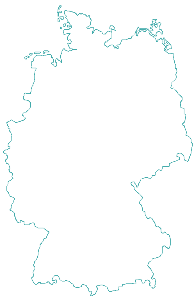
SIEMENS
Ingenuity for life



Position Paper

Siemens' Position on Decarbonization and Energy Transition in Germany

Key findings

- Reducing greenhouse gas (GHG) emissions by at least 80% by 2050 (relative to 1990) is technically feasible with existing technologies at a similar range of today's average annual total system costs
- Respective political measures needed to achieve the changes
- Required technological shifts focus on the following four major levers:
  1. Integration of fluctuating renewable energy that will have a >80% share in overall electricity generation by 2050 demanding grid extension, reinforcement and refurbishment, grid service and respective storage solutions
  2. Transformation of the conventional electricity generation towards flexible, low carbon power plants that will ensure security of energy supply and system stability
  3. A "sector coupling" approach for the heating, transport and industry sector through a combination of electrification and utilization of electricity-based synthetic fuels
  4. Intensification of energy efficiency as a basis to reduce overall primary and end energy demand along the entire value chain

Germany's energy transition

Germany is known worldwide as a global leader in renewable energy technology and for its plan to decarbonize its economy. By 2050 the country aims to achieve ambitious goals: An 80-95% reduction in CO_2eq emissions based on 1990 levels, at least an 80% share of renewable energy source in gross electricity consumption, and a 50% decrease in primary energy consumption based on 2008-levels. In order to achieve these targets by 2050, the country has to go a clear and manageable reduction pathway of CO_2eq emissions, as its aggregated CO_2 budget of 14 Gt (2015-2050) cannot be exceeded in order to stay in line with the 2°C target of the Paris Climate Agreement.

In order to radically cut Germany's total annual 887 Mt CO_2eq emissions (2015), the major focus has to be on energy, as 85% of these emissions are energy related, whereas only 15% stem from non-energy sources such as agriculture and industrial processes. 42% of the energy related emissions are generated by electricity production; the remaining emissions mainly arise from transport (28%), central heat generation for industrial processes (13%), and decentral heat generation for buildings (17%). That shows that, while a main focus has to be on the electricity sector, the decarbonization effort ultimately affects all sectors, including the transport, heating and industry sectors. And in all of these sectors, a balanced set of measures such as the electrification of heating and transport as well as the utilization of electricity-generated synthetic fuels from Power-to-X applications needs to be applied to drive the decarbonization of the economy forward.

The major focus of Germany´s energy transition is on the expansion of electrical power generation from renewable energy sources while simultaneously phasing out nuclear energy. Supporting policies have led to a 30% renewable share in gross electricity consumption in 2015, up from 10% in 2005. While this may read as a success, carbon emissions from electricity production decreased by only ~1% p.a. due to higher usage of coal, and that even increased after 2015. Therefore, to reach carbon reduction targets, the transformation of the conventional electricity generation to low-carbon emitting technologies is vital and needs to be a central pillar of the next phase of the energy transition. The second main pillar of the German energy transition is energy efficiency, e.g. with regard to buildings, industrial application as well as e-mobility in the transport sector.

Siemens' Approach

To be a leading partner in decarbonization for our customers and society, it is imperative to understand the technological and economic feasibility of a future low carbon energy system. This includes understanding the technological shifts needed for the next 30+ years, the costs these will imply and knowing when to take these steps. As an example for a country with an ambitious decarbonization plan we chose Germany to show what a transformation with at least 80% reduction in greenhouse gas (GHG) emissions could look like. For this purpose, comprehensive, multi-modal simulation tools were applied (see appendix), and we compared the results to external research studies. Obviously, the results depend on input parameters and certain assumptions – however sensitivity analysis has shown that the overall results are robust. And while these results are primarily valid for Germany, many countries will look similar when it comes to the main levers of decarbonization and transition pathways.

