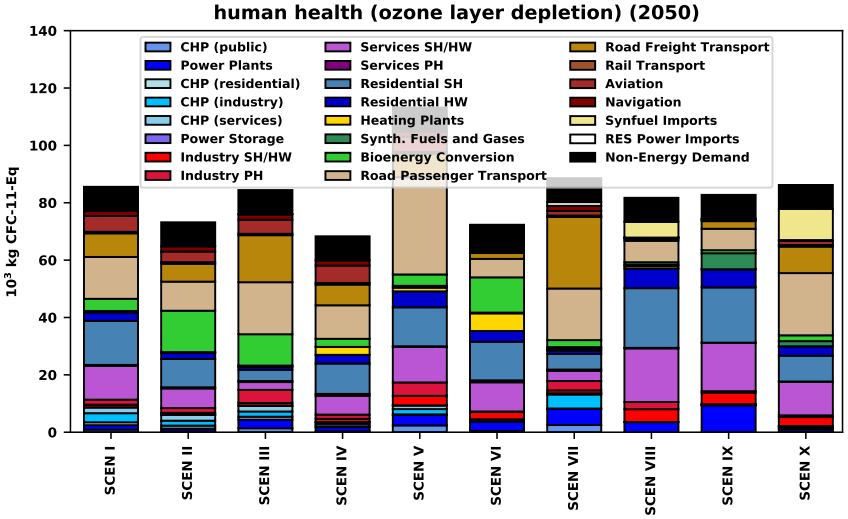

Figure 56: Human Health (Ozone layer depletion): Impacts 2050 on sector level

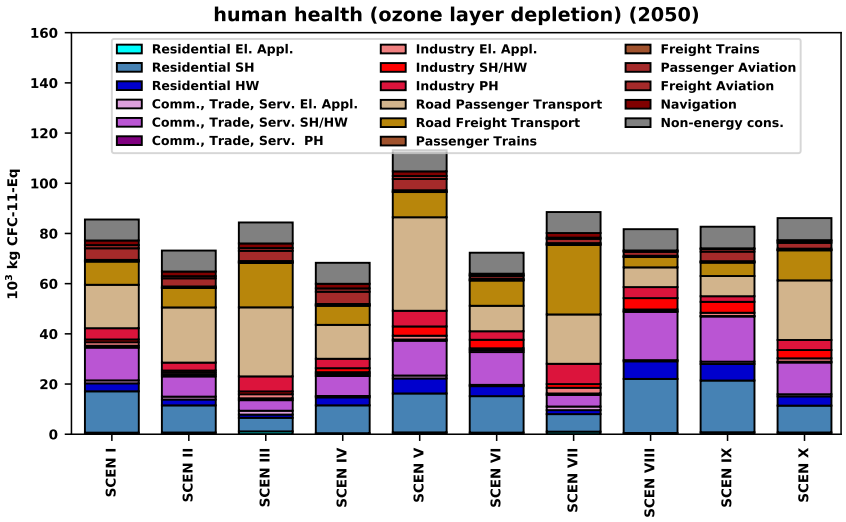

Figure 57: Human Health (Ozone layer depletion): Impacts 2050 on enduse level

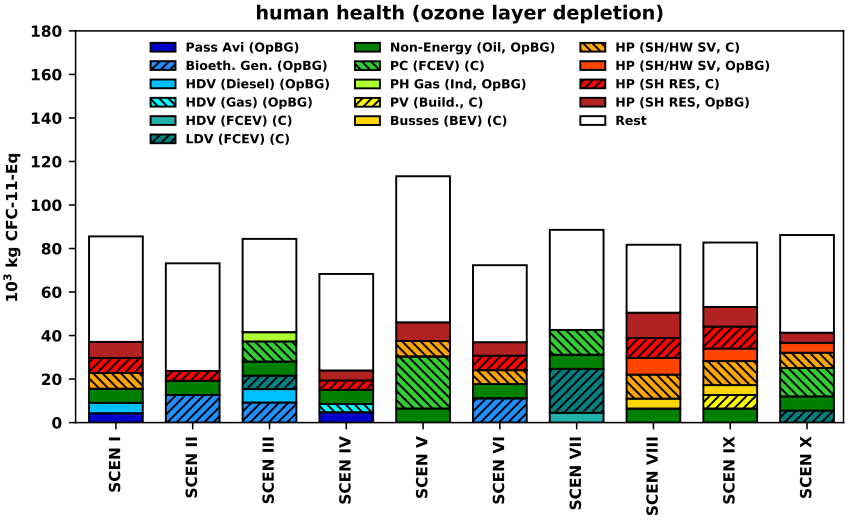

Figure 58: Human Health (Ozone layer depletion): Impacts 2050 on technology level

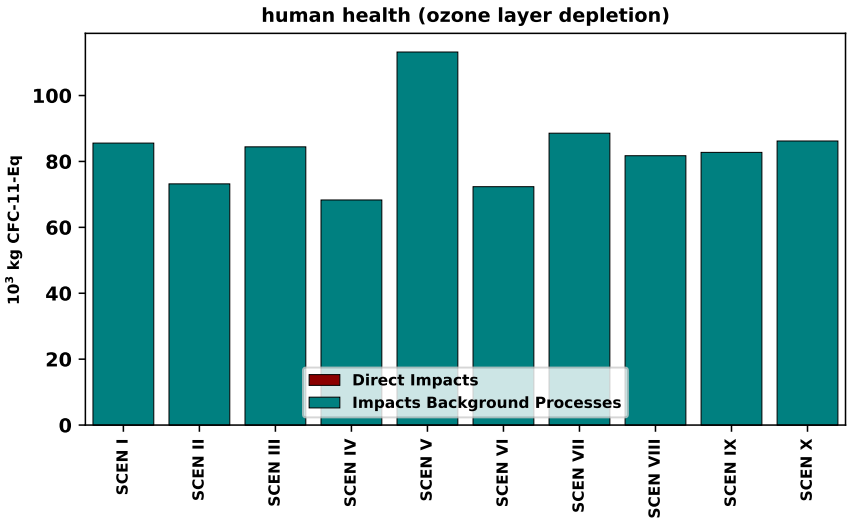

Figure 59: Human Health (Ozone layer depletion): Direct impacts and impacts from background processes (2050)

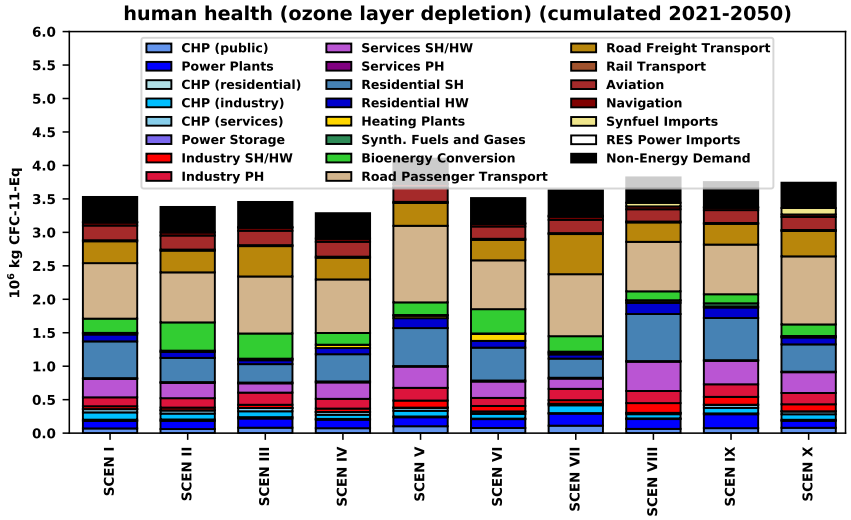

Figure 60: Human Health (Ozone layer depletion): Cumulated Impacts (2020-2050) on sector level

2.11 Human Health: Photochemical Ozone Creation

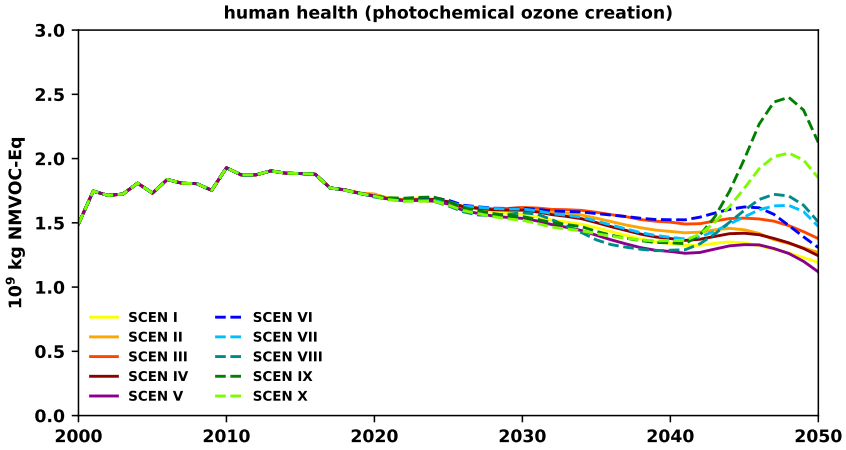

Figure 61: Human Health (photochemical Ozone creation): Development until 2050 in all scenarios

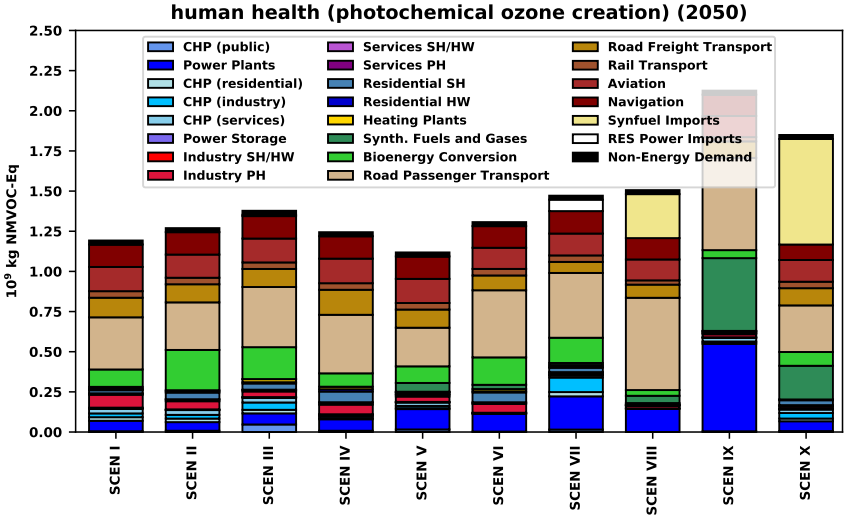

Figure 62: Human Health (photochemical Ozone creation): Impacts 2050 on sector level

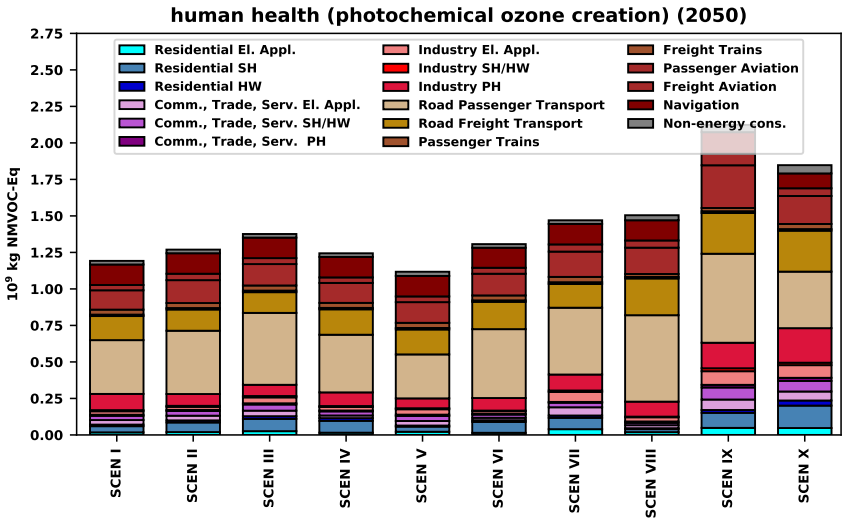

Figure 63: Human Health (photochemical Ozone creation): Impacts 2050 on enduse level

