Harmonized remodeled energy system transformation strategies for Germany - scenario results from the InNOSys project

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Contents

1 Introduction

Here we compare energy balances, installed capacities etc. for ten harmonized remodeled transformation pathways of the German energy system up to 2050. The selection, harmonization and remodeling process has been documented in [6]. As a short summary: From an extensive literature research, ten strategies for the German energy system have been selected. Five of those scenarios achieve a reduction of direct CO_2 emissions of about 80%, the other five of more than 90%. The selected studies were taken as inspiration of a remodeling of the transformation strategies, where the useful energy demand as well as transport services were harmonized (i.e. they are identical in all remodeled scenarios). This harmonization process allows an unbiased comparison of different supply side strategies for the energy system, although the original studies used as "inspiration" make very different assumptions regarding the development of, for example, population, GDP or energy consumption and transport services.

scenario number	reference	scenario in original study
I	[5]	Energiewende
II	[9]	Basis
III	[8]	A
IV	[10]	Klimaschutz 80
V	[3]	80/gering/H2/nicht beschleunigt
VI	[10]	Klimaschutz 95
VII	[7]	100%
VIII	[2]	GreenEE
IX	[4]	Optimales System
X	[1]	Technologiemix 95%

Table 1: Overview of the scenarios used as basis and inspiration for the harmonised scenario remodeling.

The analysis presented here focuses on a comparison of scenario results for the year 2050. It first compares the scenarios with respect to their technical options to decarbonize the building sector (Section 3.1), the process heat sector (Section 3.2), road passenger and road freight transport (Sections 3.3 and 3.4) including the final energy demand of the transport sector (Section 3.5). It then compares the consumption of synthetic fuels and gases (Section 3.6), imports of power and synthetic fuels and gases (P2X) (Section 3.7), the resulting electricity demand (Section 3.8) and installed capacities for power generation (Section 3.9). Additionally, the use of bioenergy (Section 3.12) and energy related direct CO_2 emissions (Section 3.13) are analyzed. In Section 4, characteristic features of each scenario are identified and discussed.

The remodeled scenarios SCEN I to SCEN V achieve a reduction of *direct* energy related CO_2 emissions by ca. 80%. They are called the moderately ambitious scenarios" or "80% scenarios". In contrast, the scenarios SCEN VI to SCEN X achieve an emission reduction of about 95%, as can be seen in Figure

13. They are called "highly ambitious scenarios" or "95% scenarios".

The remodeled scenarios SCEN I to SCEN X are based (inspired) the studies summarized in Table 1:

2 Assumptions regarding useful energy demand and transport services in all scenarios

quantity	**unit**	**2020**	**2030**	**2040**	**2050**
population	million	82	81	79	76
GDP	10^9 €	3.219	3.635	4.077	4.600
residential sector					
space heat	PJ/a	1.323	1.078	913	719
hot water	PJ/a	304	269	227	188
space cooling	PJ/a	5	6	6	7
process heat	PJ/a	141	135	124	113
ICT & illumination	PJ/a	113	107	96	86
mechanical energy	PJ/a	21	21	20	19
process cooling	PJ/a	103	99	92	85
trade, commerce, services					
space heat and hot water	PJ/a	691	639	569	496
process heat	PJ/a	95	92	89	85
mechanical energy	PJ/a	250	231	213	195
ICT & illumination	PJ/a	272	249	226	203
space cooling	PJ/a	11	11	10	10
process cooling	PJ/a	46	43	41	38
industry					
space heat and hot water	PJ/a	208	200	172	129
process heat	PJ/a	1.529	1.399	1.163	909
space cooling	PJ/a	557	503	449	396
process cooling	PJ/a	63	58	54	49
ICT & illumination	PJ/a	17	18	19	19
mechanical energy	PJ/a	35	29	22	16
passenger transport					
road	10^9 pkm/a	1.060	1.027	946	900
rail	10^9 pkm/a	100	103	107	109
aviation (domestic)	10^9 pkm/a	71	75	80	77
freight transport					
road	10^9 tkm/a	523	607	650	645
rail	10^9 tkm/a	126	149	174	218
navigation (domestic)	10^9 tkm/a	67	79	94	107
aviation (domestic)	10^9 tkm/a	2	2	3	4

Table 2: Overview of the assumptions on population, GDP, useful energy demand,and transport services in all scenarios

Table 2 summarizes assumptions on useful energy demand in the sectors residential, industry, and trade, commerce, and services, as well as on passenger and freight transport by transport mode, on population and GDP development. These boundary conditions are identical in all scenarios discussed hereafter.

3 Sector-wise comparison of scenarios

3.1 Space Heat and Hot Water in Buildings

Figure 1 shows the final energy demand in the building sector (i.e. space heat and hot water in residential and commercial buildings) by energy carrier. Compared with today (2020), the final energy demand in buildings is reduced by ca. 44% in all scenarios.

All 80% scenarios assume a mix of natural gas (of fossil origin), electric heat pumps, district heat and solar thermal heat. In some of the scenarios, also mineral oil is still used to provide space heat and hot water. All 80% scenarios except SCEN V also consume biomass in the building sector. Noteworthy features are the high share of electric heat pumps in SCEN V, which also assumes a small share of synthetic natural gas for heating. On the other hand, Scenario III stands out because a high proportion of building heat is supplied via district heating (44%). Heat pumps are only used to a very limited extent.

A common feature of the 95% scenarios (SCEN VI - SCEN X) is the fact that that no mineral oil is used any longer. Natural gas (fossil) is hardly used any more, if at all. In SCEN IX and SCEN X, however, synthetic natural gas is used in gas boilers (16% and 42%, respectively). Electric heat pumps and district heat are used to varying degrees in all scenarios. SCEN VII assumes that more of a third of the heat demand in buildings is provided by district heat. No biomass is used in SCEN VIII and SCEN IX. Solar thermal heat does not play a role in SCEN VIII. Whereas most of th 95% scenarios still use a rather broad mix of technologies and energy carriers in the building sector, SCEN VIII stands out because it almost completely relies on either district heat (19%) or electricity and electric heat pumps (79%).

3.2 Process Heat

Figure 2 shows the final energy demand for process heat (in sectors industry, residential, and service, trade, and commerce) in 2050 in the different scenarios. Compared with today (2020), the final energy demand for process heat is reduced by almost 40% in all scenarios.

The 80% scenarios still mostly rely on fossil fuels (coal, natural gas) and biomass for the provision of process heat. Compared with today, a shift from coal to gas and biomass can be noted. Biomass contributes between 18% and 29% to process heat in 2050 in those scenarios. Direct electrification increases slightly in most scenarios compared to today. Solar thermal process heat only plays a minor role in two scenarios (SCEN III and SCEN V). Except for SCEN V,

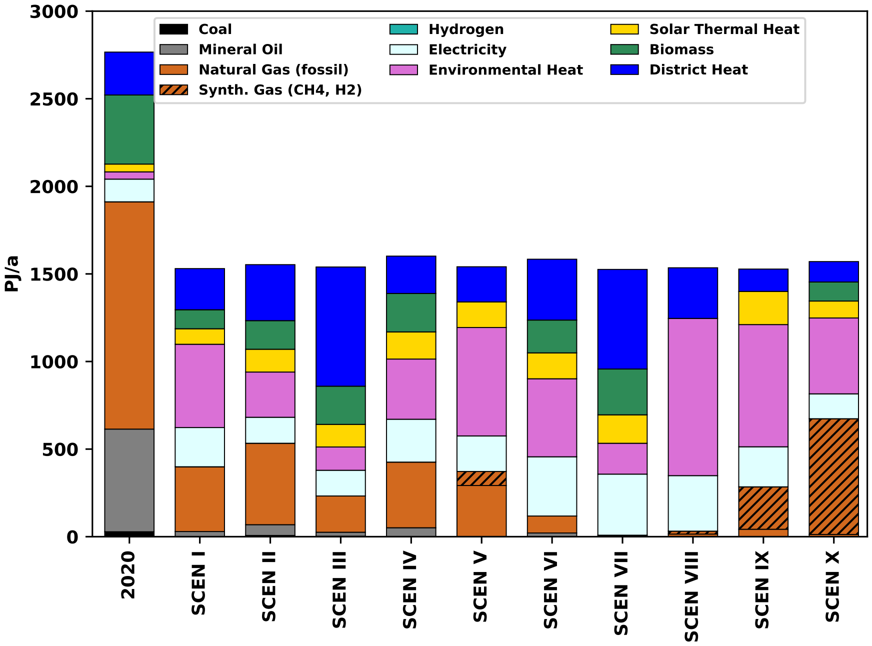

Figure 1: Final energy demand in buildings (space heat and hot water), differentiated by energy carrier

their is still a significant use of coal (between 11% and 32%) in the process heat sector. Although this is not explicitly modeled, much of the coal is used for steel production in blast furnaces. In the 80% scenarios, hydrogen is not used in any scenario. Other synthetic fuels and gases are also not used - with the exception of SCEN V, which assumes a share of 12% synthetic gas (incl. bio-methane) in the process heat sector.

The picture changes significantly in the highly ambitious strategies, as it is necessary to abandon fossil fuels to a large extent (21% or less). Coal is only used in SCEN VI (13%), as it is assumed that no alternatives for the blast furnace process are available. Main strategies to decarbonize process heat comprise the combination of biomass and direct electrification (as e.g. in SCEN VI and SCEN VII), direct electrification and hydrogen (SCEN VIII) and synthetic gases (incl. bio-methane) as the backbone of process heat supply in SCEN IX and SCEN X. Solar thermal process heat does not play a relevant role.