Required technological shifts

Reducing GHG emissions by at least 80% by 2050 relative to 1990 emissions is technically and economically feasible with existing technologies and requires a focus on the following four major levers:

1. Integration of fluctuating renewable energy that will have a >80% share in overall electricity generation by 2050 demanding grid extension, reinforcement and refurbishment, grid service and respective storage solutions.
2. Transformation of the conventional electricity generation towards flexible, low carbon power plants that will ensure security of energy supply and system stability.
3. A "sector coupling" approach for the heating, transport and industry sector through a combination of electrification and utilization of electricity-based synthetic fuels.
4. Intensification of energy efficiency as a basis to reduce overall primary and end energy demand along the entire value chain.

Digital technologies and emerging business models will enable all four of these levers. From the design and simulation of products, from processes and complete infrastructures through their operations and maintenance phases, digitalization will enhance complete value chains and amplify the above-mentioned levers, positively impacting CO_2 emissions. Digital solutions will for instance foster the integration of renewables, enable a faster transformation of the energy system towards a decentralized one, while optimizing the grid to ensure stable energy supply at all times.

Additionally, these levers will lead to an augmentation in overall electricity production capacity by 2050, roughly double the size of today, driven mainly by electrification of other sectors. Despite the increase in capacity, total primary energy use drops by nearly 40% due to utilization of more efficient technologies (e.g. electric motors for transport, heat pumps) for which predominantly renewable electricity sources are used. This should lead to a drop of almost 80% of fossil primary sources.

In order to close the gap between the increasing sustainable energy generation by renewables and consumption in economic centers, an extension of the transmission grid is indispensable. Reinforcement and refurbishment on a distribution level are crucial to provide an infrastructure for the future energy system that is able to manage an increasing electrification driven by sector-integration. The intelligent transmission and distribution grid therefore, with increasing flexibility needs, has to be enhanced by electricity interconnectors into a European grid.

Lever 1: Integration of fluctuating renewable energy

In order to decrease carbon emissions, we have to produce more electricity from carbon neutral sources. Of the 32% renewable share in electricity production in 2016, 19%-points are based on the fluctuating sources wind and solar. The share of renewables in electricity production however will rise to >80% with onshore wind energy having the largest share followed by solar PV. Hence the integration of variable renewable generation will become a system challenge with regard to grid design and system stability demanding a more dynamic grid operation, respective storage capacities for voltage and frequency control and an advanced demand side management avoiding re-dispatch.

Electrical storage solutions can compensate short-term electricity shortage to stabilize daily load profiles and improve grid stability, but, based on current cost estimations, are not feasible to act as a long-term storage solution. For this purpose, gas-fired power plants with both Combined Cycle (CC) and Single Cycle (SC) turbines can provide the necessary backup power and keep the energy system flexible and reliant. In times of temporary oversupply by renewables, heat storage (low and high temperature) also becomes an important technology, which can preserve energy and is – under current cost assumption compared to electrical storage system – a competitive technology. In addition, Power-to-X technologies such as power-to-hydrogen are another key lever to balance consumption vs. renewable production. By transforming renewable based surplus electricity to gaseous or liquid fuels this storage provides an option for high volume, long-term seasonal energy storage. Additionally, it can be used for other sectors' mainly industrial processes and transportation. Synthetic fuels from renewable sources will therefore undoubtedly gain importance.

In order to close the gap between increasing sustainable energy generation by renewables and consumption in economic centers, an extension of the transmission grid is also indispensable. An optimized combination of DC and AC transmission as well as underground gas-insulated transmission lines (GIL) will be the backbone of a reliable transmission grid. This demand will be even more amplified by an increased electricity need resulting from sector integration.