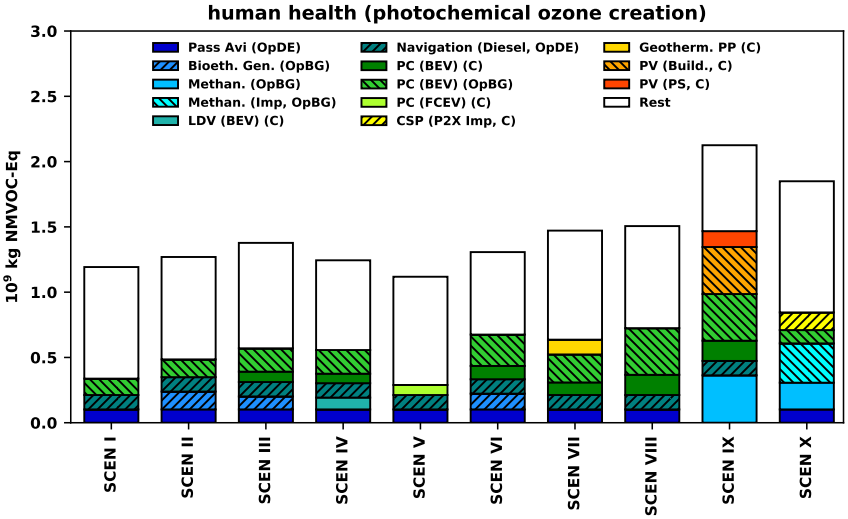

Figure 64: Human Health (photochemical Ozone creation): Impacts 2050 on technology level

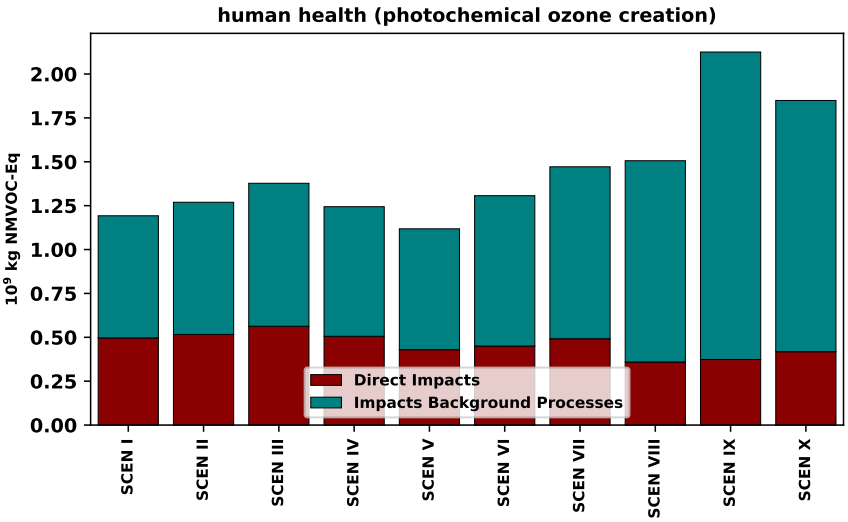

Figure 65: Human Health (photochemical Ozone creation): Direct impacts and impacts from background processes (2050)

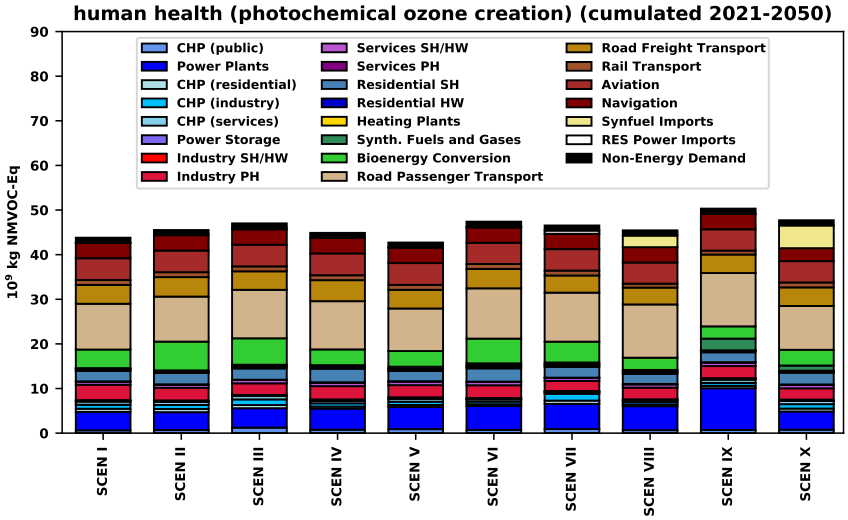

Figure 66: Human Health (photochemical Ozone creation): Cumulated Impacts (2020-2050) on sector level

2.12 Human Health: Respiratory Effects, inorganics

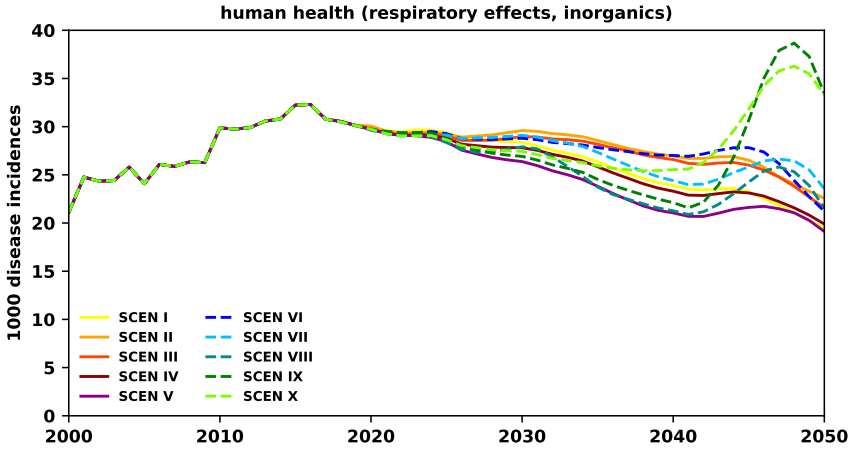

Figure 67: Human Health (respiratory effects, inorganics): Development until 2050 in all scenarios

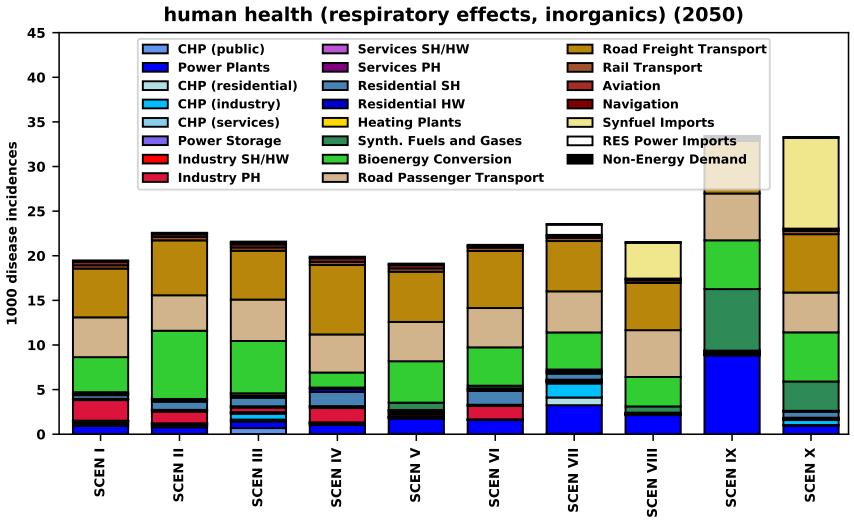

Figure 68: Human Health (respiratory effects, inorganics): Impacts 2050 on sector level

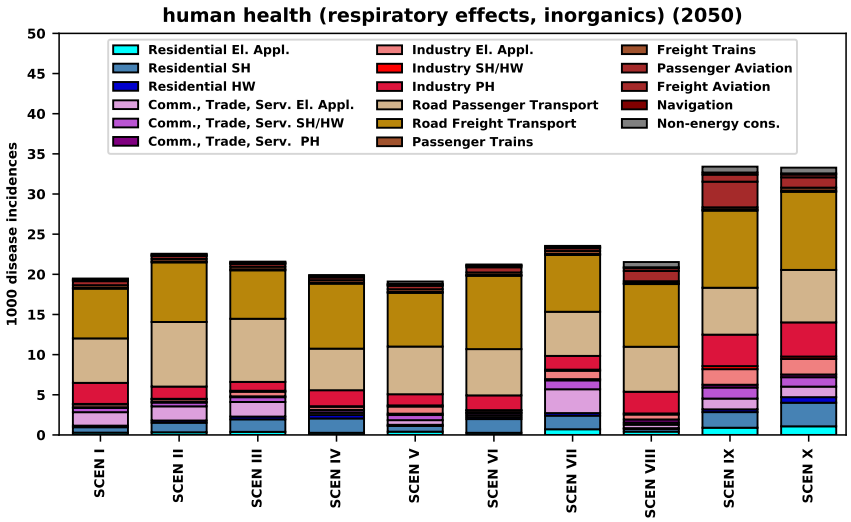

Figure 69: Human Health (respiratory effects, inorganics): Impacts 2050 on enduse level

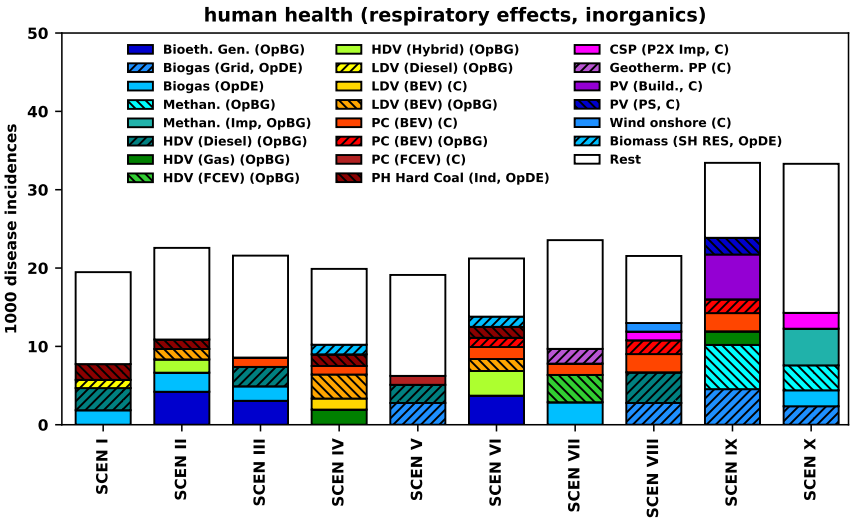

Figure 70: Human Health (respiratory effects, inorganics): Impacts 2050 on technology level