3.3 Road Passenger Transport

Figure 3 shows the road passenger transport service differentiated by power train technology in all scenarios. Compared to today (2020), the road passenger transport service decrease slightly by 16% in all scenarios

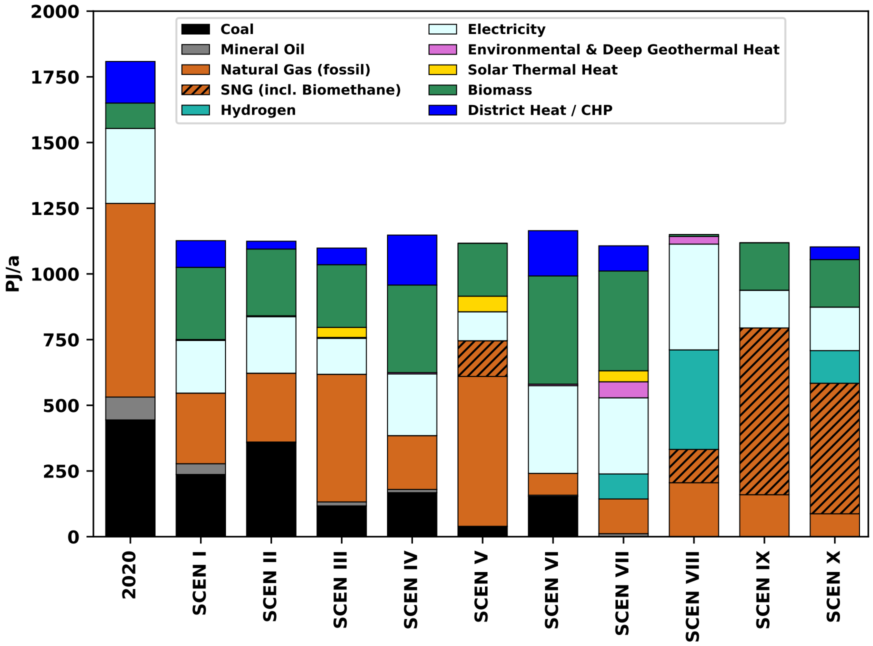

Figure 2: Final energy demand for process heat (industry, service, trade & commerce, residential), differentiated by energy carrier

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The 80% scenarios foresee a significant increase in Battery Electric Vehicles (BEVs) and Plug-In-Hybrids (PHEV) respectively Electric Range Extenders (EREV) compared to today. Pure Internal Combustion Engines (ICEs) will play a minor role in 2050 (25% in SCEN II, 20% in SCEN V). SCEN I, SCEN III, and SCEN V assume that Fuel Cell Electric Vehicles (FCEV) will enter the passenger car market in Germany. In particular in SCEN III (17%) and SCEN V (47%), they contribute significantly to the total passenger service. In contrast, FCEVs are unable to establish themselves on the market in SCEN II and SCEN IV. Gas motors are expected to play a moderate role in SCEN I, SCEN IV, and SCEN V.

The picture changes significantly in the 95% scenarios. Pure ICEs (Diesel or Otto motors) are not used any longer (exception: 4% in SCEN VI). SCEN VIII and SCEN IX assume that the passenger car fleet will be purely BEVs. SCEN VI assumes a BEV share of two thirds, while PHEVs/EREVs and a few ICE provide the remaining passenger service. Interestingly, only two scenarios (SCEN VII and SCEN X) assume that FCEVs can achieve a significant market share in 2050.

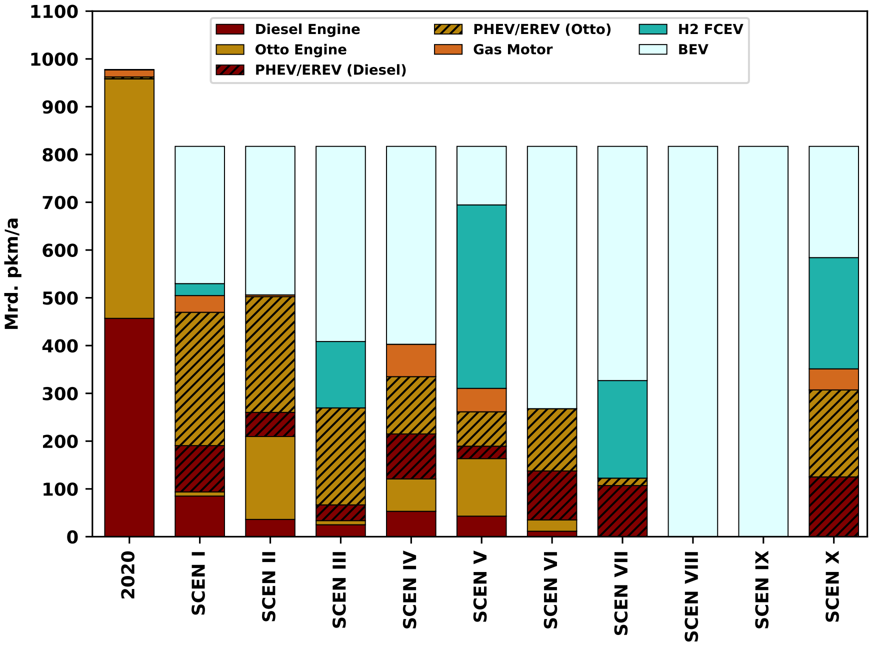

Figure 3: Passenger transport services cars in 2050, differentiated by power train technology

3.4 Road Freight Transport

Figure 4 shows the road freight transport service differentiated by power train technology in all scenarios. Compared to today (2020), the road freight transport service increases by roughly 25% until 2050 in all scenarios.

In the 80% scenarios in 2050, combustion engines are still the dominating power train technologies. However, Diesel motors are to some extend replaced by EREVs/ PHEVs (SCEN II) or gas motors (SCEN I, SCEN II, SCEN IV). In SCEN IV, gas motor driven trucks dominate the road freight transport service with 48% of the total freight transport service. FCEVs are only considered to be an option for the decarbonization of the road freight transport in SCEN III with a market share of 29% and SCEN V (market share: 16%). BEVs (if applicable, including trolley trucks (TTs)) play more than a niche existence only in SCEN II (market share: 11%) and SCEN IV (market share: 25%). Note that the diesel fuels used in the 80% scenarios is mostly of fossil origin. Only SCEN I and SCEN V assume a significant consumption of synthetic fuels in the (freight) transport sector, as can be seen in Figure 5.

The five scenarios aiming at a reduction of the energy related CO_2 emissions by ca. 95% pursue very different strategies to decarbonize the road freight transport: SCEN VII relies entirely on trucks powered by fuel cells (and an

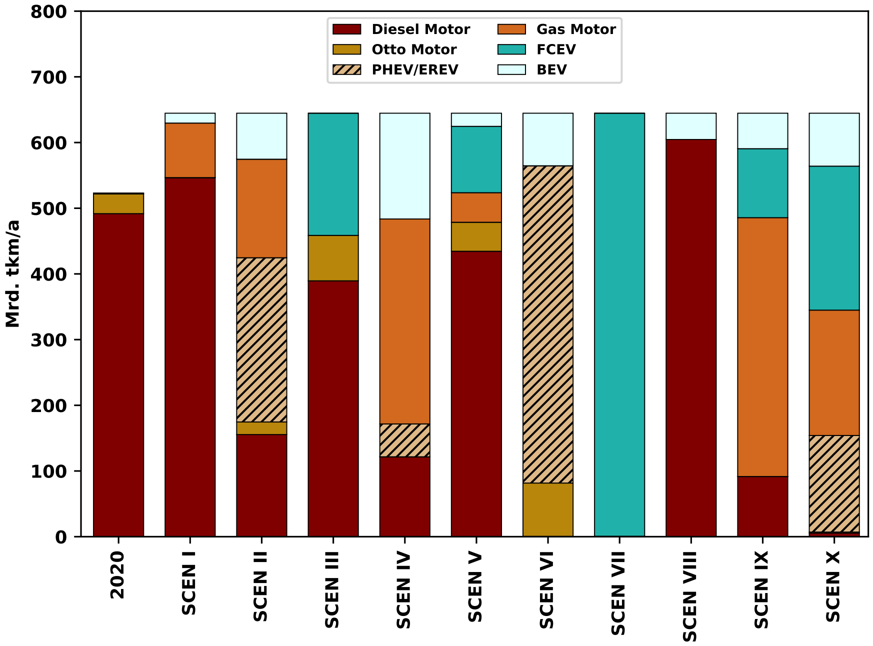

Figure 4: Freight transport services trucks in 2050, differentiated by power train technology

electric motor). SCEN VIII, on the other hand, assumes that Diesel motors will hardly be replaced by alternative propulsion technologies and keep a market share of 94% in 2050. Nevertheless, in order to reduce CO_2 emissions, the corresponding diesel fuels are produced synthetically (see also Section 3.5 and Figure 5). In SCEN VI, the dominating power train technologies are Hybrids (PHEV/EREV) using mostly biofuels or synthetic fuels (Figure 5). Gas motors are expected to play a major role in SCEN IX and SCEN X. Similar to Diesel fuels used mainly in the scenarios SCEN VI and SCEN VIII, the gas is no longer of fossil origin, but is produced synthetically in a CO_2 neutral manner.

3.5 Final Energy Demand Transport

Figure 5 illustrate the resulting final energy demand in the transport sector (freight and passenger transport, road, rail, aviation, and navigation) in the different scenarios and for today (2020). In all scenarios, the final energy demand of the transport sector decreases significantly compared to today. This is mainly a consequence of efficiency improvements of existing power train technologies and higher (final energy) efficiency of new (emerging) power train technologies (such as BEVs, PHEVs, EREVs, and FCEVs) compared with internal combustion engines. As the transport services - both passenger and freight transport -

are identical in all scenarios, the differences in the final energy consumption of the transport sector in the scenarios reflect the different transport technology mixes and the different efficiencies of each transport technology.

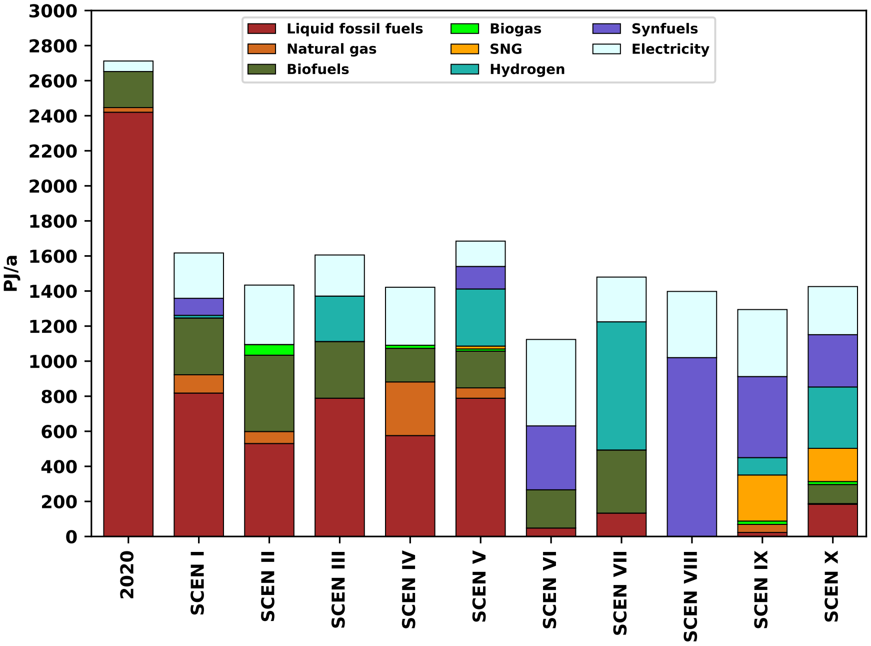

Figure 5: Final energy demand in the transport sector (all modes) in 2050, differentiated by energy carrier

The final energy demand of the transport sector is dominated by the road transport (passenger and freight). Therefore, the final energy demand as depicted in 5 mainly reflects the power train technologies for road passenger transport (Figure 3) and road freight transport (Figure 4), plus the replacement of fossil fuels and gases with synfuels and SNG. It becomes clear that synthetic fuels play only a minor role in the 80% scenarios. SNG is here not used at all. In these scenarios, the electrification of the transport sector is either trough FCEVs or BEVs. Fossil fuels still account for roughly 50% of the final energy demand. Biofuels replace fossil fuels; they account for 12% to 30% of the total demand.