In addition, an intensive grid extension, reinforcement and refurbishment on a distribution level are crucial to provide an infrastructure for the future energy system that not only balances local generation, distributed energy systems and storage, but also e-mobility and flexible demand side management. Such a grid extension and refurbishment will integrate hardware, automation and digital technologies. Grid services and grid cyber-security will enable a maximum of security of supply and grid resilience. Furthermore auxiliary services managing the necessary flexibility will be increasingly important within a smart market. Finally, the intelligent transmission and distribution grid with its increasing flexibility needs has to be enhanced with the help electricity interconnectors embedding it within the European grid.

Lever 2: Transformation of conventional electricity generation

The decarbonization of the conventional power generation towards a flexible, reliable and most of all low-carbon emitting system is vital to decarbonize the energy sector. The reason being that conventional energy generation will remain indispensable for the next decades in order to keep power available for the energy system.

Gas fired power plants, both CC and SC turbines, and gas engines, will play a major role for decarbonization. During the first transition years they will act as base load and as intermediate system. Later, with an increasing share of renewables in the system, they will be used more and more as a backup system. The choice of technology will depend on load factors, on the application – e.g. Combined Heat and Power generation (CHP) or peaker plants, which run only during peak power demand –, on the requirements on flexibility and on the supply purpose (e.g. public vs. self-supply). Gas engines, for example, are very suited for self-supplying systems because of their flexibility, and they are an important lever for distributed energy systems (DES).

For backup electrical energy supply, which due to its nature runs on low full load hours, technologies with relative low investment cost will gain importance: For example SC gas turbine power plants in combination with energy efficient technologies such as flexible, efficient CC power plants.

An early coal-to-gas shift, starting this decade, comes at low CO_2 abatement cost and can contribute to a 50% CO_2 reduction by 2035, simply by higher efficiency of CC power plants and the lower carbon intensity of natural gas in comparison to coal. As such, electricity generation from gas compared to 2015 will double by 2050 while coal will be phased out. However, as gas for heating gets gradually replaced, overall consumption of natural gas will approximately halve by 2050.

Additionally, the gradual decarbonization of conventional power allows for time to advance various other technologies, e.g. drive down costs for e-mobility or implement game changing new technologies yet to be developed. A delay in retirement of coal fired power plants will increase overall system cost and demand a shift to other sectors, e.g. a faster electrification of the transport sector in order to meet Germany's ambitious emissions reduction goal.

Finally, when aiming for a carbon-free, reliable energy supply, a fuel switch from natural gas towards green synfuels will also be necessary.

Lever 3: Sector coupling for the heating, transport and industry sector – Electrification and Electricity-based synthetic fuels

Sector integration is an important building block to reach overall emission reductions as it enables higher efficiency, supports system stability and balances renewable energy generation and cross-sectoral demand. A measured approach of electrification as well as utilization of synthetic fuel production for the heating and transport sector not only makes economic sense, it ensures the energy system's security, power supply and flexibility.

Integrating the heating sector

As of today, heating is mostly generated through fossil fuels with renewables having merely a 13% share. Electrification of decentral and central heat plays a decisive role in the decarbonization of the industry and building sector, thereby gradually replacing fossil fuels.

Whereas decentral heating is mainly electrified through heat pumps combined with utilization of solar thermal systems, we see a shift towards a mix of biomass, resistive heater and heat pumps for the electrification of central heating (industrial and district heating). From an economic point of view, the electrification of central heating should happen sequentially: In the first decades, electrification of heat at temperatures of <150 °C through conventional and novel high temperature heat pumps in combination with resistive heating and thermal energy storages. Heating at higher temperatures (>150°C) will still be mainly fueled by combustion of gas and coal. At this higher range, utilization of biomass and electrification due to higher costs is likely to happen mainly in the final decades before 2050. But these technologies can then substitute gas and coal to achieve the utmost final CO_2 targets. In this higher temperature range electrification is also in competition with electricity-based synthetic fuels, where we estimate a significant share of overall synfuel application.