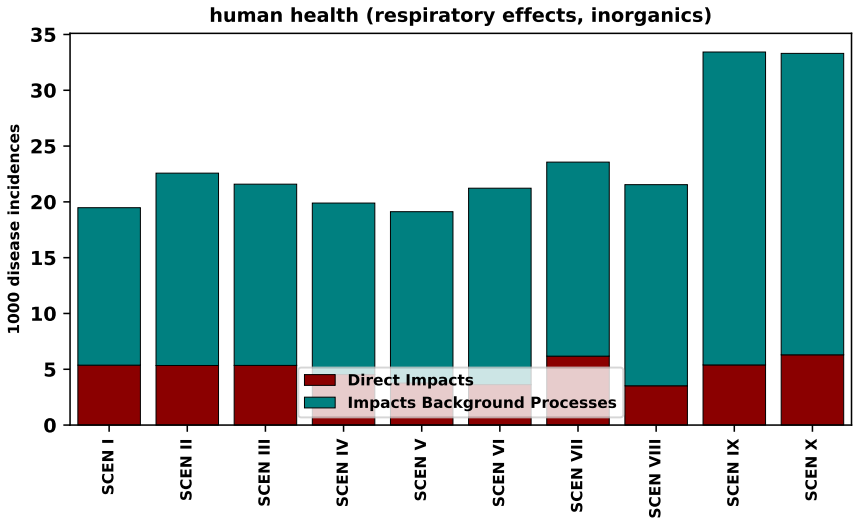

Figure 71: Human Health (respiratory effects, inorganics): Direct impacts and impacts from background processes (2050)

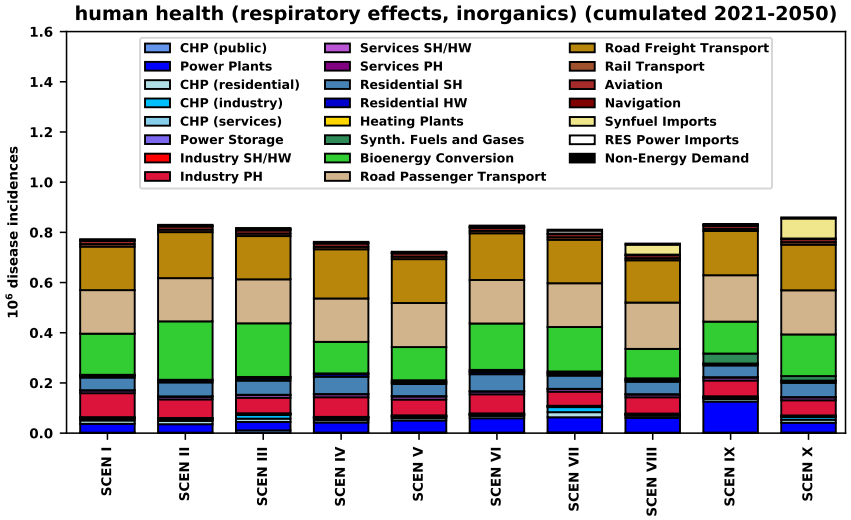

Figure 72: Human Health (respiratory effects, inorganics): Cumulated Impacts (2020-2050) on sector level

2.13 Resources: Fossils

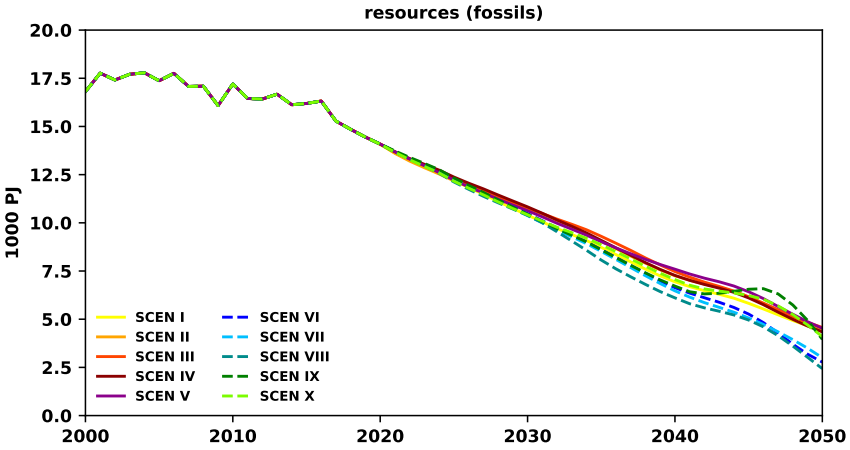

Figure 73: Resources (fossils): Development until 2050 in all scenarios

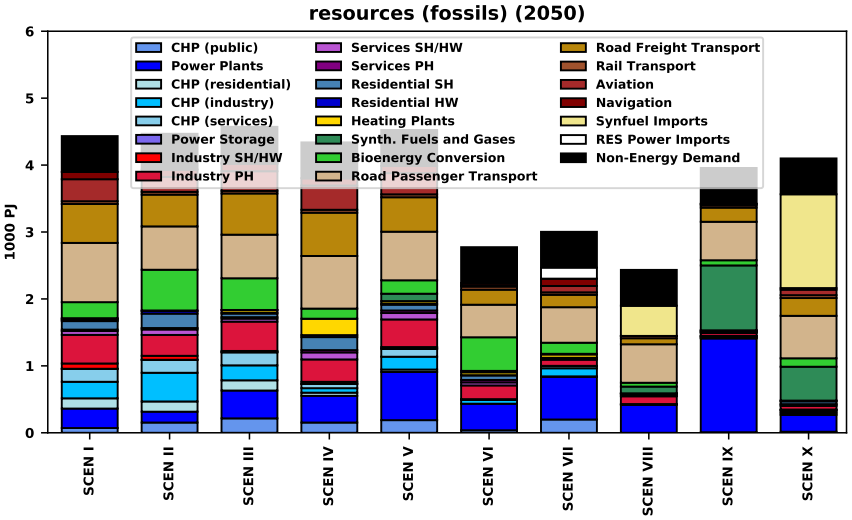

Figure 74: Resources (fossils): Impacts 2050 on sector level

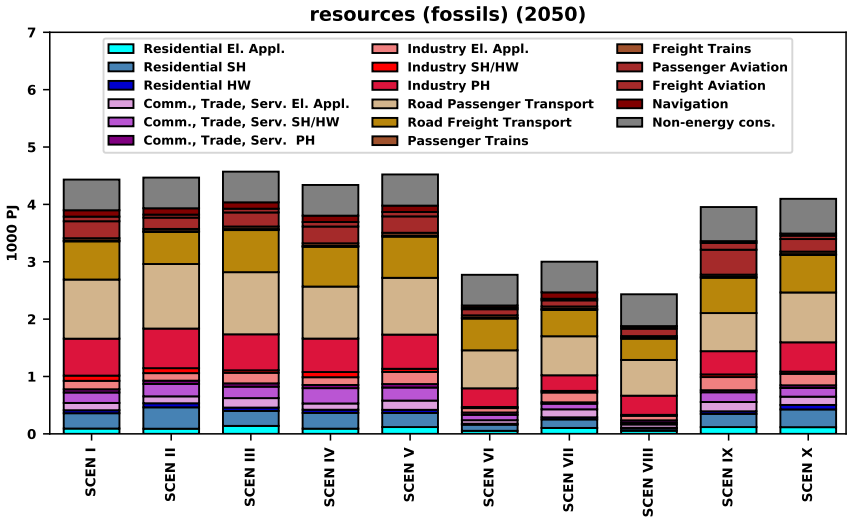

Figure 75: Resources (fossils): Impacts 2050 on enduse level

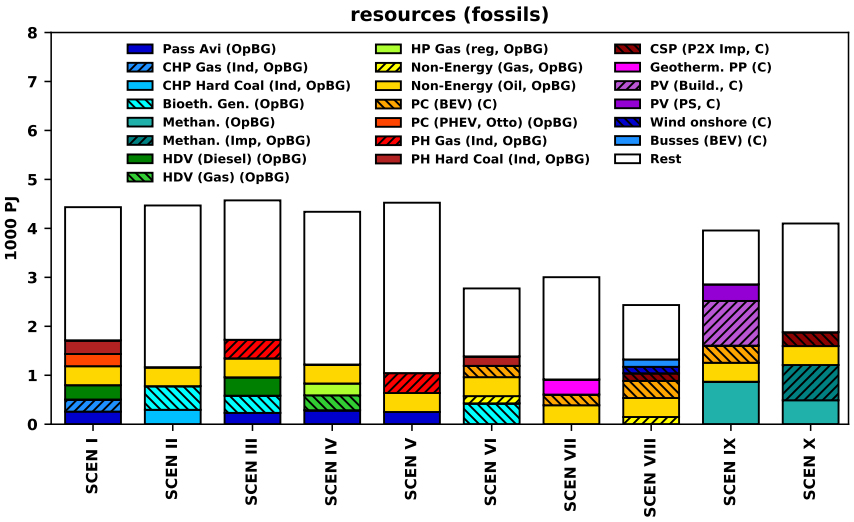

Figure 76: Resources (fossils): Impacts 2050 on technology level

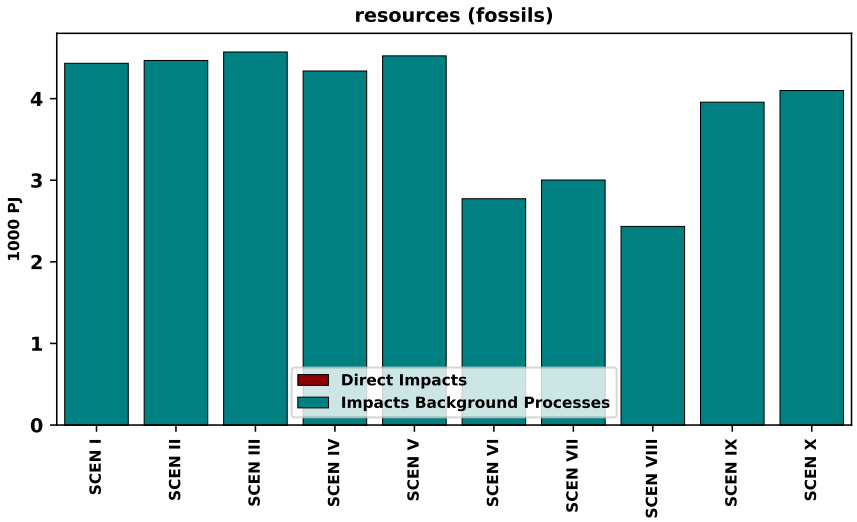

Figure 77: Resources (fossils): Direct impacts and impacts from background processes (2050)