This picture changes in the 95% scenarios: Fossil fuels (including natural gas) are hardly used anymore. In ICEs they are replaced by synfuels and SNG. Thus, direct and indirect electrification (the latter through hydrogen, synfuels and synthetic gases) significantly reduces the CO_2 emissions of the transport sector. Biofuels still play an important role in some scenarios (e.g. 24% in SCEN VII). However, some scenarios such as SCEN VIII and SCEN IX do not use (liquid) biofuels at al. SCEN VIII, which largely continues to rely on ICEs and has a correspondingly high demand for liquid fuels, is in particular notable here, as it neither uses biofuels nor hydrogen nor (synthetic or biogenic) gas.

3.6 Consumption of synthetic gases and fuels

The strategies for an indirect electrification of heat and transport discussed in Sections 3.1-3.4) (as well as the use of hydrogen for power generation) result in demands for Hydrogen, synthetic Methane, and synthetic liquid fuels as depicted in Figure 6. Note that the demand for H_2 as a feedstock for the generation of SNG and Synfuels is not included in this figure.

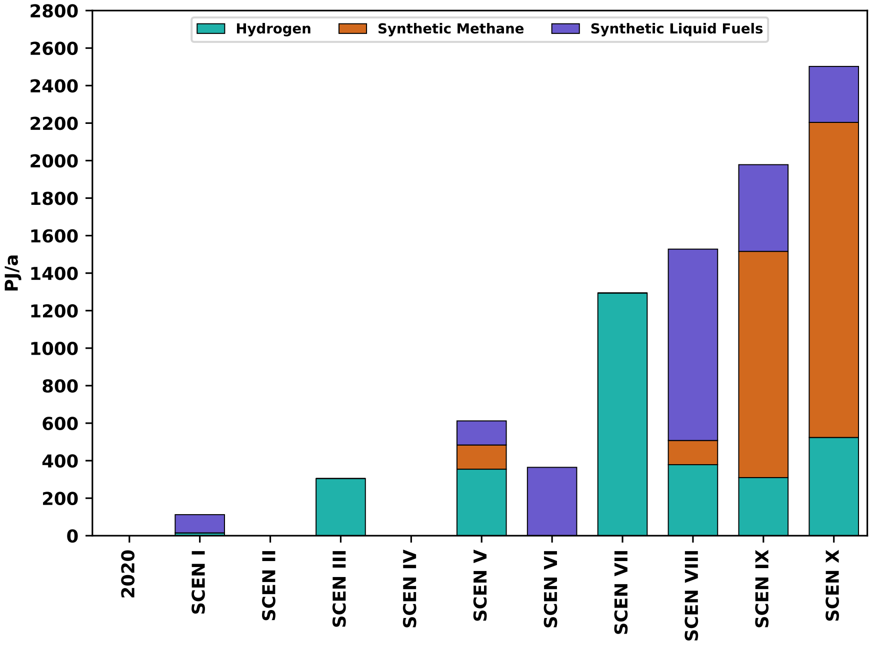

Figure 6: Consumption of synthetic H_2, synthetic CH_4 and synthetic liquid fuels in end-use sectors and for power generation in 2050

In the 80% scenarios, the demand for synthetic fuels and gases generally is low. In SCEN II and SCEN IV, P2X is not required at all to achieve the CO_2 emission results. In SCEN I and SCEN V synfuels are used to some extend in the transport sector. SCEN III and SCEN V use Hydrogen both for freight and passenger road transport (Figure 5). In SCEN V, synthetic natural gas (SNG) is also required to replace natural gas to some extent in the process heat sector (Figure 2).

In the 95% scenarios, the demand for P2X is generally much higher than in the moderately ambitious scenarios. The only exception is SCEN VI, where

365 PJ of synfuels are used in the transport sector, less than in SCEN V. In the other 95% scenarios, the demand for P2X lies between ca. 1.300 PJ/a (SCEN VII) and more than 2.500 PJ/a. SCEN VII relies solely on Hydrogen, which is used prominently in road freight transport (Figure 4), but also in passenger cars (Figure 3) as well to a lesser extent for process heat (Figure 2). In SCEN VIII, Hydrogen and synthetic methane is used only for process heat, but not in the transport sector. As the road freight transport is dominated by Diesel trucks in this scenario, synfuels are used to obtain (largely) CO_2 neutrality of road freight transport. In SCEN IX, Hydrogen is required for road freight transport, but not for process heat nor passenger cars. Synthetic methane (SNG) largely replaces natural gas in the industry sector and in gas motor trucks. SNG is also used in the building sector where the replacement of gas (or oil) boilers with electric heat pumps, biomass boilers or district heat is not feasible. Synfuels are used in Diesel trucks. SCEN X is the scenario that uses P2X the most (2.500 PJ/a). In the passenger car segment, Hydrogen, SNG and synfuels (in PHEVs and EREVs) are used (Figure 3). In road freight transport, both FCEVs, trucks with as motors and PHEVs /EREVs are used (Figure 4). The latter two are fueled with SNG and Synfuels to a large extent. Similar to SCEN IX, SNG is used in the building and in the process heat sectors in gas burners (Figures 1 and 2).

3.7 Power and Power-to-X Imports

In all scenarios, the sum of all net imports decrease strongly compared with 2020. While SCEN I - SCEN V still import significant amounts of fossil fuels, these imports are drastically reduced in SCEN VI-X.

In SCEN VIII and SCEN X, Hydrogen, SNG and/or Synfuels are not only produced in Germany, but also imported from countries with more favorable production characteristics (i.e. higher solar irradiation and/or better wind conditions than in Germany, see Figure 7). In SCEN VIII imports all Synfuels (ca. 1.000 PJ/a), whereas Hydrogen and SNG is produced domestically. SCEN X imports almost 2.200 PJ/a of Hydrogen, SNG and Synfuels at a domestic consumption of ca. 2.500 PJ/a.

SCEN III and SCEN VII assume a net import of power of 63 TWh/a (SCEN III) and 262 TWh/a (SCEN VII), respectively (Figure 7). The import balance for electricity is balanced in the other scenarios.

3.8 Electricity Demand

The development of the electricity demand between today and 2050 is determined by two opposing factors: On the one hand, efficiency improvements in "classic" consumers (illumination, information, communication, mechanical energy) have resulted in a decline in electricity demand here. However, the different degrees of direct and indirect electrification of heat and mobility as discussed in the previous sections lead to an increase in the demand. Whereas the "classic" power demand is identical in all scenarios, the differences in gross power

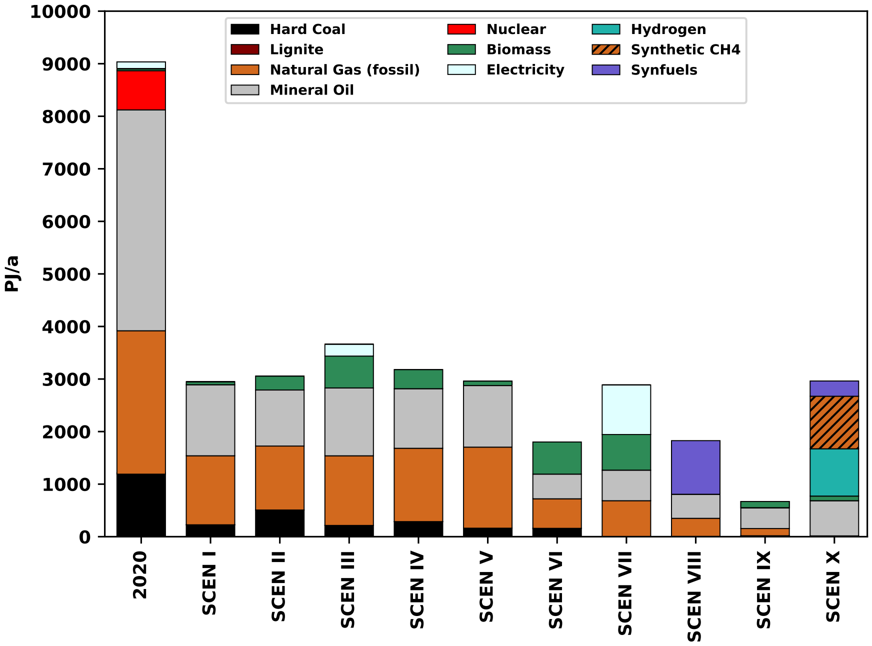

Figure 7: Net imports in 2050

demand between the scenarios (see Figure 8) result from the different electrification strategies of heat (electric heat pumps and resistance heaters) and transport (PHEVs, BEVs) in the sectors industry, trade, commerce and service, residential, and transport. The largest increase in the gross electricity demand is cased by indirect electrification via P2X (hydrogen, synfuels and SNG).

Since P2X is only required to a small extent in most of the 80% scenarios, the gross electricity consumption of these scenarios (528-598 TWh/a) is in the same order of magnitude as today (577 TWh in 2020). The only exception in the 80% category is SCEN V (733 TWh gross power consumption), as SCEN V assumes ca. 600 PJ of P2X in 2050, much more than in SCEN III (305 PJ) or SCEN I (112 PJ) (see also Figure 6).