Building insulation, which can decrease general heating demand by almost 20%, only considering new buildings, best goes hand in hand with building automation. Apart from additional savings, building automation also addresses comfort effects such as ensuring good air quality Furthermore, ithelps to ensure high efficiency levels over long time and is a prerequisite to integrate the building infrastructure into the electricity system, flattering load profiles while contributing to system stability. In combination, both measures allow finding the right tradeoff between cost, energy savings and ecological lifecycle.

Finally, heat storage in the low and medium temperature range is identified as a main lever for balancing demand and supply. Heat storage can maximize the energy savings and energy efficiency potential of other technologies, can facilitate the use of renewable and waste heat and improve flexibility. Nevertheless, taking autarchy into consideration, electrical storage systems in decentral units, are expected to play an important role and eventually will become an indispensable part of any decentral energy system (DES) application.

Integrating the transport sector

In contrast to the heating sector, electrification of some parts of the transport sector has already happened. Today, rail and public transport in cities (subway, trams, urban trains) are close to a 100% being run by electric power. In line with the growing demand for public transport this sector certainly will continue to grow. A further modal shift from individual transport to public transport, road to rail would be an additional lever for decarbonization. However this possibility was not taken into account for the simulations underlying our results, since the share of public transport/rail has rather decreased in the past, despite stated political goals to increase it.

In comparison to rail, the road transport sector relies heavily on combustion engines, and continues to grow both globally and in Germany. In 2017 alone, more than 45 million passenger's cars were registered in Germany, almost 2% more in comparison to the previous year. Hence, similar to the heating sector, electrification, together with electricity-generated synthetic fuels, plays a decisive role to decarbonize the road transport sector. Due to current costs and km reach, we expect a significant share of electrified vehicles mainly after 2030. Also, infrastructure like charging stations need to be installed nationwide first so that road transport can deliver its share to the overall decarbonization of the economy. In parallel, green synfuel applications such as hydrogen in refineries or methanol based vehicles will improve the conventional fuel mix and hence lower overall emissions.

Whereas electrification of passenger transport is mainly driven by e-cars, for long-hauled freight transport e-highway trolley systems represent a high potential, flexible technology. Operations in sections without overhead catenary infrastructure can be achieved by equipping trucks on e-highways with hybrid solutions such as batteries or Power-to-Gas/Power-to-Liquid solutions. For short distances (e.g. delivery trucks in urban areas), battery driven vehicles become an attractive technology.

The electrification of the road transport sector (both passenger cars and freight road transport) as well as utilization of electricity-based synthetic fuels will lead to a reduction in liquid fuel (crude oil) demand by almost 70%, which in turn will make Germany also less dependent on oil imports.

Besides road transport, decarbonization of the air and sea transport sector is of utmost importance and will be driven through a combination of electrification including hybrid systems and synfuel utilization, e.g. hydrogen. Of the total cost of ownership, fuel consumption for today's aircrafts has a >50% share. Hybrid or full electric drives will lower overall fuel consumption and increase aerodynamic efficiency by distributed propulsion. They also will have significant lower noise effects which is especially relevant for night air traffic at airports. Hybrid propulsion systems below 100 seats are expected to enter the market by 2030. For larger planes, electricity-based synthetic fuels will be utilized.

For the shipping sector, we see an increasing demand for on-shore power supply to decrease CO_2 as well as particulate matters emissions such as PM10. For example, the combustion of marine fuels to generate electric power during lay times in ports is a major contributor to local air pollution. Within eight hours a berthed cruise ship produces approximately as many emissions and particular matter as 6,000 cars driving 1,000 km. With Siemens' SIHARBOR shore connection system, berthed ships can draw the energy they need from onshore without having to use their own generators. This way they can meet increasingly stronger environmental regulations at ports worldwide. Sea traffic is responsible for about 2% of the global emissions and likely to increase by 50-250% in 2050. Hybrid drive systems for ferry boats use excess energy which is stored in batteries to drive without diesel combustion. With the hybrid system up to 15% of CO_2 Emissions can be reduced. A study shows that alone in Norway it is profitable to substitute 7 out of 10 ferries by battery driven or hybrid alternatives.