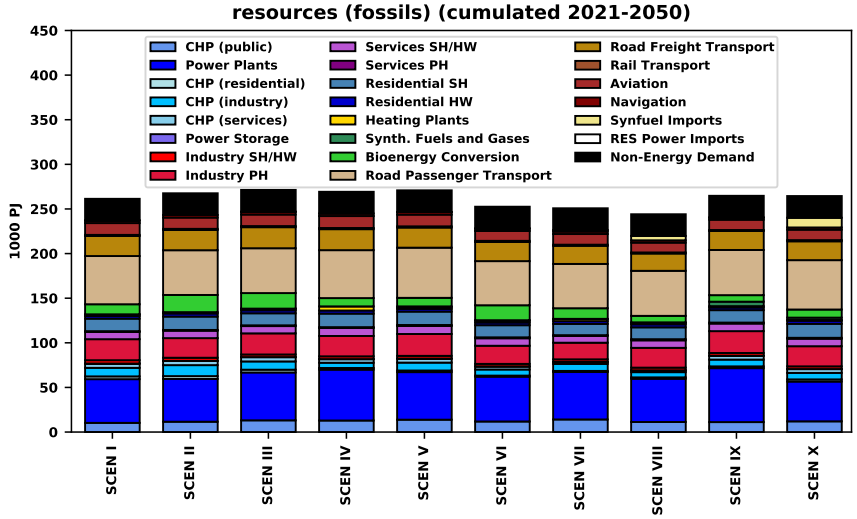

Figure 78: Resources (fossils): Cumulated Impacts (2020-2050) on sector level

2.14 Resources: Minerals and Metals

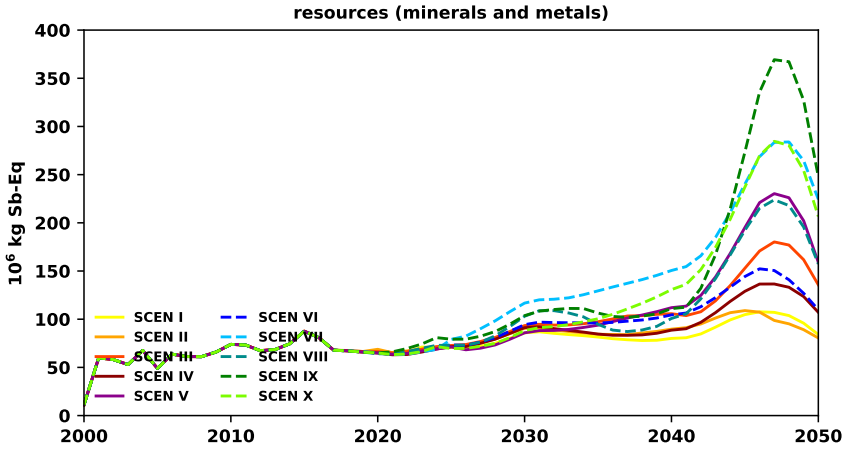

Figure 79: Resources (minerals and metals): Development until 2050 in all scenarios

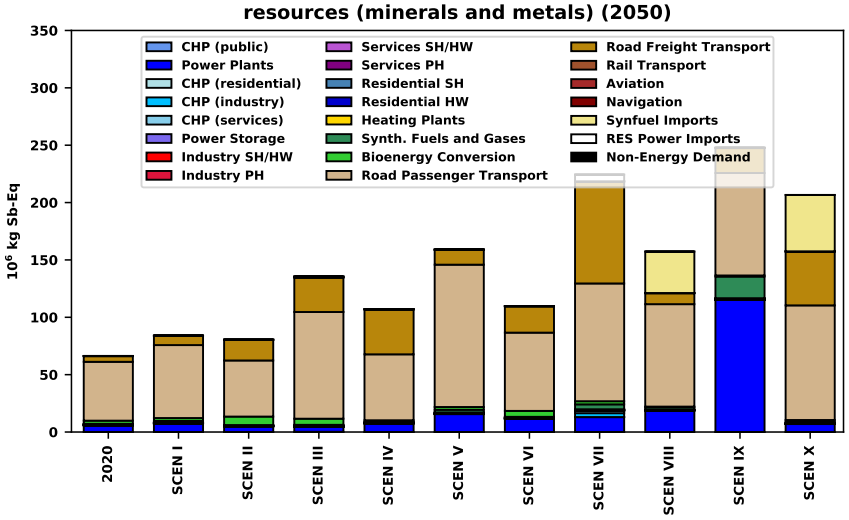

Figure 80: Resources (minerals and metals): Impacts 2050 on sector level

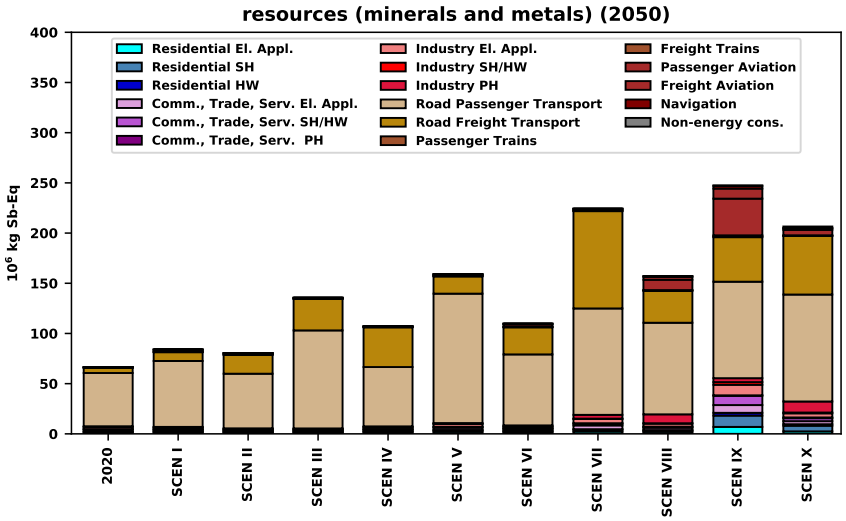

Figure 81: Resources (minerals and metals): Impacts 2050 on enduse level

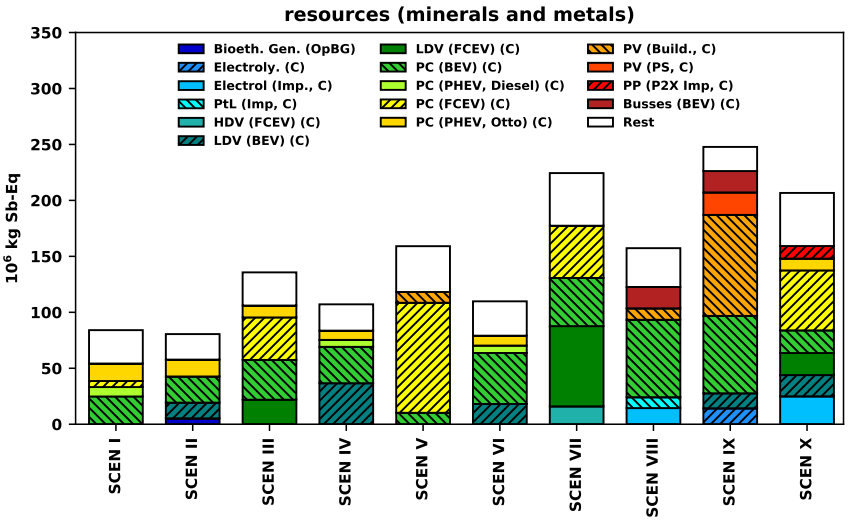

Figure 82: Resources (minerals and metals): Impacts 2050 on technology level

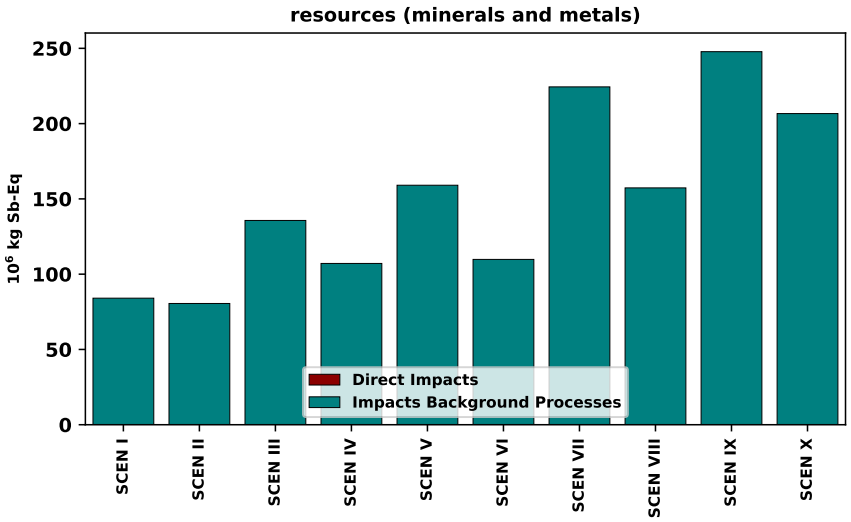

Figure 83: Resources (minerals and metals): Direct impacts and impacts from background processes (2050)

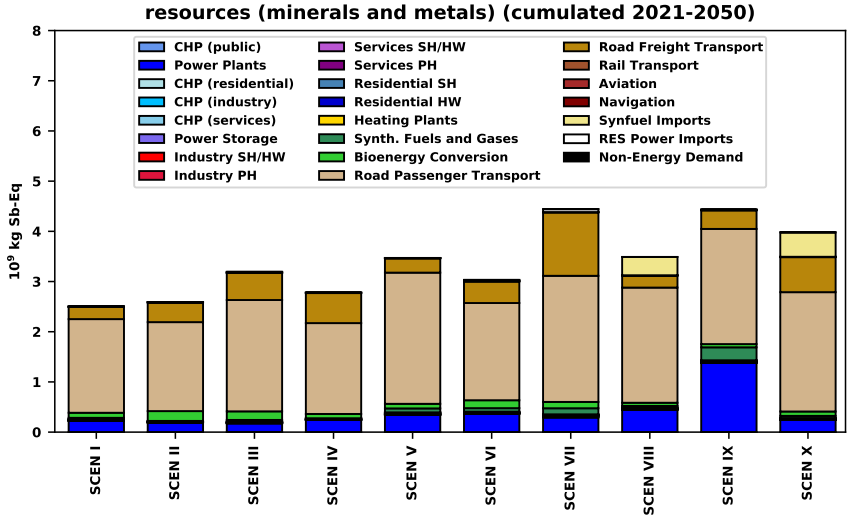

Figure 84: Resources (minerals and metals): Cumulated Impacts (2020-2050) on sector level