As P2X becomes much more important as a means to decarbonize heat and mobility in the highly ambitious scenarios SCEN VI - SCEN X (see P2X demand in Figure 6). As a consequence, the power demand in these scenarios is much higher (924-1.682 TWh/a) than in the 80% scenarios (Figure 8). However, the higher power demand also reflects higher degrees of direct electrification of the end use sectors in the 95% scenarios. Note that Figure 8) shows also the electricity required for the production of synthetic fuels and gases which are then imported to Germany (see also Figure 7). It illustrates that in SCEN VIII and SCEN X, the power demand for P2X generation abroad is (much) higher

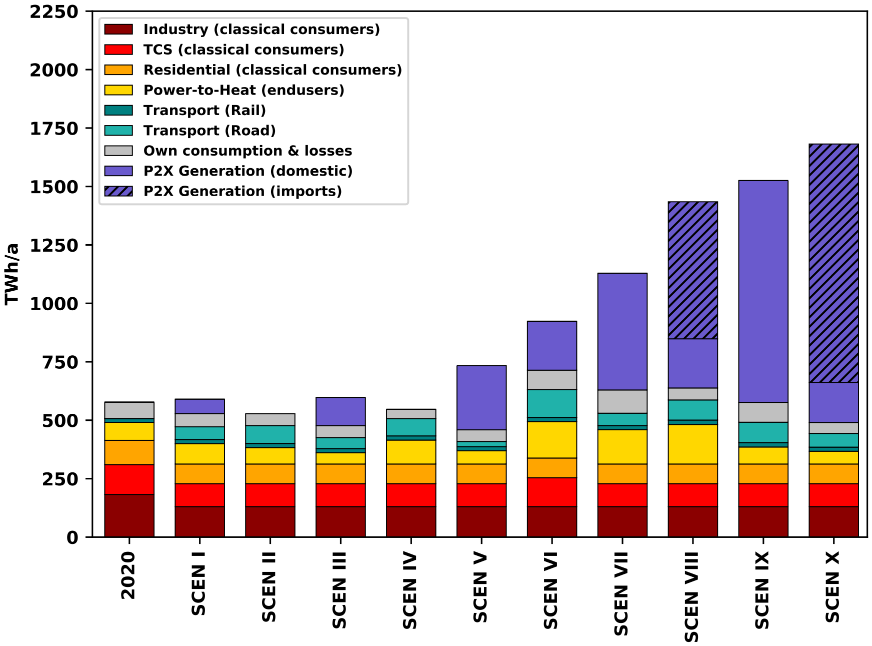

Figure 8: Gross electricity demand in 2050, including (foreign) electricity consumption for P2X imported by Germany

than the domestic power consumption for synfuels and SNG.

3.9 Installed capacity for power generation

The national demand for electricity, power imports and the portfolio of the national power production determine the nationally installed capacities of power generation technologies (see Figure 9. Estimates of the installed capacities in the 80% scenarios range between almost 300 GW (SCEN II) and almost 500 GW (SCEN V), for the 95% scenarios between almost 400 GW (SCEN X) and more than 1.200 GW (SCEN IX).

In all scenarios, the backbone of the power supply is PV as well as onshore and offshore wind (in sum between 56% and 87% in 80% scenarios and between 61% and 94% in 95% scenarios). The relative shares of onshore and offshore wind and PV vary significantly even within one scenario group: In the 80% scenarios, the share of PV in the total installed capacity ranges between 18% (minimum installed capacity: 64 GW) and 33% (maximum installed capacity: 161 GW), in the 95% scenarios between 18% (minimum installed capaciy: 88 GW) and 75% (maximum installed capacity: 913 GW). Onshore wind contributes between 23%/81GW and 52%/180 GW in the moderately ambitious scenarios and between 15%/135GW and 53%/267GW in the highly ambitious

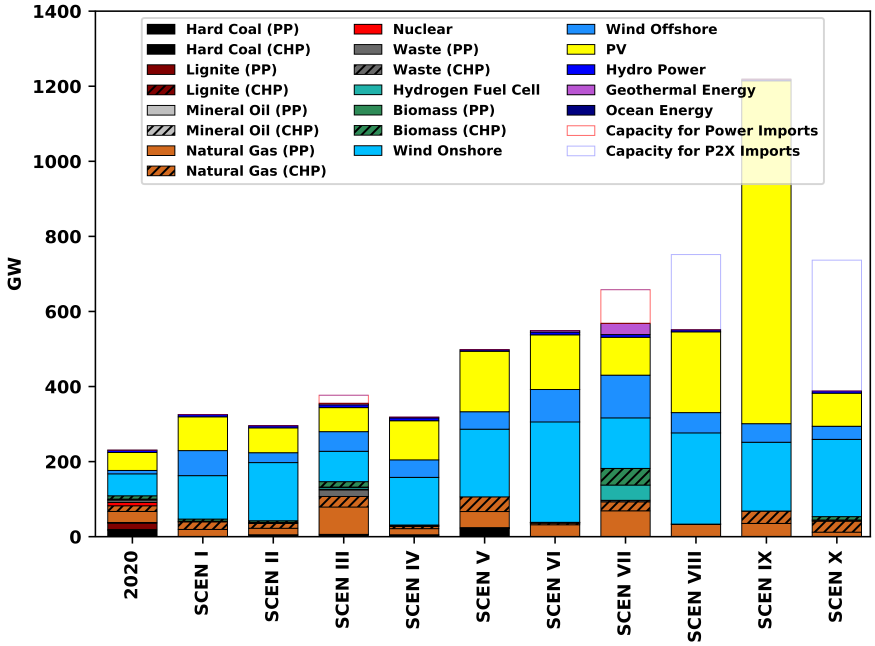

Figure 9: Gross installed capacity for electricity generation in 2050 in Germany, including capacities abroad for net power and P2X imports

scenarios. Ranges for offshore wind are 9%/26GW and 21%/67GW in 80% scenarios and 4%/35GW and 20%/114GW in 95% scenarios.

Conventional power plants (coal, oil, gas, nuclear, waste) make up still between 9% and 36% of the total installed capacity in 2050 in the moderately ambitious scenarios. In the highly ambitious scenarios, this range decreases to 6%-17%, mostly gas-fired power plants. Combined heat and power generation (CHP) still plays a (minor) role in 2050. In the 80% scenarios, its share in total installed capacity ranges between 3% and 16%, the 95% between 0% and 20% (SCEN VII). Geothermal energy is not expected to play a significant role in the future. The only exception is SCEN VII with 5%.

The role of biomass power plants is viewed very differently. While many scenarios assume no biomass at all for power generation (SCEN V, SCEN VI, SCEN VIII, SCEN IX), biomass still contributes 8% to the installed capacity in SCEN VII, for example, and 4% in SCEN III. In both cases, biomass is mainly used in CHP plants.

3.10 Power Generation

Figure 10 compares the power generated by the power plant portfolio. As already evident from Figure 9, wind and PV power provide the backbone of the national power generation in Germany (between 75% and 83% in the moderately ambitious scenarios and between 74% and 95% in the highly ambitious scenarios).

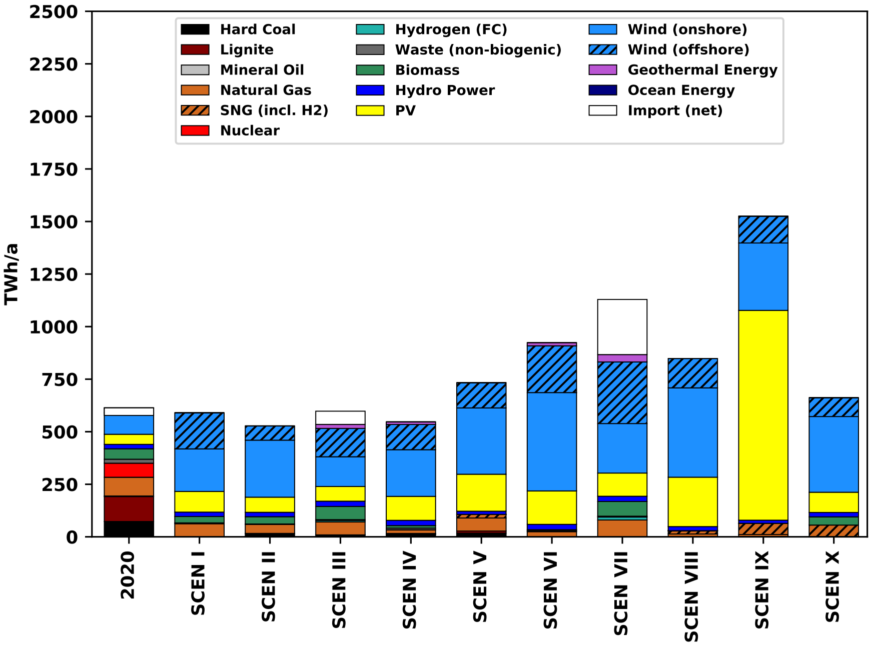

Figure 10: Power generation per energy carrier, including net power imports

Power generation from biomass plays a significant role in most of the 80% scenarios (except for SCEN V) and in two of the five 95% scenarios (SCEN VII and SCEN X). In the highly ambitious scenarios, gas power plants are often fired with SNG, providing balancing energy and grid stabilization without fossil CO_2 emissions. Geothermal power generation plays a small role in two moderately ambitious and two highly ambitious scenarios. An outstanding feature of SCEN IX is the fact that PV power makes up more than two thirds of the entire national power generation. In any other scenario, the PV share in gross power generation does not exceed 28% of the gross power demand.

3.11 District Heat

The future role of district heating is interpreted very differently in the scenarios (see Figure 11). There are no systematic differences between the scenario classes, neither in the total amount of district heat, nor in the distribution between CHP and heating plants or between energy carriers. Estimates for district heat generation range from ca. 200 PJ/a to more than 800 PJ/a in the 80% scenarios and from ca. 120 PJ/a to more than 700 PJ/a in the 95% scenarios. There is generally no one technology or energy source that dominates district heating generation. However, the high proportion of district heating from biomass, geothermal, and solar thermal heating plants in SCEN III and SCEN VII is striking.

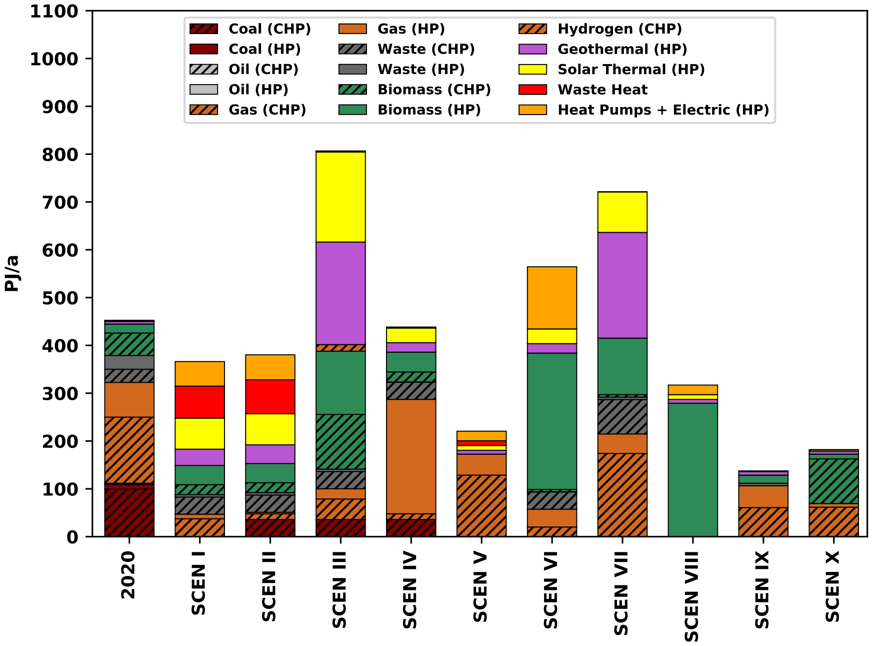

Figure 11: District heat generation per energy carrier. District heating generation in CHP plants is shown hatched.