Finally, in comparison to other sectors, innovative disruptions and game changing technologies are likely to occur in the passenger transport sector through behavioral changes such as increasing sharing options or autonomous vehicles on the road and in the air, which should reduce the number of vehicles but also further increase overall travel kilometers and electricity demand.

Integrating Industry

Decarbonization of the industry sector is not only needed for energy related emissions arising, e.g. from heat processes (see above), but also from processing feedstock, which so far is mainly based on fossil fuels and raw materials. For example, in industrial processes 'green hydrogen' might be the front-runner for the implementation of synfuels in energy systems. In addition, green hydrogen can be used for hydro-treating crude oil or as a reducing agent.

Finally, to reach the utmost CO_2 emission reduction target of >90%, carbon capture and storage (CCS) solutions for non-energy related emissions such as lime decomposition for the cement industry could also be a viable option.

Lever 4: Energy efficiency

Energy efficiency is another very important means to reach overall emission reduction targets by reducing overall primary energy demand. It is based on efficiency measures from the demand as well as the generation side.

On the demand side, it implies technologies such as highly efficient electrical drives, heat pumps, building automation, trains and so on. On the generation side fuel utilization efficiency is vital, e.g. co-generation of power and heat (CHP) wherever applicable. Moving towards a more holistic and systematic approach of energy systems, efficiency can be further increased by integrating an energy management system with distributed energy solutions. This enables flexibility both on the generation and demand side, e.g. for intelligent load shifting.

Despite the fact that from a cost-optimized perspective, direct electrification of heating and transport sector leads to an increase by almost 50% in electricity demand, total primary energy use drops by nearly 40%. This is mainly due to the utilization of more energy efficient technologies such as electric motors for transport or heat pumps. For these technologies preferably renewable electricity sources are used, which therefore should lead to a drop of almost 80% of use of fossil primary sources until 2050.

Economic implications

Despite these energy system changes, we see that the average annual total system costs to achieve an overall 80% GHG reduction target are expected to be in a similar range compared to the base year 2015 (with taking an annual investment with a depreciation of ten years into consideration).

In addition, we see a strong shift from an operational expenditure (OPEX) dominated system, which is reliant on massive import of fossil fuels to an energy system, where capital expenditure (CAPEX) considerations play a much higher role. This results in a higher importance for power plant investment conditions, e.g. financial risks, predictability of political measures, or marketable full load hours. Hence an alternate market design is needed, e.g. one that rewards firm capacity.

In comparison to the continuation of the existing system (business as usual without any further limitations on CO_2 emissions) the system costs are certainly higher. But this would come at a very high price: The target incl. aggregated CO_2 budget of 14 Gt and therefore the necessary climate change counter measures would not be achieved.

Political recommendations

The above mentioned changes will not be achieved without respective political measures – some of them are described below. Neglecting or postponement would lead to increased total system cost and a shift towards intensifying other levers, e.g. earlier adaptation of electric transport.

1. Ramp up of renewable energy

Fluctuating renewable energy is low in OPEX and high in CAPEX. Investment conditions, in particular the cost of capital, play a major role for a cost-effective deployment of renewable and should be at the heart of political considerations. Ideal investment conditions require predictable, trustworthy, linear and technology-specific extension plans for renewable energy. Extension plans should be visible early, include a long-term perspective, and their ambition should be in line with the agreed climate targets. To address market-related risks, market-based dispatch should be supported by clear curtailment rules.

2. Switch of remaining conventional electricity generation to low carbon fuels and redesign of the electricity market

In addition to a ramp up of renewable energy there is a need to accelerate the switch of the remaining conventional electricity generation to low carbon fuels and to redesign the electricity market to ensure sufficient investment into a sustainable, secure and efficient energy system.