2.15 Resources: Land Use

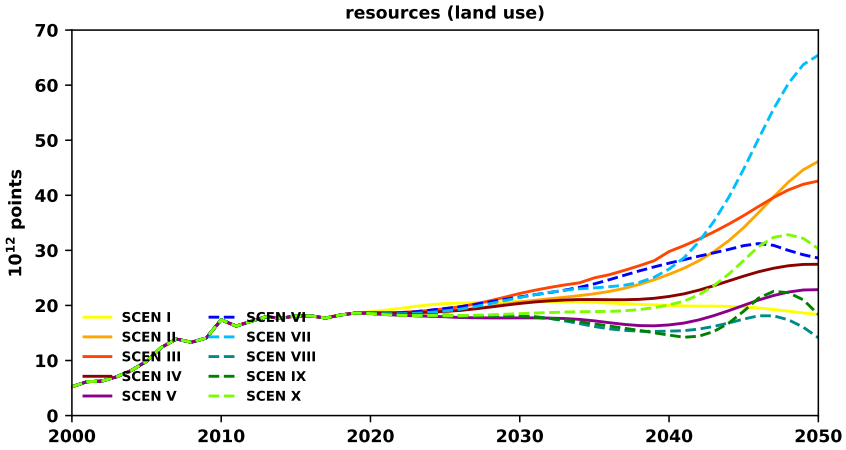

Figure 85: Resources (land use): Development until 2050 in all scenarios

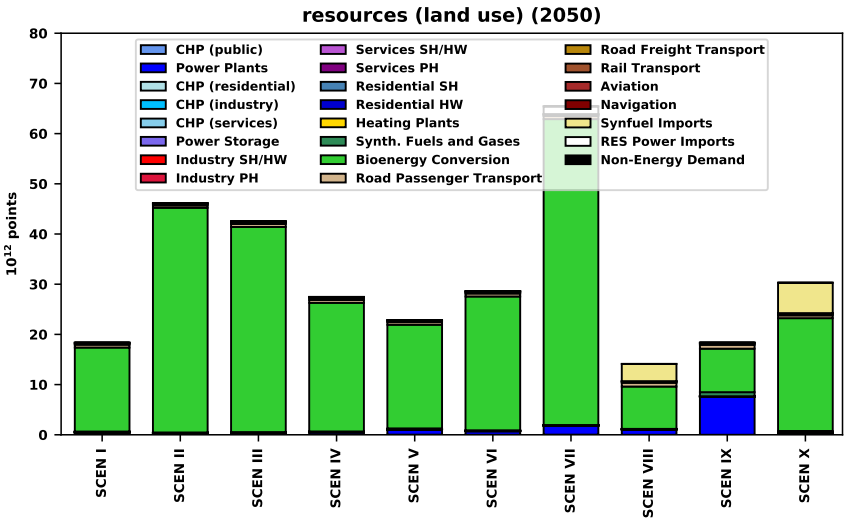

Figure 86: Resources (land use): Impacts 2050 on sector level

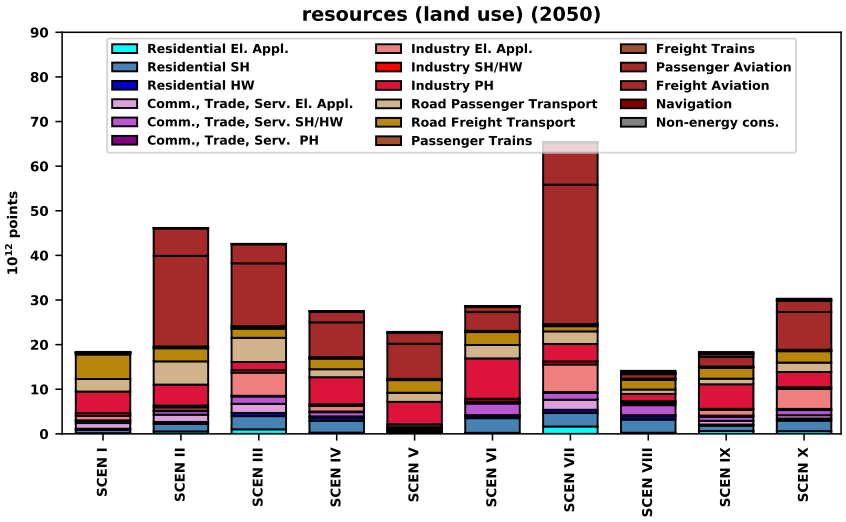

Figure 87: Resources (land use): Impacts 2050 on enduse level

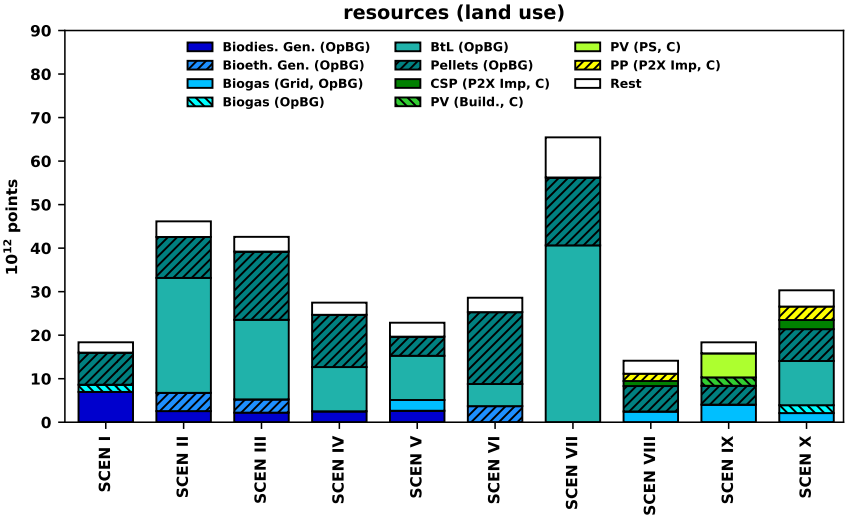

Figure 88: Resources (land use): Impacts 2050 on technology level

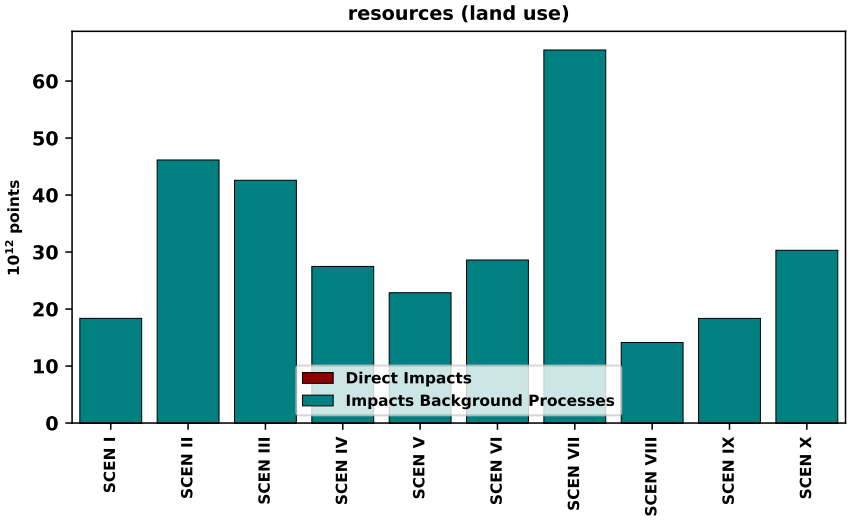

Figure 89: Resources (land use): Direct impacts and impacts from background processes (2050)