3.12 Bioenergy

The scenarios differ strongly with respect to bioenergy consumption. The lowest estimate can be found in SCEN VIII with 641 PJ/a, the highest demand occurs in SCEN VII (1634 PJ/a). There is no clear tendency towards higher or lower biomass consumption in moderately and highly ambitious scenarios.

There is a tendency for higher biomass consumption in the industry sector in 2050 compared to 2020, both in terms of the absolute consumption and in terms of the share. In contrast, biomass consumption in the residential sector decreases in all scenarios (e.g. to 3% or less of the available biomass in SCEN I and SCEN VIII). While one scenarios refrain from the use of biofuels in the transport sector (SCEN VIII), other scenarios allocate a significant share of the available bioenergy to the transport sector (e.g.SCEN I or SCEN II).

There is also no unanimous view on how much biomass should be used to generate electricity. SCEN VI allocates only 5% of the total biomass to power

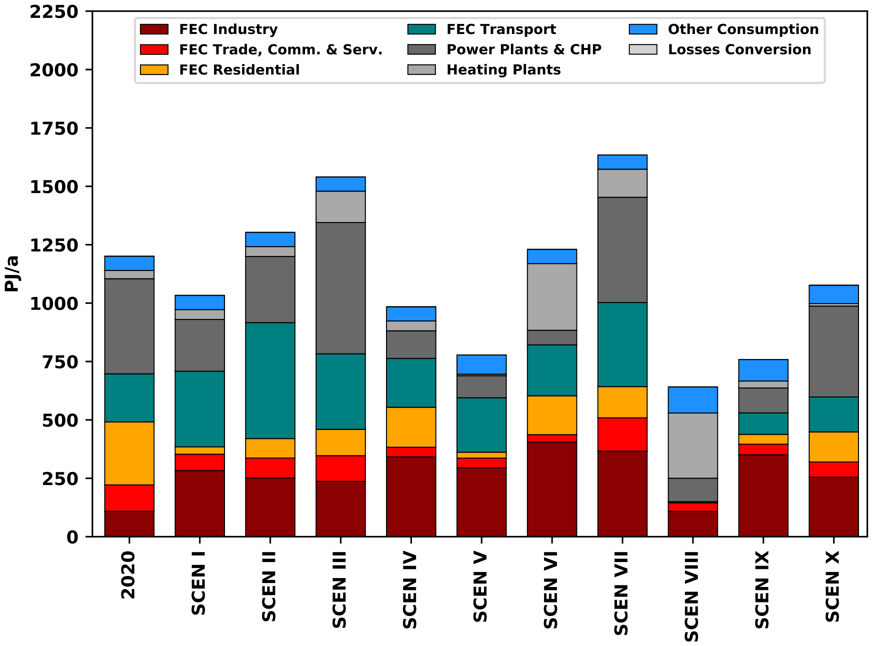

Figure 12: Bioenergy consumption in the enduse and conversion sectors

plants (incl. CHP), whereas SCEN III and SCEN X use more than a third of the available biomass for the generation of power (and CHP heat).

3.13 Energy-related (direct) CO_2 emissions)

Figure 13 shows the direct, energy related CO_2 emissions by emission sector in all scenarios in comparison with today (2020). It becomes clear that in the moderately ambitious scenarios (SCEN I - SCEN V), CO_2 emissions are reduced by on average 82% compared with 1990 levels. The highly ambitious scenarios achieve an emission reduction of (on average) 95%.

In the moderately ambitious scenarios, industry and transport tend to be responsible for most of the remaining emissions. However, there is no such trend in the highly ambitious scenarios, where it depends strongly on the assumptions in the individual sectors.

3.14 System costs

Figure 14 compares the cumulated system costs (2020-2050) in all ten scenarios. Cumulated system costs range between almost 4.000 billion €$_{2010}$ (SCEN II) to almost 5.900 billion €$_{2010}$ (SCEN VII). Cumulated system costs in moderately

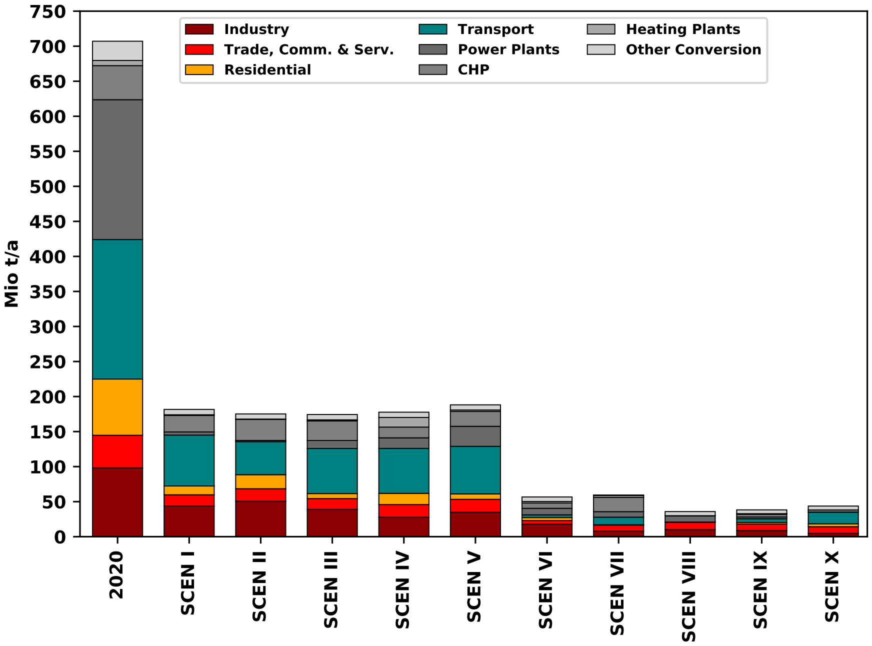

Figure 13: Energy related (direct) CO_2 emissions in 2050

ambitious scenarios are on average ca. 20% smaller than those in highly ambitious scenarios. The largest contribution to system costs stems from power generation (incl. CHP), followed by the residential and industry sectors. In SCEN VIII and SCEN X, the high imports of P2X products result in a high share of those imports in the total cumulated system costs. Note that the costs for the transport sector comprise only the generation of fuels, but no costs associated with the construction of vehicles.

Investment costs contribute to total system costs between 24% and 29% in the moderately ambitious scenarios (SCEN I - SCEN V) and between 31% and 39% in the highly ambitious scenarios (SCEN VI - SCEN X). In this cumulated view, operation costs thus still dominate the cumulated system costs.

4 Characteristic features of the individual scenarios

As mentioned above in Section 1, useful energy demand and transport services are identical in all scenarios. Therefore, this section only discusses characteristic features of each scenario on the supply side - buildings, process heat, transport - and their consequences for P2X and electricity demand, etc.

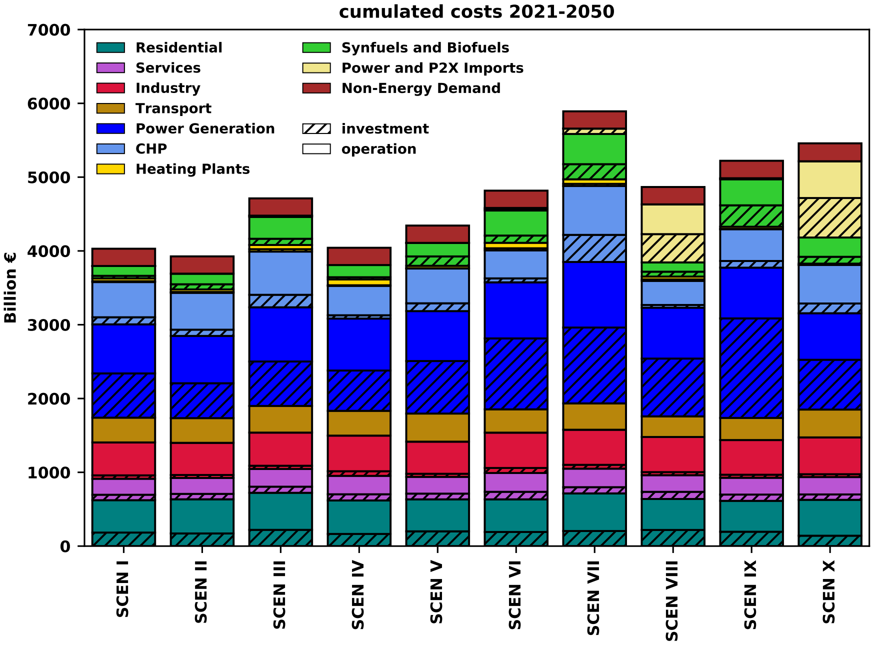

Figure 14: Cumulated system costs and cost components in billion €$_{2010}$

4.1 Scenario I

In the **building sector** (Figure 1), SCEN I is characterized by a dominant use of electric heat pumps. Gas burners cover a quarter of the heat demand; district heat contributes 15%. Biomass and solar thermal heat make small contributions to the heat demand in buildings. Occasionally, oil burners are still in use.

The main energy carriers that provide **process heat** are natural gas (24%), biomass (24%), coal (21%) and electricity (18%, Figure 2). Solar thermal process heat does not play a role; neither do synthetic gases (Hydrogen or SNG). A small percentage of process heat is met by oil burners.

In terms of **passenger cars**, SZEN I is essentially relying on a mix of hybrids (PHEVs and EREVs), which contribute almost the half of the entire road passenger transport service, and BEVs (35%, Figure 3). Conventional ICEs (11%), gas motors and FCEVs only play a minor role.

Road freight transport is dominated by trucks with diesel engines (Figure 4). However, 15% of the mileage is carried out by trucks with gas motors. BEVs or Trolley Trucks (TTs) play only a very small role (2%), other power train technologies (such as FCEVs) are not used at all.

As a consequence of the strategies pursued in the car and truck sector, the liquid fuels make up the largest part (77%) of the **final energy demand in the transport sector** (including aviation, navigation, and rail, see Figure 5).

However, a biofuel blending quota of 28% and a share of synfuels of 8% in total liquid fuels helps reducing fossil CO_2 emissions in the transport sector. The direct electrification of the transport sector is not far advanced (16% of total energy demand). The demand for natural gas is low (6%). Bio-Methane or SNG are not used.

To summarize the demand for synthetic liquid and gaseous energy carriers (**P2X**): In SCEN I, only small quantities (112 PJ/a) of P2X are required (see Figure 6). Hydrogen is used in fuel cell cars, wheres synthetic diesel fuel is mainly used in trucks. All P2X fuels are produced entirely in Germany (no imports, see Figure 7)).

The **gross power demand** in Germany is 590 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the end-use sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 87 TWh/a and 54 TWh/a, respectively. Domestic generation of P2X requires 62 TWh/a.