Because decarbonizing the conventional electricity mix is becoming the major challenge to meet climate commitments policy makers should implement measures that drive a predictable exit for the most CO_2 intensive power plants. Additionally, electricity markets need to be redesigned to trigger investments in a clean, reliable and affordable energy system decoupled from out-of-market payments or support schemes.

3. Accelerate the decarbonization of other sectors with sector integration

Transport: Policy makers need to push for eMobility solutions – on roads, for trains, busses, shipping and air. Road-based eMobility solutions, next to the "shift to rail", are the key driver for an efficient and sustainable future of transport. Especially emissions from road freight are significant and set to grow even further. eHighway, Siemens' electrified heavy road freight solution, enables significant emissions reductions and cost competitive truck operations at the same time.

To reduce the increasing GHG emissions in Road freight transport, based on the expected results of eHighway-pilot projects in Germany, we recommend a roll out of a catenary infrastructure and hybrid-catenary trucks. The benefits to Germany could be even greater if its implementation was coordinated internationally. Therefore Germany should begin work on the international coordination without any delay, preferably on an EU-level.

Power-to-X Technologies: Power-to-X can help decarbonizing, e.g. the industry or transport sector. Green hydrogen produced by wind or solar energy could substitute "grey" hydrogen (today about 99%) produced by natural gas or liquid gas. The use of green hydrogen alone within the desulphurization process for diesel and petrol production could reduce CO_2 emissions by 90%.

In the steel industry there are also pilot projects ongoing aiming demonstrating how green hydrogen can contribute to the decarbonization of CO_2-intensive processes.

Policy makers are therefore asked to adjust the regulatory framework which hinders the use of Power-to-X technologies, such as the green hydrogen usage in industrial processes (refineries, chemicals, etc.) for CO_2-reduction.

4. Use energy as efficiently as possible

Not wasting energy is a cost-effective pillar of a low-carbon economy as it reduces the need for capital intensive investments in the electricity sector.

For that reason, the "Energy efficiency first" principle should be underpinned by a politically agreed upon, binding ambitious energy efficiency target. At the same time, the policy should be technology neutral: It should be the task of the market players to find the best and most cost efficient solution to reach the target.

Additionally the political and regulative framework should be long lasting and avoid negative interdependencies which lead to conflicting incentives in the market. Also, policy makers should sharpen the public awareness for energy efficiency and promote – through digitalization – energy monitoring. This, in turn, necessitates the implementation of energy management systems.

Finally, it takes clear incentives for investments in energy efficiency, e.g. via public R&D support schemes or tax credits.

5. Introducing carbon pricing

Putting a price on carbon should capture the true cost associated with carbon emissions. It should be sufficiently relevant to trigger a shift towards low-carbon technologies in line with the commitments of the COP21 Paris Agreement.

In Europe, the mere volume-based emission trading scheme has not delivered the desired effect. Germany and other EU member states have introduced a variety of policy measures reducing CO_2 emissions and in consequence distorting the carbon market. This will not change. In consequence, Siemens considers introducing carbon pricing mechanism inevitable. This could take the shape of a carbon tax or a cap & trade scheme with a relevant price floor. The predictable price signal is crucial to create a reliable framework for investors.

Additional policy measures should be taken to limit the risk of undermining the decarbonization effect of carbon pricing. Siemens supports the European Commission's proposal to introduce a cap on CO_2 emissions in EU legislation.

Siemens joined the Carbon Pricing Leadership Coalition of the World Bank (CPLC) in 2016 to advocate the introduction of carbon pricing globally.

Appendix

Description of scenario modeling approach

Within Siemens, a broad range of experience exists regarding modeling and simulation tools. In order to derive the findings of this white paper, two main types of simulation tools were used.