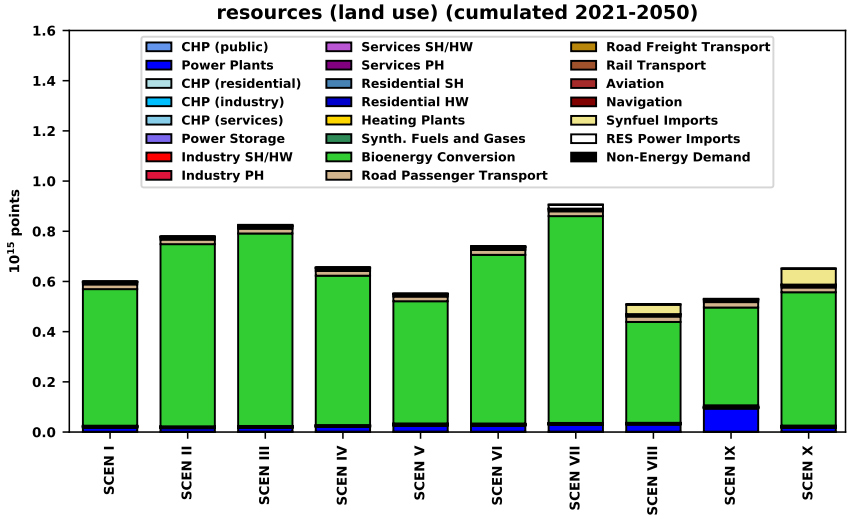

Figure 90: Resources (land use): Cumulated Impacts (2020-2050) on sector level

2.16 Resources: Dissipated Water

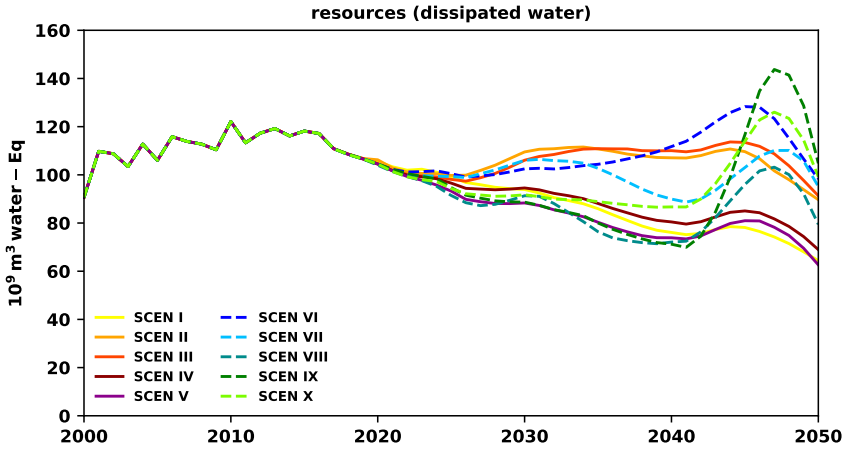

Figure 91: Resources (dissipated water): Development until 2050 in all scenarios

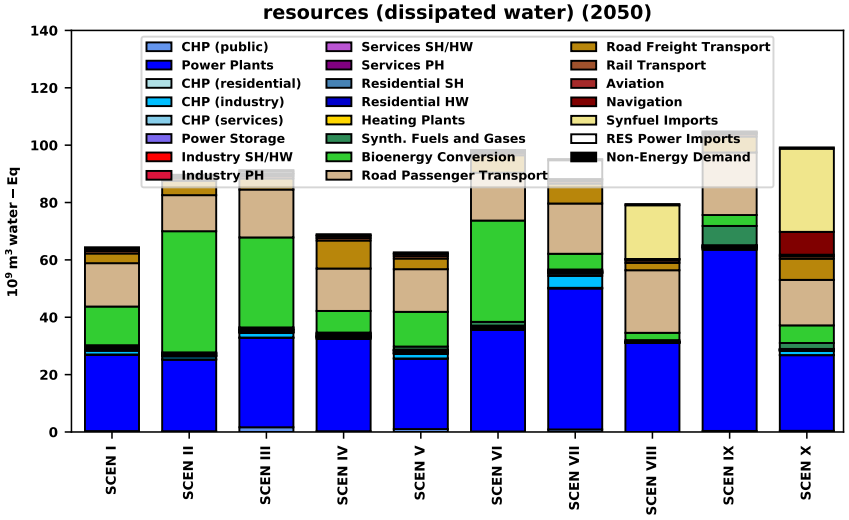

Figure 92: Resources (dissipated water): Impacts 2050 on sector level

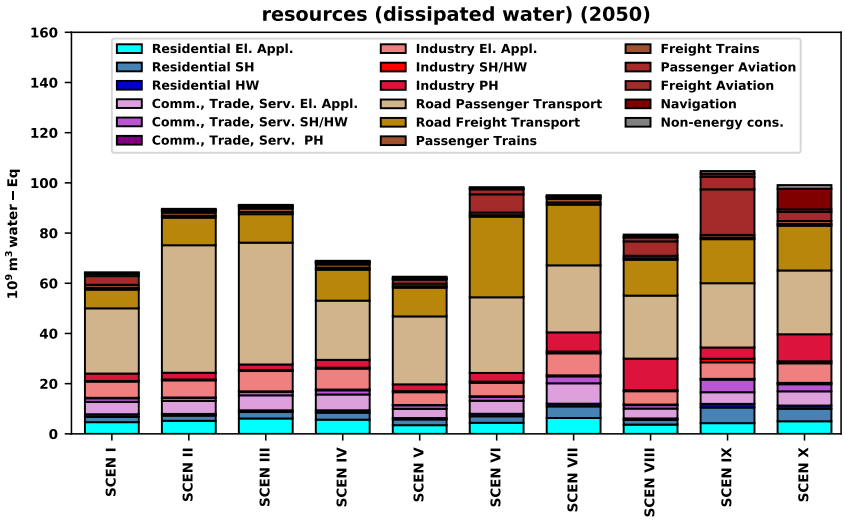

Figure 93: Resources (dissipated water): Impacts 2050 on enduse level

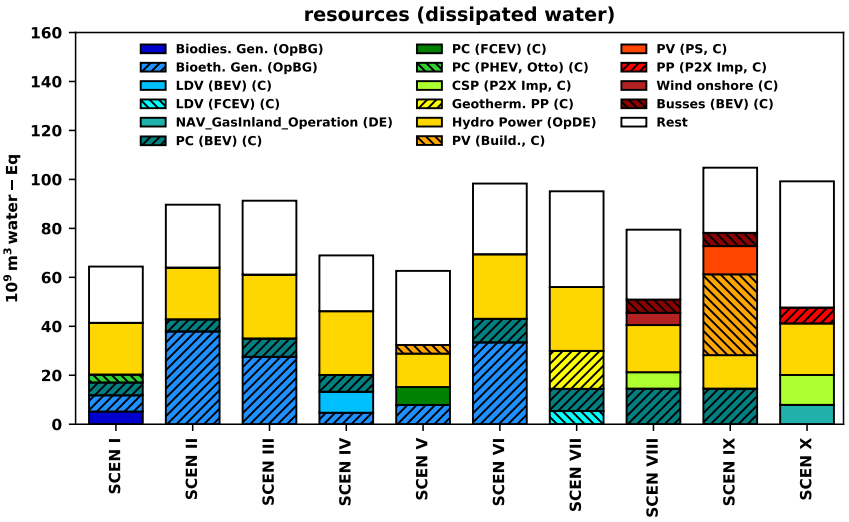

Figure 94: Resources (dissipated water): Impacts 2050 on technology level

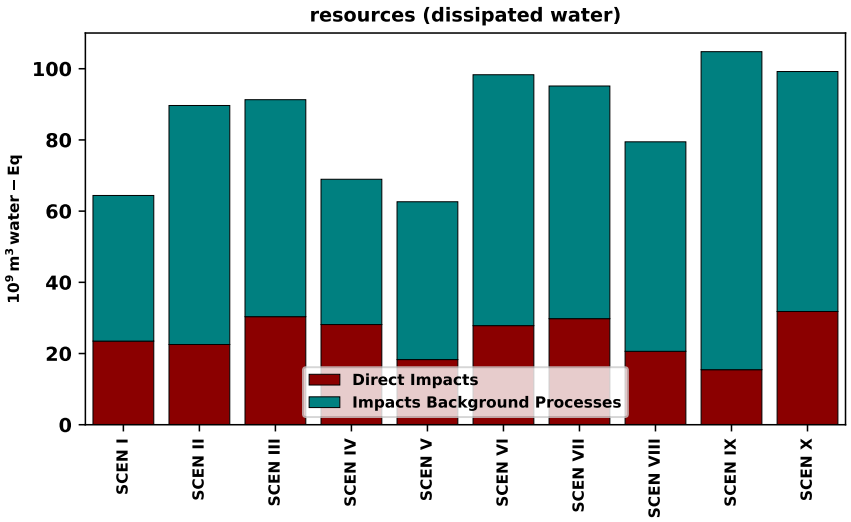

Figure 95: Resources (dissipated water): Direct impacts and impacts from background processes (2050)

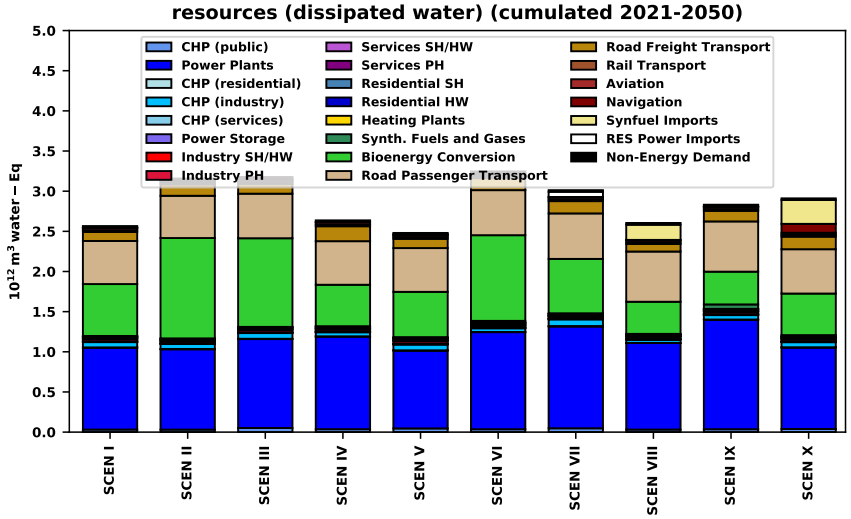

Figure 96: Resources (dissipated water): Cumulated Impacts (2020-2050) on sector level

2.17 EU Environmental Footprint

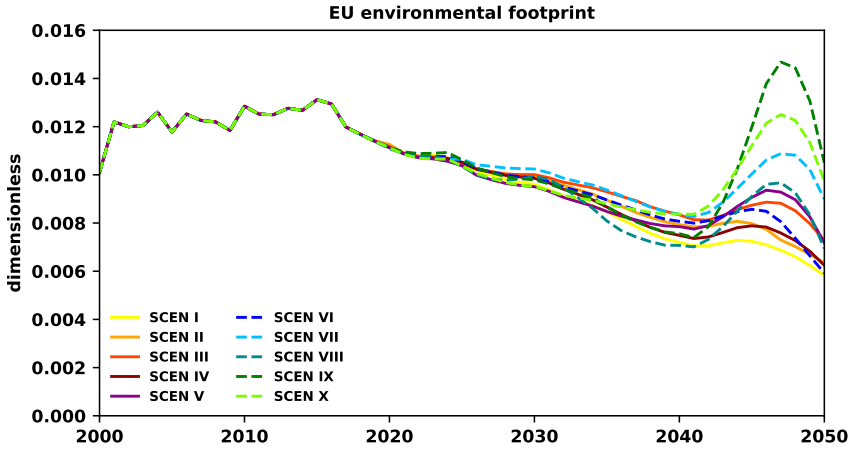

Figure 97: EU Environmental Footprint: Development until 2050 in all scenarios

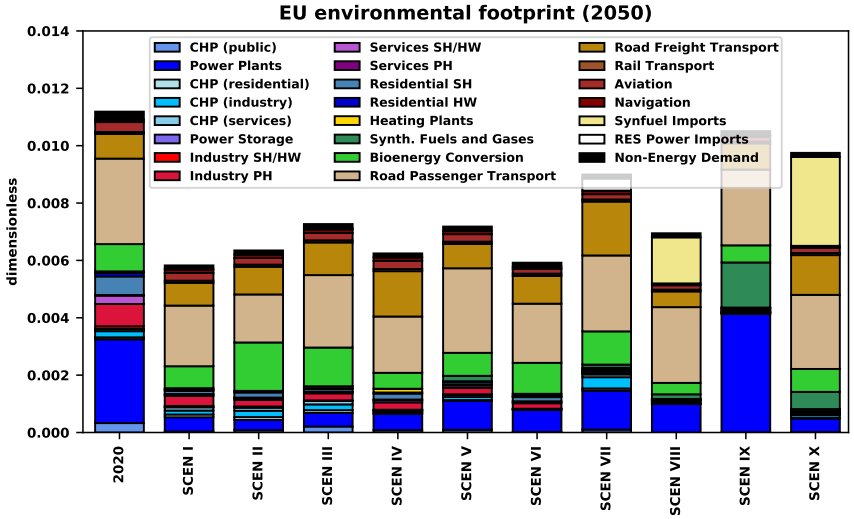

Figure 98: EU Environmental Footprint: Impacts 2050 on sector level

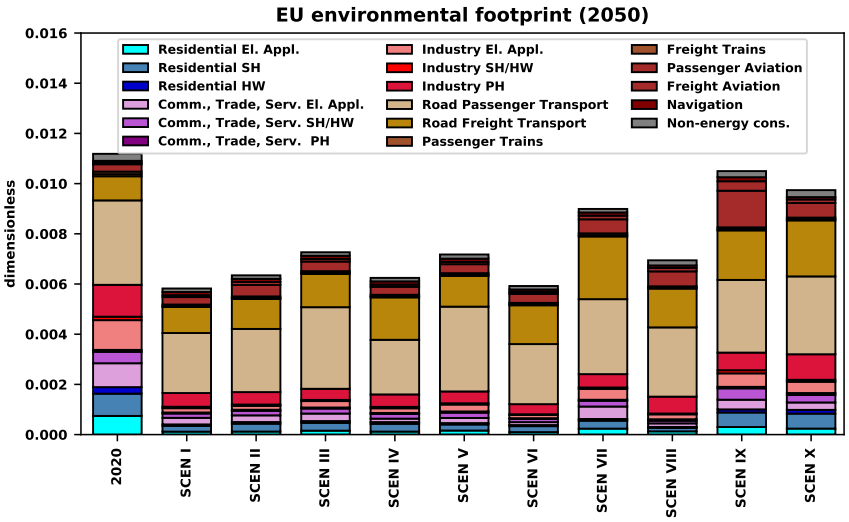

Figure 99: EU Environmental Footprint: Impacts 2050 on enduse level

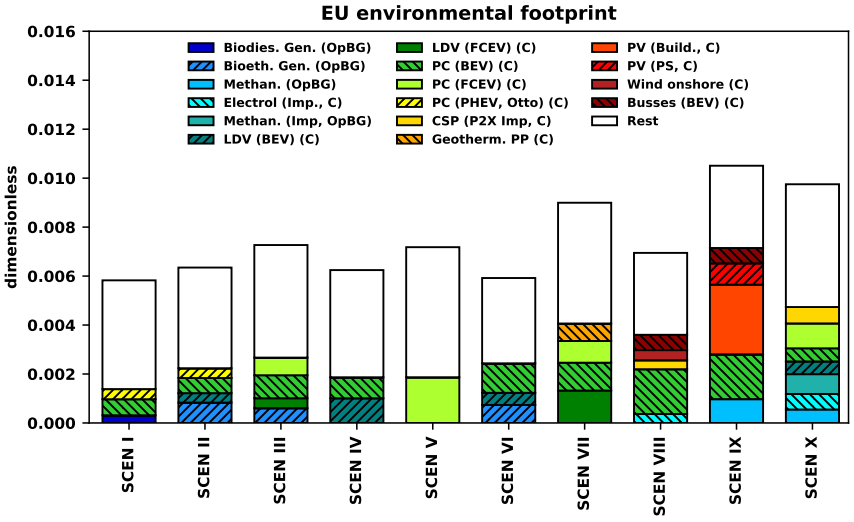

Figure 100: EU Environmental Footprint: Impacts 2050 on technology level

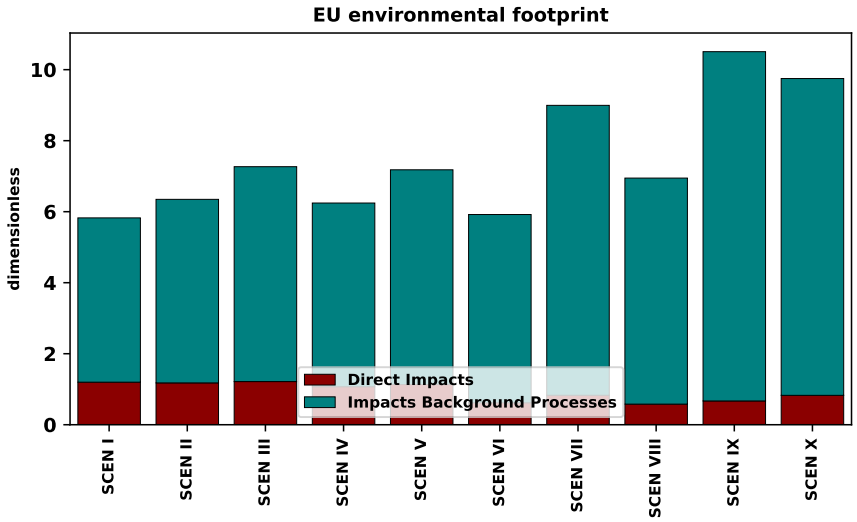

Figure 101: EU Environmental Footprint: Direct impacts and impacts from background processes (2050)