In 2050, **power generation capacities** of 325 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (116 GW), PV (90 GW) and offshore wind (67 GW). Together, they account for 84% of the total installed capacity. Flexible power generation is provided by gas power plants (39 GW), biomass power plants (6 GW) and hydro power (6 GW). Geothermal power plants and power generation in fuel cells are not relevant in this scenario. Coal and oil power plants are phased out. Combined heat and power generation (CHP) still plays a minor role (27 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (374 TWh/a) and PV (98 TWh) dominate the power generation portfolio (share in gross power generation: 80%), backed by natural gas (63 TWh/a), Biomass (30 TWh/a) and hydro power (21 TWh/a). No net electricity imports are required in this scenario.

The demand for **district heat** is approx. 370 PJ/a (see Figure 11). Roughly 75% is generated in heating plants, the rest in CHP plants. The largest share is from waste heat and solar thermal heat (18% each), biomass (17%), electric heat pumps and electric resistance heaters (14%), natural gas (13%), and waste (11%).

Biomass consumption is summarized in Figure 12. SCEN I assumes a bioenergy demand of ca. 1.000 PJ/a. Most of the bioenergy is used in the transport sector (31%), in the industry (27%) and for power and district heat generation (25%).

All the decarbonization measures implemented in the end-use and conversion sectors yield a reduction of **direct CO_2 emissions** by 82% compared to 1990 (Figure 13).

4.2 Scenario II

In the **building sector** (Figure 1), SCEN II is characterized by a relatively high share of conventional heating systems, mainly natural gas (30%), but also mineral oil (4%). District heating contributes roughly one-fifth of the heat demand in buildings. Minor contributions stem from solar thermal heat and biomass.

Dominant energy carriers in the **process heat** sector (Figure 2) are coal (32%), biomass and natural gas (each 23%) and electricity (19%). District heating plays a minor role. Solar thermal heat and synthetic gases are not used at all in the process heat sector.

The **passenger car** sector is dominated by BEVs (38%) and Hybrids (PHEVs, EREVs, 36%, see Figure 3). A quarter of the total road passenger transport service is met by conventional ICEs. Neither FCEVs nor vehicles with gas motors enter the market.

Hybrid trucks and trucks with gas motors contribute significantly to the **road freight transport** (see Figure 4). BEVs and TTs still account for 11% of the total freight mileage. Conventional ICEs contribute merely 27%. As in the passenger car sector, FCEVs are not used at all for road freight transport.

Liquid fuels make up two thirds of the **final energy demand in the transport sector** (Figure 5). Biofuels account for nearly half of the total liquid fuel demand. The relatively high share of gas motor trucks is reflected in the demand of natural gas and biogas/bio-methane (5% and 4%, respectively). Electricity accounts for roughly a quarter of the energy demand in the transport sectors. Synthetic fuels and gases (including hydrogen) are not used in the transport sector.

In SCEN II, no synthetic fuels or gases (**P2X**) are used (see Figure 7).

The **gross power demand** in Germany is 528 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 70 TWh/a and 76 TWh/a, respectively.

In 2050, **power generation capacities** of 296 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (155 GW) and PV (66 GW). The installed capacity of offshore wind is comparably low (26 GW). However, wind and PV account together for 84% of the total installed capacity. Flexible power generation is provided by gas power plants (30 GW), biomass power plants (6 GW) and hydro power (6 GW). Geothermal power plants and power generation in fuel cells are not relevant in this scenario. 5 GW of hard coal power plants are still in the grid. Lignite and oil power plants are phased out. Combined heat and power generation (CHP) still plays a minor role (23 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (339 TWh/a) and PV (72 TWh) dominate the power generation portfolio (share in gross power generation: 78%), backed by natural gas (43 TWh/a), Biomass (34 TWh/a) and hydro power (21 TWh/a). No net electricity imports are required in this scenario.

The demand for **district heat** is approx. 380 PJ/a (see Figure 11). Roughly 75% is generated in heating plants, the rest in CHP plants. The largest share is from waste heat (19%) and solar thermal heat (17%), biomass (16%) electric heat pumps and electric resistance heaters (14%), and waste (11%).

Biomass consumption is summarized in Figure 12. SCEN II assumes a bioenergy demand of ca. 1.300 PJ/a. Most of the bioenergy is used in the transport sector (38%), for power and district heat generation (25%) and in the industry (19%).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct $\mathbf{CO_2}$ emissions** by 82% compared to 1990 (Figure 13).

4.3 Scenario III

In the **building sector** (Figure 1), SCEN III is characterized by a large share of district heat (44%), followed by biomass (14%) and gas burners (13%). A striking feature of this scenario is the low share of electric heat pumps (ca. 12%), the lowest share in all scenarios considered here. Like in all other 80% scenarios, solar thermal heat contributes in a single-digit percentage.

Process heat (Figure 2) is predominantly provided by natural gas (44%). However, biomass (22%) and electricity (12%) also contribute significantly. District heating and solar thermal process heat play small roles. Synthetic fuels are not used to generate process heat.

The characteristic feature of the **passenger car** sector in SCEN III is the dominance of BEVs (50%, Figure 3). Moreover, the share of fuel cell vehicles (FCEVs) is comparatively high (17%). Hybrids contribute 29%, ICEs 5% to the road passenger transport service. Gas motors are not used at all.

More than two thirds of the **road freight transport** is carried out with conventional internal combustion engines (Figure 4). However, FCEVs contribute 29% to the total freight mileage. Hybrids, BEVs, TTs or trucks with gas motors are not used.

Liquid fuels account for more than two thirds of the **final energy demand in the transport** sector (Figure 5). The biofuel blending quota is nearly 30%. Synfuels, on the other hand, are not used. The high share of FCEVs both in the car and truck sector results in a high demand for hydrogen (16%) in this scenario. Other gases (natural gas, SNG, bio-methane) are not used. Electricity makes up 15% of the total final energy demand in the transport sector.

In SCEN III, **P2X** is only required in the form of Hydrogen (ca. 300 PJ/a, mainly for FCEV cars and trucks, but also for electricity generation in electric fuel cells, see 9). SNG or synthetic liquid fuels are not used in this scenario. The Hydrogen is generated entirely in Germany (no imports).

SCEN III assumes significant net **electricity imports** (227 PJ/a resp. 63 TWh/a) to Germany. This corresponds to roughly 10% of Germany's gross power consumption.

The **gross power demand** in Germany is 598 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 48 TWh/a and 47 TWh/a, respectively. Domestic generation of P2X requires 121 TWh/a.

In 2050, **power generation capacities** of 355 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (81 GW), PV (64 GW), and offshore wind (52 GW). Together, they account for 56% of the total installed capacity. Flexible power generation is provided by gas power plants (101 GW), biomass power plants (16 GW) and hydro power (6 GW). Geothermal power plants (4 GW) and power generation in Hydrogen fuel cells (5 GW) play a minor role. 6 GW of hard coal power plants are still in the grid. Lignite and oil power plants are phased out. Combined heat and power generation (CHP) still plays a significant role (56 GW_{el}). To supply the net power imports of Germany, another 41 GW of installed capacity abroad (onshore and offshore wind, PV, CSP) are necessary.

Biomass consumption is summarized in Figure 12. SCEN III assumes a bioenergy demand of ca. 1.540 PJ/a. Most of the bioenergy is used for the generation of electricity and district heat (45%), in the transport sector (21%) and in the industry (15%).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (276 TWh/a) and PV (70 TWh) dominate the power generation portfolio (share in national gross power generation: 65%), backed by natural gas (62 TWh/a), Biomass (63 TWh/a), hydro power (25 TWh/a), geothermal power (19 TWh/a) and hard coal (9 TWh). Moreover, 63 TWh/a of electricity (net) are imported each year.

SCEN III has a comparably high demand for **district heat** of more than 800 PJ/a (see Figure 11). Roughly 70% is generated in heating plants, the rest in CHP plants. The largest share is from biomass (31%), (deep) geothermal energy (27%), and solar thermal energy (23%).

waste heat (19%) and solar thermal heat (17%), biomass (16%) electric heat pumps and electric resistance heaters (14%), and waste (11%).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct CO_2 emissions** by 82% compared to 1990 (Figure 13).

4.4 Scenario IV

The **building sector** (Figure 1) in SCEN IV is characterized by a balanced mix of all technical options. Electric heat pumps and gas burners each contribute roughly on e quarter to the heat demand. Biomass, district heating and solar thermal heat as well as some oil burners also provide space heat and hot water.

The striking feature of the **process heat** sector (Figure 2) is the dominance of biomass (29%) and a relatively strong (direct) electrification (20%). District heating also contributes significantly (17%). On the other hand, fossil energy carriers (gas: 18%, coal: 15%, oil: 1%) contribute in sum much less than in the other moderately ambitious scenarios. Synthetic energy carriers are not used here.

In the **passenger car** sector, SCEN IV relies strongly on BEVs (51%) and hybrids (27%), with minor contributions from conventional ICEs (14%) and gas motors (8%) (see Figure 3). FCEVs are not assumed to enter the passenger car market.

The dominant strategy to decarbonize the **road freight transport** at least partially is the use of trucks with gas motors, which account for nearly half of the truck fleet. BEVs and TTs contribute another 25%. Trucks with conventional combustion engines (19%) and hybrids (8%) lead a niche existence. FCEVs are not used at all.

The **final energy demand of the transport sector** is characterized by a relatively large direct electrification (23%) and a high gas demand (23%, of which 1% point is from biogas). Liquid fuels contribute slightly more than half of the final energy demand, the biofuel blending quota is 25%. Synfuels, SNG and Hydrogen are not used at all.

In SCEN IV, no synthetic fuels or gases (**P2X**) are used (see Figure 7).

The **gross power demand** in Germany is 547 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 102 TWh/a and 74 TWh/a, respectively.

In 2050, **power generation capacities** of 319 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (127 GW), PV (104 GW), and offshore wind (47 GW). Together, they account for 87% of the total installed capacity. Flexible power generation is provided by gas power plants (22 GW), biomass power plants (2 GW) and hydro power (6 GW). Geothermal power plants (2 GW) play a minor role. 5 GW of hard coal power plants are still in the grid, whereas lignite and oil power plants are phased out. Combined heat and power generation (CHP) still plays a minor role (10 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (342 TWh/a) and PV (114 TWh) dominate the power generation portfolio (share in gross power generation: 83%), backed by hydro power (25 TWh/a), natural gas (17 TWh/a), geothermal power (13 TWh/a), biomass (12 TWh/a) and hard coal (12 TWh/a). No net electricity imports are required in this scenario.

The demand for **district heat** is approx. 440 PJ/a (see Figure 11). Roughly 75% is generated in heating plants, the rest in CHP plants. The largest share is from natural gas (57%) and biomass (14%), but also waste and coal (8% each).