Overview of the ESDP modeling approach

The ESDP (Energy System Development Plan) tool is a Siemens in house development for energy system optimization. It features a cost-optimizing macroeconomic (partial) equilibrium model that simultaneously optimizes both the (hourly) operation schedules and the capacities within an energy system. A macroeconomic cost function is constructed covering the investment, fixed and variable operation costs of each technology as well as its transportation infrastructure. Costs are aggregated over several simulated years and discounted to a net present value in today's terms that is effectively optimized to yield the system's optimal development pathways. The modeling approach is multi-modal, i.e. allows directly considering couplings between several energy sectors, like electricity, heat, or gas. The system can be parameterized to either optimize the energy system for single years of interests, but is typically operated to determine optimal development paths from today onwards for a chosen horizon of interest. The model can be employed for point model studies that allow for a compact data preparation, or can model several distinct regions with the required interconnection capacity in between. The system allows defining several scenarios that can either be determined as the fully cost optimized solutions or be more or less determined by user choices. One or more main development scenarios are typically enriched and compared with several sensitivity analyses. The tool thus allows a holistic and robust view of the possible developments paths of an energy supply system.

The main inputs to ESDP are

- Technology Map ("Tech Map"): available technologies and their technical and economic description (e.g. efficiency, investment costs per installed power, technical and financial lifetime, ...), different scenarios, and scenario-dependent side conditions (e.g. fixed capacities for some technologies)
- "Volume data": large data sets such as the time-dependence structure of a given demands or renewable availability time series (based in weather data, possibly with regional resolution).

The primary outputs are operation schedules for each technology, cost-optimal capacities for technology to be optimized and market prices for each of the modeled energy forms for each modeled hour, assuming perfect market conditions. From these primary outputs further secondary outputs can be derived, as total system costs and CO_2 emissions, technology specific CAPEX, OPEX, and annual revenues per kW, or statistics on the required flexibility of a technology's operation.

'DeCarb' modeling of the Division Power and Gas

The 'DeCarb' model has been setup within Siemens PG to analyze the deep decarbonization path by a sector coupling approach for Germany. Energy demand, energy mix and CO_2 emissions are separately modeled for the different end-user sectors such as industry, transport, heat supply and power generation. Main guideline for the modelling is the 'Klimaschutzplan 2050' defining the CO_2 emission reduction targets up to 2050 on a sector by sector basis. For each sector clean-energy technologies are evaluated in terms of ability to replace previous fossil fuel based techniques. Technologies are evaluated related to their efficiency level, CO_2 emissions, cost and economics using numerous external studies as reference for current status and future development of efficiency and CAPEX and OPEX cost. Basic assumptions of scenario analysis such as economic development and general energy demand projection is taken from IHS Rivalry scenario.

All clean-energy technologies are characterized in general by electrification of previously fossil fuel based applications. If power is mainly generated by renewables in the longer run, this results in significant reduction of emissions. For applications where direct electrification doesn't fit because of e.g. limited range or insufficient energy density (e.g. aviation, shipment, high temperature industrial heat) 'green synfuel' (hydrogen, methane, methanol) with production based on renewables are considered. Some technologies (e.g. e-mobility and heat pumps) also provide a substantial advantage in overall efficiency and thereby lower overall energy demand. The timed implementation of the technologies, starting point and amount, is defined by the projected status of technologies and predetermined emission reduction by the time.

Besides modeling of a sufficient energy supply a special focus is given to security of supply. In a sector coupling approach, power becomes the backbone of total energy system. On the other hand power generation would be mainly based on renewables characterized by fluctuating generation. In modeling 'green synfuels' are identified as important pillars to sustain supply security beside battery storage and demand side management.

Main outputs of the modeling are the sectoral energy demand and CO_2 emissions, the energy mix and the required capacities by technologies. Main outputs are verified by reference to external studies dealing either with an entire sector coupling or a single sector modeling for Germany. Special reference is done to the Fraunhofer-ISE study 'Was kostet die Energiewende?" as the most comprehensive study available so far.