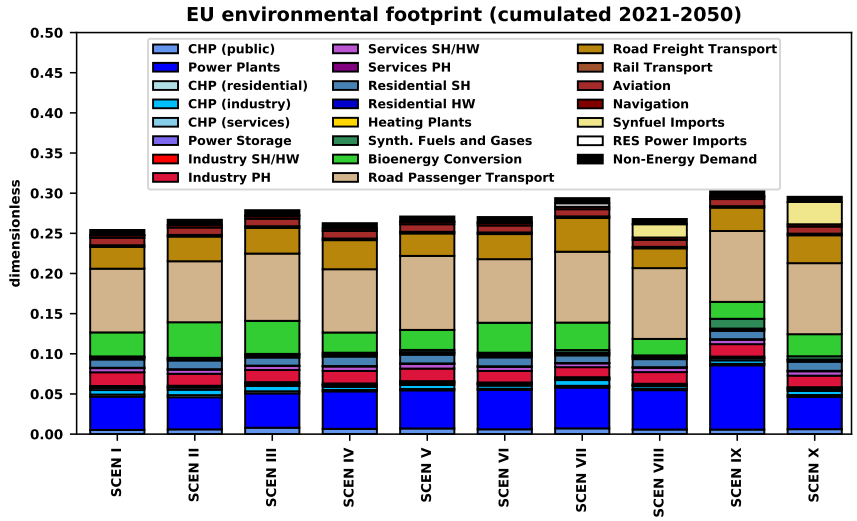

Figure 102: EU Environmental Footprint: Cumulated Impacts (2020-2050) on sector level

3 Cross-scenario comparison of results for all indicators

3.1 Cross-scenario comparison on scenario level

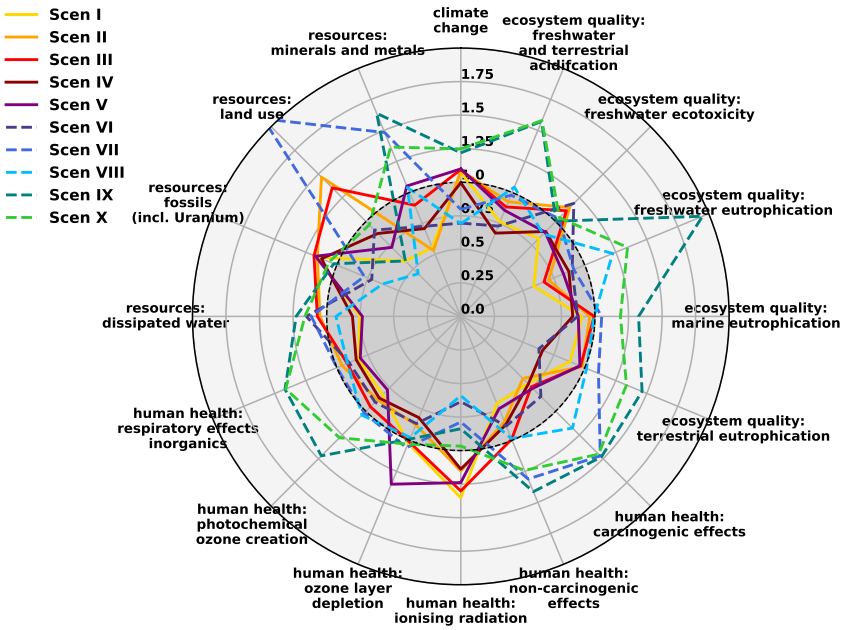

Figure 103: Comparison of the *normalized* impacts of all scenarios. All impacts are normalized to the average value in 2050 of each indicator across all scenarios.

3.2 Comparison of average and extreme scenario performance on scenario and sector level

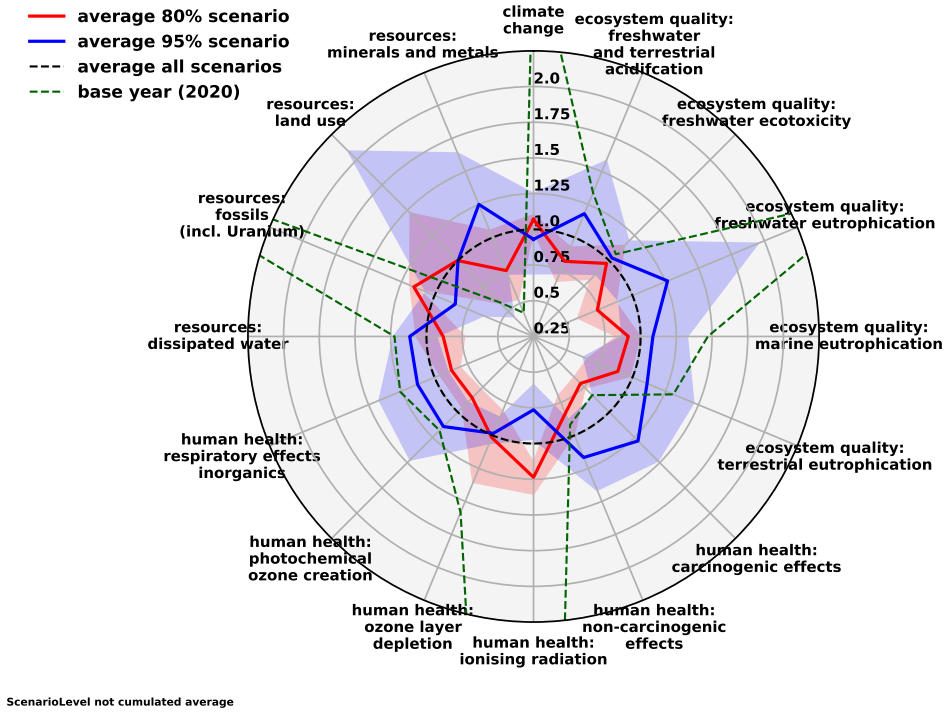

Figure 104: Comparison of normalized results for 2050 on ***scenario level***. Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

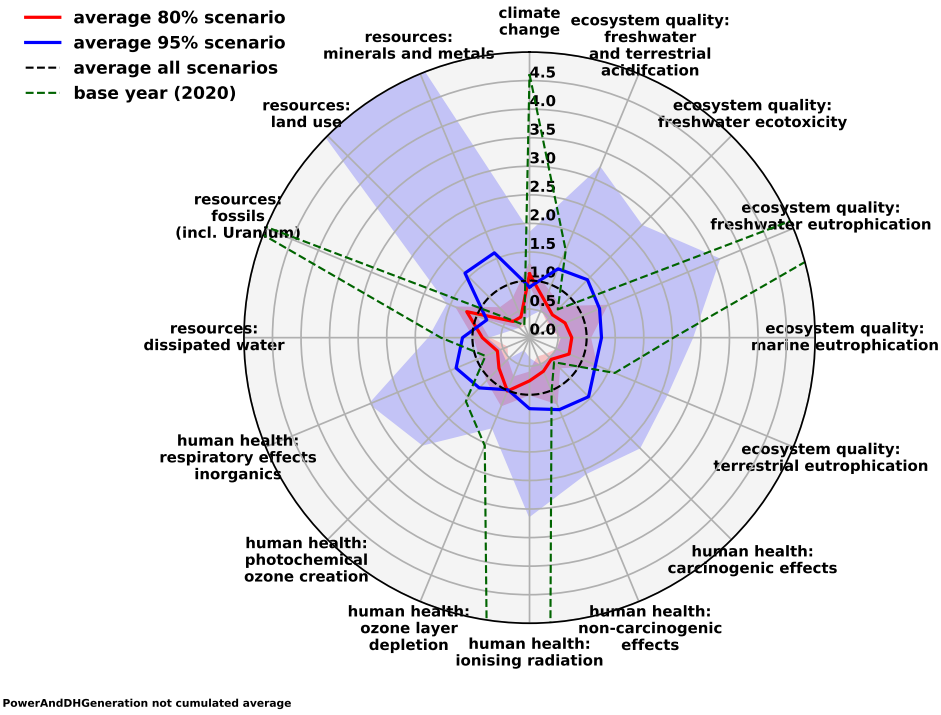

Figure 105: Comparison of normalized results for 2050 for ***power and district heat generation*** (power plants, heating plants, CHP plants). Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

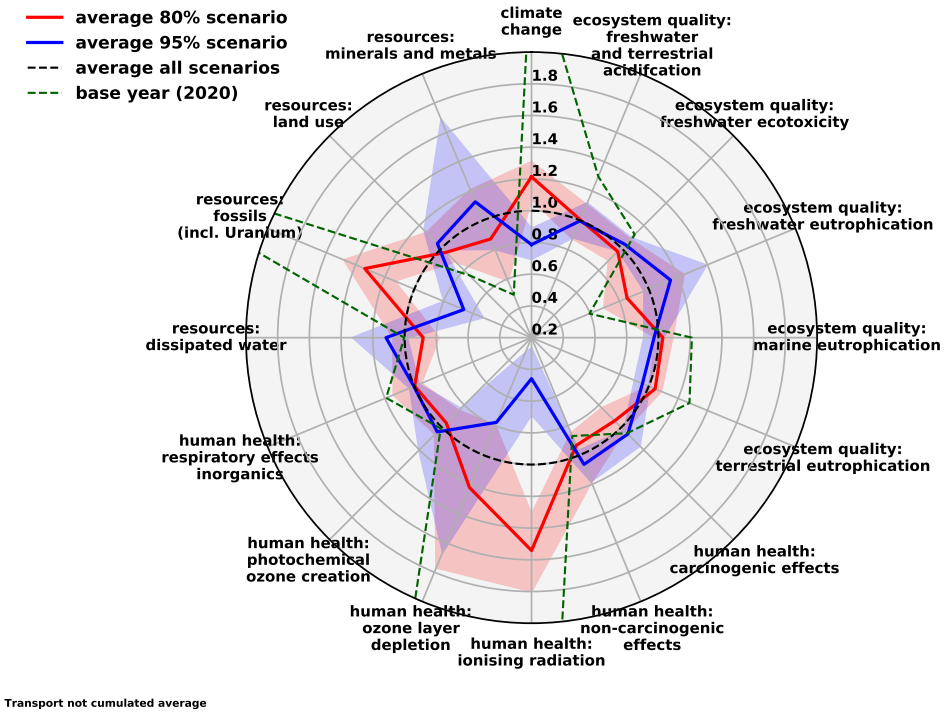

Figure 106: Comparison of normalized results for 2050 for ***passenger and freight transport*** (road, rail, aviation, navigation). Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