Biomass consumption is summarized in Figure 12. SCEN IV assumes a bioenergy demand of ca. 1.000 PJ/a. Most of the bioenergy is used in the industry sector (35%), the transport sector (21%), and in the residential sector (17%). Biomass consumption for the generation of electricity and district heat is comparably low (16% or 160 PJ/a).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct CO_2 emissions** by 82% compared to 1990 (Figure 13).

4.5 Scenario V

SCEN V's striking feature in the **building sector** is the high share of electric heat pumps (more than 50%, Figure 1). The remaining heat demand is primarily met by gas burners. About one fifth of gas consumption is generated synthetically (SNG). Biomass is not used at all in the building sector at all.

The characteristic feature of the **process heat** sector in SCEN V is the very high share of gas (almost two thirds, see Figure 2), followed by biomass (18%). As in the buildings sector, a significant share of the gas used in the process heat sector is synthetic natural gas (SNG). In contrast, the degree of direct electrification of the process heat generation is low (10%). Solar thermal heat is assumed to contribute 5% to the total final energy demand for process heat in this scenario. District heat is not used at all.

For **passenger cars** in Scenario V, it is noticeable that almost the half of the total mileage is provided by FCEVs. BEVs contribute another 15%. The share of hybrids is a low 12% (the lowest share of all 80% scenario), that of conventional ICEs is 20%. Gas motors contribute the remaining 6% to the total mileage (Figure 1).

The **road freight transport** is still dominated by trucks with conventional internal combustion engines (75%, see Figure 4). Innovative gas motors contribute another 7%. FCEVs (16%) and especially BEVs/TTs (3%) are barely gaining acceptance in the truck market.

Liquid fuels account for two thirds of the **final energy demand in the transport sector** (Figure 5). The (average) blending quota of biofuels is 19%. Synfuels make up 11% of the total liquid fuel consumption. The relative large share of FCEVs both in the car and the truck segment result in relatively high demand of Hydrogen (19%). Compared to the other moderately ambitious scenarios, direct electrification of the transport sector is the lowest (8%). Natural gas, biogas and SNG make up 6% of the total final energy demand in the transport sector.

In SCEN V, more than 600 PJ/a of **P2X** products are consumed in 2050 in enduse-sectors (see Figure 6, excluding H_2 consumption as feedstock for SNG and Synfuel production). Hydrogen is mainly used in the transport sector. Small amounts of H_2 are fed into the natural gas grid and used by natural gas consumers. However, these amounts of H_2 are not included in Figure 6. SNG (ca. 130 PJ/a) is mainly used in the building and process heat sector, but to a lesser extent also in gas motors (trucks and cars). Also almost 130 PJ/a of Synfuels are used in the transport sector. SCEN V assumes that P2X products are produced entirely in Germany (no P2X imports).

The **gross power demand** in Germany is 733 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 56 TWh/a and 22 TWh/a, respectively. Domestic generation of P2X requires 274 TWh/a.

In 2050, **power generation capacities** of 498 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (180 GW), PV (161 GW), and offshore wind (47 GW). Together, they account for 78% of the total installed capacity. Flexible power generation is provided by gas power plants (82 GW) and hydro power (6 GW). Biomass and geothermal power plants do not play a role. 21 GW of hard coal and 1 GW lignite power plants are still in the grid. Combined heat and power generation (CHP) still plays a significant role (40 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (435 TWh/a) and PV (176 TWh) dominate the power generation portfolio (share in gross power generation: 83%), backed by natural gas (incl. SNG, 79 TWh/a), hard coal (18 TWh/a), hydro power (15 TWh/a) and lignite (10 TWh/a). No net electricity imports are required in this scenario.

The demand for **district heat** is approx. 380 PJ/a (see Figure 11). Roughly 58% is generated in CHP plants, the rest in heating plants. The largest share is natural gas (78%), with smaller contributions from electric heat pumps and resistance heaters (9%) and others.

Biomass consumption is summarized in Figure 12. SCEN V assumes a low bioenergy demand of ca. 780 PJ/a. Most of it is used in the industry sector (38%) and as biofuels in the transport sector (30%). Bioenergy demand for power and district heat generation is comparably low (101 PJ/a, 13%).

All the decarbonization measures implemented in the end-use and conversion sectors yield a reduction of **direct CO_2 emissions** by 81% compared to 1990 (Figure 13).

4.6 Scenario VI

In SCEN VI, space heat and hot water in the **building sector** is mainly provided by electric heat pumps (ca. 40%). The remaining heat is mainly provided by district heat, biomass, solar thermal heat. Fossil fuel burners are not totally phased out - they still contribute 7% to the total final energy demand in the building sector.

For the provision of **process heat**, SCEN VI relies predominantly on biomass (35%) and direct electrification (29%). District heat also contributes 15%. Also in 2050, a certain amount of (fossil) natural gas and coal is used to generate process heat (7% and 13%, respectively). No synthetic gases (H_2 or SNG) are used.

The decarbonization strategy for the **passenger car sector** in SCEN X focuses on BEVs, which make up two thirds of the passenger car fleet. Almost all the remaining cars are hybrids; only 4% of the passenger car fleet still consists of ICEs. FCEVs do not enter the market; neither do gas motors.

In the **road freight transport**, the scenario relies largely on hybrid trucks. Only a few ICEs remain in the market and are supplemented by BEVs/TTs (12%-13% each).

The power train technologies in the car and truck segment largely determines the **final energy consumption in the transport sector** (Figure 5). In SCEN VI, liquid fuels make up more than 50% of the total final energy demand: 32% synfuels, 19% biofuels and 4% fossil fuels. 44% of the final energy demand is electricity, as a result of high shares of BEVs and hybrids in the car and truck sector. Neither FCEVs nor gas motors are used in the road traffic. As H_2 and gas are also not required for aviation, navigation, and rail, the transport sector does not consume any hydrogen nor methane (fossil, biogenic or synthetic).

In terms of **P2X** products, only synfuels for transport (365 PJ/a) are required in SCEN VI (see Figure 6). All synfuels are produced in Germany (no imports, Figure 7).

The **gross power demand** in Germany is 924 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 338 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 156 TWh/a and 119 TWh/a, respectively. Domestic generation of P2X requires 209 TWh/a.

In 2050, **power generation capacities** of 549 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (267 GW), PV (145 GW), and offshore wind (87 GW). Together, they account for 91% of the total installed capacity. Flexible power generation is provided by gas power plants (36 GW) and hydro power (7 GW). Biomass (1 GW) and geothermal power plants (4 GW) do not play a significant role. Coal and oil power plant are phased out. Combined heat and power generation (CHP) still plays a small role (5 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (691 TWh/a) and PV (159 TWh) dominate the power generation portfolio (share in gross power generation: 92%), backed by natural gas (incl. SNG, 25 TWh/a), hydro power (25 TWh/a), geothermal energy (15 TWh/a) and biomass (5 TWh/a). No net electricity imports are required in this scenario.

The demand for **district heat** is approx. 564 PJ/a (see Figure 11). Almost 90% is generated in heating plants, the rest in CHP plants. The largest share is from biomass (51%), electric heat pumps and electric resistance heaters (23%), and gas (10%).

Biomass consumption is summarized in Figure 12. SCEN VI assumes a bioenergy demand of ca. 1.230 PJ/a. Most of the bioenergy is used in the industry (33%), for power and district heat generation (28%) and in the transport (18%) and residential sectors (14%).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct CO_2 emissions** by 94% compared to 1990 (Figure 13).

4.7 Scenario VII

A characteristic feature of the **building sector** in SCEN II is that more than a third of the heat demand is provided by district heat. Also the share of biomass is comparably high (17%). Electric heat pumps and electric resistance heaters provide another third of the heat demand. The Remaining heat demand is met by solar thermal energy. Gas or oil boilers are not used any longer in this scenario.

For the provision of **process heat**, SCEN VI relies predominantly on biomass (34%) and direct electrification (including heat pumps, 32%). Gas burners are still in use (13%). They burn solely (fossil) natural gas. Hydrogen contributes with 9% to the generation of process heat. The remaining heat is provided by district resp. CHP heat (9%) and solar thermal process heat (4%).

The **passenger car** fleet in SCEN VII consists of BEVs (60%), FCEVs (25%) and Hybrids (PHEVs, EREVs). ICEs are no longer used, nor are cars with gas motors.

In the **road freight transport**, FCEVs dominate totally the market.

Due to the high shares of FCEVs in the truck and car sector, almost 50% of the **final energy demand in the transport sector** is Hydrogen in SCEN VII (see Figure 5). Biofuels (24%)and fossil liquid fuels (9%) are used in hybrid cars and in aviation and navigation. Electricity makes up the remaining 17%, it is used in BEV and hybrid cars as well as in electric trains.

In terms of **P2X** products, only hydrogen is used in SCEN VII (almost 1.300 PJ/a). H_2 is mainly used in the transport sector (Figure 5), but also for process heat (Figure 2) and for power generation (as a long term storage). The hydrogen required in the scenario is entirely produced in Germany (Figure 7).

The **gross power demand** in Germany is 1.129 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the enduse sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 147 TWh/a and 53 TWh/a, respectively. Domestic generation of P2X requries 500 TWh/a.

In 2050, **power generation capacities** of 568 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (135 GW), offshore wind (101 GW), and PV (101 GW). Together, they account for 61% of the total installed capacity. Flexible power generation is provided by gas power plants (93 GW), H_2 fuel cells (41 GW) and hydro power (7 GW). Biomass (44 GW) and geothermal power plants (30 GW) also play a significant role. Coal and oil power plant are phased out. Combined heat and power generation (CHP) make up 113 GW_{el}. To supply the net power imports of Germany, another 90 GW of installed capacity abroad (onshore and offshore wind, PV, CSP) are necessary.

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (529 TWh/a) and PV (110 TWh) dominate the power generation portfolio (share in national gross power generation: 74%), backed by natural gas (80 TWh/a), biomass (70 TWh/a), geothermal energy (35 TWh/a), hydro power (25 TWh/a) and hydrogen (fuel cells, 14 TWh/a). Furthermore, net imports of 262 TWh/a are expected in this scenario.

In SCEN II, the demand for **district heat** comparably high (721 PJ/a, see Figure 11). Two thirds is generated in heating plants, the rest in CHP plants. The largest share is from geothermal energy (31%), gas (30%), biomass (17%), solar thermal (12%) and waste (10%).

Biomass consumption is summarized in Figure 12. SCEN VII assumes a bioenergy demand of ca. 1.630 PJ/a. Most of the bioenergy is used in for power and district heat generation (35%) and in industry and transport (22% each).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct CO_2 emissions** by 94% compared to 1990 (Figure 13).