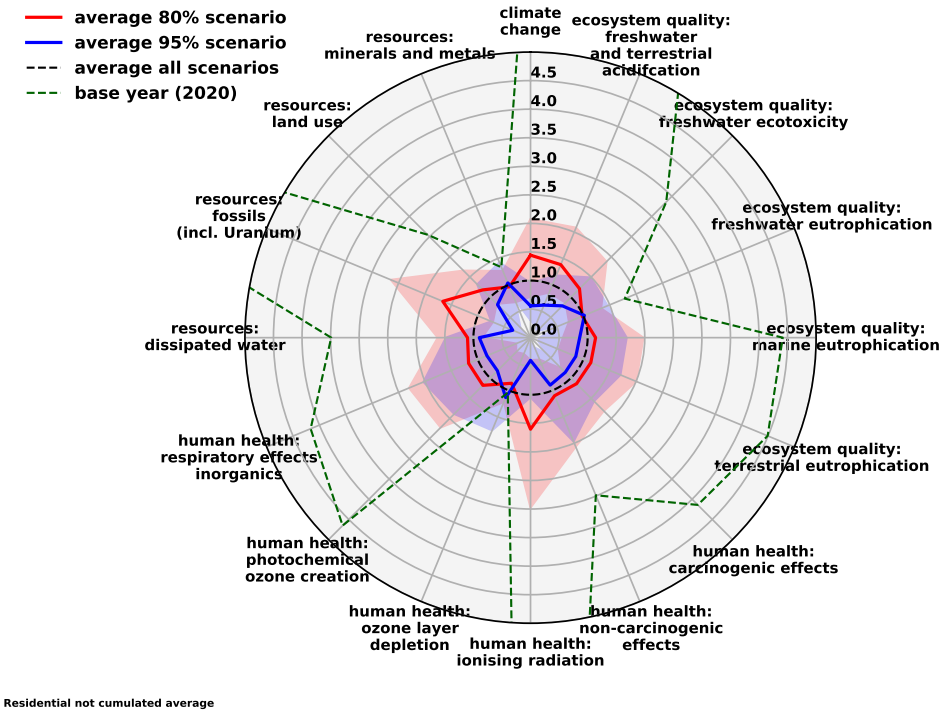

Figure 107: Comparison of normalized results for 2050 for the ***residential sector*** (space heat and hot water). Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

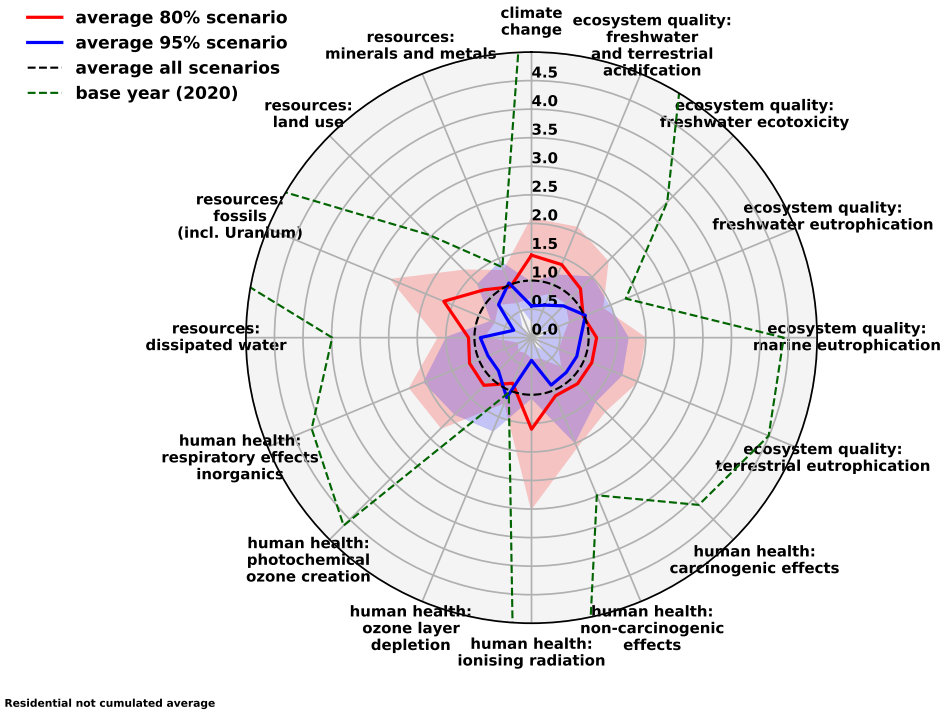

Figure 108: Comparison of normalized results for 2050 for the ***service sector*** (space heat, hot water, process heat). Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

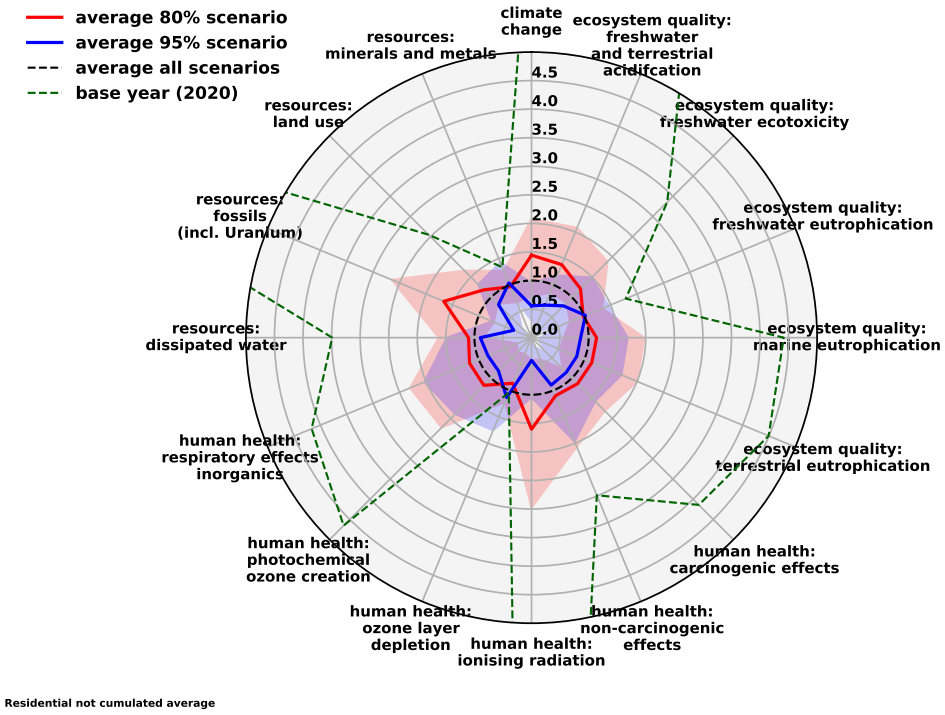

Figure 109: Comparison of normalized results for 2050 for the ***industry sector*** (space heat, hot water, process heat). Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

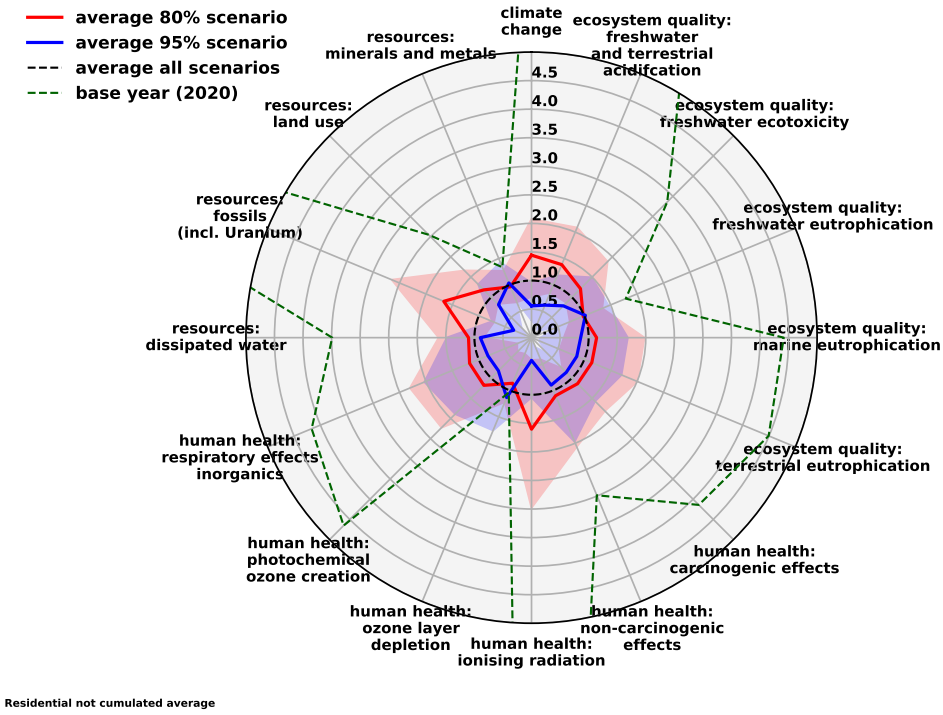

Figure 110: Comparison of normalized results for 2050 for the ***generation of synthetic fuels and gases and bioenegy conversion***. Red line: Average normalized indicator values for all 80% scenarios in 2050. Red area: Range of normalized results for all 80% indicators in 2050. Blue line and blue area: same for 95% scenarios. Green dashed line: Results for base year. All results are normalized to the average of all scenarios in 2050.

4 Additional Information

4.1 Model sectors

The following sectors are explicitly modeled in the foreground systems:

- Residential Sector
  - Generation of space heat (SH)
  - Generation of hot water (HW)
  - CHP autoproduction (generation of space heat, hot water, and electricity)
- Industry Sector
  - Generation of space heat and hot water (SH/HW)
  - Generation of process heat (PH)
  - CHP autoproduction (generation of process heat, space heat, hot water, and
- Sector Services (incl. Trade and Commerce)
  - Generation of space heat and hot water (SH/HW)
  - Generation of process heat (PH)
  - CHP autoproduction (generation of process heat, space heat, hot water, and electricity)
- Transport
  - Road passenger transport
  - Road freight transport
  - Rail transport (passengers and freight)
  - Aviation (passenger and freight)
  - Navigation
- Conversion Sector (national)
  - Power Plants (w/o public CHP plans)
  - Power Storage
  - (Public) CHP Plants
  - Heating Plants
  - Generation of synthetic fuels and gases
  - Bioenergy conversion
- Other sectors
  - Imports of (renewable) power
  - Imports of (renewable) synthetic fuels and gases
  - Non-energy demand

4.2 End-use Applications

Environmental impacts on the level of model sectors are allocated to the following end-use applications:

- Residential Sector
  - Generation of space heat (including Power-to-Space-Heat)
  - Generation of hot water (including Power-to-Hot-Water)
  - Electric Appliances (w/o electric appliances for the generation of space heat and hot water)
- Industry Sector
  - Generation of space heat and hot water (including Power-to-Space-Heat-And-Hot-Water)
  - Generation of process heat (including Power-to-Process-Heat)
  - Electric Appliances (w/o electric appliances for the generation of process heat, space heat and hot water)
- Services Sector (including trade and commerce)
  - Generation of space heat and hot water (including Power-to-Space-Heat-And-Hot-Water)
  - Generation of process heat (including Power-to-Process-Heat)
  - Electric Appliances (w/o electric appliances for the generation of process heat, space heat and hot water)
- Transport
  - Road passenger transport
  - Road freight transport
  - Rail passenger transport
  - Rail freight transport
  - Aviation (passenger)
  - Aviation (freight)
  - Navigation
- Others
  - Non-energy demand

List of Figures

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Note

The quantitative impact assessment results are also published in an Excel file on the project home page, see https://www.innosys-projekt.de/en.