4.8 Scenario VIII

The striking feature of the **building sector** in this scenario is the very high share of electric heat pumps, which provide nearly 80% of the building heat demand. The remaining demand is almost entirely met by district heat. Only 2% of the building heat demand is provided by gas boilers (which use ca. 50% bio-methane and synthetic methane).

A striking feature of SCEN VIII is it's high degree of electrification of the **process heat** sector: Roughly one third each of demand for the process heat is covered by electricity and hydrogen, the majority of the remaining demand by gas burners. However, the gas burners use almost 40% SNG, which increases the share of direct or indirect electrification of the process heat sector to almost 80%.

The **passenger car fleet** is entirely dominated by BEVs.

The **road freight transport** is dominated by ICEs with Diesel motors (which mainly use synthetic fuels). BEVs/TTs make up only 6% of the truck fleet. Other power train technologies are not used.

As the truck sector almost entirely relies on diesel trucks and also the jet fuel is synthetically generated, the demand for synfuels is very high in SCEN VIII: Synfuels make up almost three quarter of the total **final energy demand in the transport sector** (Figure 5). Power contributes the remaining 27%, as a consequence of a BEV share of 100% in the passenger car fleet.

In SCEN VIII, more than 1.500 PJ/a of **P2X** products are required (Figure 6): 379 PJ/a Hydrogen (for process heat, without H_2 as feedstock for SNG and synfuel generation), 129 PJ/a SNG (fed into the gas grid) and more than 1.000 PJ/a synfuels (for transport, see Figure 5). The synfuels are entirely imported from abroad (Figure 7).

The **gross power demand** in Germany is 848 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the enduse sectors (Power-to-Heat and electric mobility in

BEVs and Hybrids) account for 169 TWh/a and 86 TWh/a, respectively. Domestic generation of P2X requries 210 TWh/a. Importing synfuels will require another 586 TWh of electricity (abroad) for synfuel generation. The total electricity demand (domestic and abroad) thus adds up to 1.434 TWh/a.

In 2050, **power generation capacities** of 551 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (243 GW), PV (215 GW), and offshore wind (52 GW). Together, they account for 93% of the total installed capacity. Flexible power generation is provided by gas power plants (33 GW) and hydro power (6 GW). Biomass and geothermal power plants do not play a role. Coal and oil power plant are phased out. No CHP plants are in the grid. To provide power for P2X generation abroad, which are then exported to Germany, another 348 GW (wind onshore, wind offshore, PV, CSP) are necessary (not shown).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), Wind onshore and offshore (565 TWh/a) and PV (235 TWh) dominate the power generation portfolio (share in gross power generation: 94%), backed by natural gas (incl. SNG, 29 TWh/a) and hydro power (20 TWh/a). No net imports of electricity are assumed in this scenario.

The demand for **district heat** is approx. 317 PJ/a (see Figure 11). 100% is generated in heating plants. The largest share is biomass (88%).

Biomass consumption is summarized in Figure 12. SCEN VIII assumes a restricted bioenergy consumption of ca. 641 PJ/a. Most of the bioenergy is used in for power and district heat generation (60%) and in industry (17%) and transport (16%).

All the decarbonization measures implemented in the end-use and conversion sectors yield a reduction of **direct CO_2 emissions** by 96% compared to 1990 (Figure 13).

4.9 Scenario IX

In SCEN IX, a large part of the heat demand in the **building sector** is covered by electric heat pumps. However, almost 20% is provided by gas burners, which use mainly SNG. Solar thermal heat and district heat contribute roughly 10% each.

The main characteristics of the **process heat** sector in SCEN IX is the strong reliance on SNG, which provides 57% of the heat demand (gas in total: 71%). The remaining demand is met by electricity (13%) and biomass (16%). Hydrogen, solar thermal energy, coil, oil or district & CHP heat are not used at all. The degree of direct or indirect electrification of process heat is thus 70% in this scenario.

The **passenger car fleet** is entirely dominated by BEVs.

SCEN IX relies on trucks with gas motors in order to decarbonize the **road freight transport**. They account for 60% of the vehicle fleet and use mainly SNG. Trucks with Hydrogen fuel cells (16%), Diesel motors (14%) and BEVs/TTs are also in use.

The remaining diesel trucks (which exclusively use synthetic Diesel fuel) as well as the synfuel demand in aviation lead to a high share of synfuels (36%) in the **final energy demand in the transport sector** (Figure 5). The high SNG demand (20%) is caused by the gas motor trucks, which use also lower quantities of biogas (1%) and natural gas (4%). The dominance of BEVs in the car sector (and - to a much lesser segment - in trucks) as well as the power demand for electric trains lead to a electricity share of 30%. H_2 consumption is comparatively low (8%); H_2 is used in exclusively in trucks.

In SCEN IX, almost 2.000 PJ/a of **P2X** products are required (Figure 6): 310 PJ/a Hydrogen (for transport and as feed-in into the natural gas grid, but without H_2 feedstock for SNG and synfuel production), more than 1.200 PJ/a SNG (for buildings, transport, process heat and power generation) and 462 PJ/a synfuels (for aviation and trucks). All P2X products are entirely generated in Germany (Figure 7)

The **gross power demand** in Germany is 1.525 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the end-use sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 73 TWh/a and 87 TWh/a, respectively. Domestic generation of P2X requires 949 TWh/a.

In 2050, **power generation capacities** of 1.219 GW are installed in Germany (Figure 9). Backbone of the electricity supply are PV (913 GW), onshore wind (183 GW), and offshore wind (50 GW). Together, they account for 94% of the total installed capacity. Flexible power generation is provided by gas power plants (68 GW) and hydro power (6 GW). Biomass and geothermal power plants do not play a role. Coal and oil power plant are phased out. Combined heat and power generation (CHP) are still significantly used (33 GW_{el}).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), PV (998 TWh/a)) and Wind onshore and offshore (448 TWh/a) dominate the power generation portfolio (share in gross power generation: 95%), backed by natural gas (incl. SNG, 62 TWh/a) and hydro power (15 TWh/a). No net imports of electricity are assumed in this scenario.

The demand for **district heat** in SCEN IX is comparably low (138 PJ/a, see Figure 11). About half of it is generated in heating plants, the rest in CHP plants. The largest share is from gas (incl. SNG, 77%), and biomass (12%).

Biomass consumption is summarized in Figure 12. SCEN IX assumes a restricted bioenergy consumption of ca. 758 PJ/a. Most of the bioenergy is used in the industry (46%), for power and district heat generation (37%) and transport (12%).

All the decarbonization measures implemented in the end-use and conversion sectors yield a reduction of **direct CO_2 emissions** by 96% compared to 1990 (Figure 13).

4.10 Scenario X

In the **building sector** in SCEN X it is striking that more than 40% of the heat demand is met by gas burners, which, in turn, use mainly SNG as fuel. The remaining heat demand is mostly provided by electric heat pumps. District heat, biomass and solar thermal heat each contribute 7% or less to the final energy demand for space heat and hot water.

Process heat is mainly provided by gas burners in SCEN X (53%), which use 85% SNG and 15% fossil natural gas. The remaining process heat demand is met by biomass (16%), electricity (15%) and Hydrogen (11%). Thus, the process heat sector is directly or indirectly electrified by 71%.

In this scenario, the **passenger car** fleet consists of approximately 30% each of BEVs, FCEVs, and Hybrids. Passenger cars with gas motors do not grow out of their niche existence. ICEs are no longer used.

In the road freight transport, SCEN X relies on a mix of FCEVs (34%), trucks with gas motors (30%, using mainly SNG and bio-methane), hybrids (23%) and BEVs/TTs (13%). The fuel for the hybrid vehicles is largely produced synthetically.

The broad technology mix both in the car and the truck sector results in an corresponding broad energy carrier mix in the **final energy demand in the transport sector** (Figure 5). Hydrogen (cars, trucks) accounts for the largest share (25%) of final energy consumption among all energy carriers, followed by synfuels (hybrid cars and trucks, aviation, 21%), electricity (BEVs, trolley trucks, railways, 19%), SNG (cars and trucks with gas motors, 13%), fossil fuels (13%), biofuels (8%), and smaller amounts of biogas.

P2X consumption amounts to more than 2.500 PJ/a (see Figure 6): 524 PJ/a Hydrogen (for industry, transport, and feed-in into the natural gas grid, but without H_2 feedstocks for SNG and synfuel production), almost 1.700 PJ/a SNG (for buildings, process heat and the transport sector) and almost 300 PJ/a of synfuels in the transport sector (aviation and trucks, see Figure 5). 88% (2.190 PJ/a) of the P2X products are imported from abroad (Figure 7).

The **gross power demand** in Germany is 662 TWh/a in 2050 in this scenario (Figure 8). "Classical" demand (illumination, information, communication, mechanical energy, cooling) in the end-use sectors consumes 313 TWh/a. New consumers in the end-use sectors (Power-to-Heat and electric mobility in BEVs and Hybrids) account for 55 TWh/a and 59 TWh/a, respectively. Domestic generation of P2X requires 171 TWh/a. Importing synfuels will require another 1.020 TWh of electricity (abroad) for synfuel generation. The total electricity demand (domestic and abroad) thus adds up to 1.682 TWh/a.

In 2050, **power generation capacities** of 388 GW are installed in Germany (Figure 9). Backbone of the electricity supply are onshore wind (206 GW), PV (88 GW), and offshore wind (35 GW). Together, they account for 85% of the total installed capacity. Flexible power generation is provided by gas power plants (41 GW), biomass power plants (9 GW) and hydro power (6 GW). Geothermal power plants do not play a role. Coal and oil power plant are phased out. Combined heat and power generation (CHP) are still significantly used (38 GW_{el}). To provide power for P2X generation abroad, which are then exported to Germany, another 348 GW (wind onshore, wind offshore, PV, CSP) are necessary (not shown).

The resulting **gross power generation** is shown in Figure 10. As expected from the installed capacities in this scenario (Figure 9), wind (onshore & offshore, 450 TWh/a) and PV (96 TWh/a)) dominate the power generation portfolio (share in gross power generation: 82%), backed by natural gas (SNG, 56 TWh/a), biomass (39 TWh/a) and hydro power (21 TWh/a). No net imports of electricity are assumed in this scenario.

The demand for **district heat** is approx. 182 PJ/a (see Figure 11). 85% is generated in CHP plants, the rest in heating plants. The largest share is from biomass (57%), and gas (incl. SNG, 38%).

Biomass consumption is summarized in Figure 12. SCEN X assumes a restricted bioenergy consumption of 1.077 PJ/a. Most of the bioenergy is used for power and district heat generation (37%), in the industry (24%), in transport (14%) and in the residential sector (12%).

All the decarbonization measures implemented in the enduse and conversion sectors yield a reduction of **direct CO_2 emissions** by 96% compared to 1990 (Figure 13).

List of Figures

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Note

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